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SOIL CHEMISTRY

Assessment of Metal Pollution of Roadside Landscapes in the North of Western Siberia Using Statistical Modeling

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Abstract—The article presents an assessment of roadside soil and plant pollution by motor vehicles in the Arctic zone of Western Siberia. The studies were conducted on the Surgut-Salekhard highway near Novy Urengoy and on one of the winter roads south of the town of Tazovsky. A detailed geochemical characteristic of the parent rocks and soils in the study areas is provided. Chemical pollution was mild, since northern roads usually have low to medium traffic intensity. Statistical modeling based on the consistent application of factor and discriminant analyses of multivariate statistics was used to detect and identify pollutants and the pollution level. It has been shown that the Cd–Pb–Zn–Cu–Ni association in soils indicates the motor vehicles pollution. An additional source of impact in the urban area was residential construction through the Ca–Mn–Co–Sr–Zn association. Similar parageneses have been identified in the study of the solid phase of snow collected at the soil sampling sites, indicating the decisive role of aerotechnogenic transfer of metals in pollution of natural and urban environments. Low activity of lateral and radial migration of metals has been shown even in an acidic medium, attributed to the widespread peat horizon that functions as a compound geochemical barrier: alkaline, biogeochemical, and sorptive. A change in the chemical composition of indicator plant species has been established, caused largely by aerotechnogenic transfer of metals coming from motor transport and road surfaces. Soil pollution within the former winter road and in roadside landscapes has been found to be local. However, there were traces of disturbed soil cover, and soil thawing and an increase in the seasonally thawed layer thickness have been established. In general, chemical pollution caused by the impact of motor transport was not pronounced, and the content of the studied metals was below the standards established for soils (MPC and TPC). Calculation of the toxicity probability index (MERMQ) for contaminated soils showed low to moderate risk levels.

Keywords: soils, parent rocks, discriminant analysis, geochemical associativity, indicator plant species

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INTRODUCTION

Anthropogenic impact on Arctic landscapes is mainly caused by economic minerals extraction, industrial operations, urbanization, and motor transport. The development of natural resources in the Far North is linked to the construction and expansion of the road network. In the Yamal-Nenets Autonomous District, the total length of motorways is 5664 km, of which about 1000 km are winter roads [16]. The 344 km Salekhard-Nadym motorway is currently under construction. There are a large number of dirt roads within the licensed areas. At the same time, the growth of traffic load on northern ecosystems is associated with the risks of chemical pollution of roadside landscapes, in particular with heavy metals. The task of identifying pollutants entering the environment through road and vehicle operation has been largely solved: sources and their corresponding metal groups have been identified [5, 28, 34, 35].

The assessment of the impact caused by motor vehicles is often based on the study of the chemical composition of snow cover [18, 25, 26, 28, 34]. This is a reliable and inexpensive way to obtain information about the entry of pollutants through airborne transport. In the Arctic zone, most motorways are classified as roads with low or medium traffic intensity, which, as a rule, causes but a mild impact on natural complexes, manifested in low concentrations of metals in roadside soils [12, 32]. This is partly due to the leaching regime of northern soils, reducing the possibility of pollutant concentration. As a result, research is more often focused on snow cover or rain runoff pollution, while direct assessments of Arctic soil pollution from vehicle traffic are less common [9, 19, 29].

Increased dust load on roadside landscapes leads to higher soil alkalinity, which is especially noticeable given the low pH values of soils in tundra environments. A significant increase in the acid-alkaline

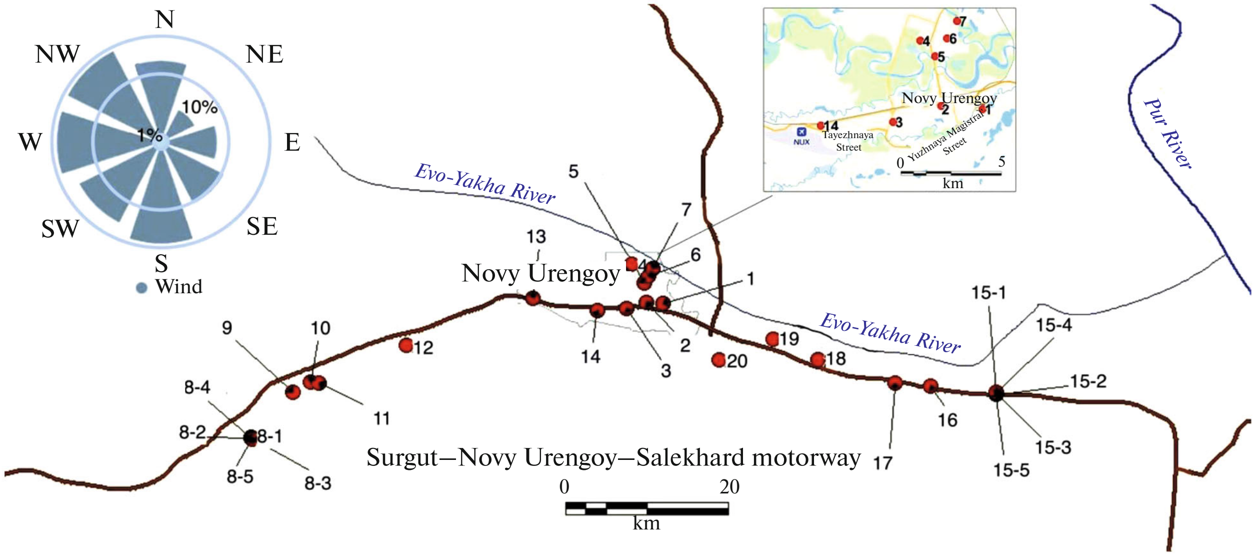

Fig. 1. Location of the sampling sites network along the Surgut—Novy Urengoy—Salekhard motorway.

index leads to a change in plant communities [27] and a decrease in metal mobility [20, 30, 32, 35, 36].

The aim of the study was to identify the role of motor vehicles in the contamination of tundra natural environments adjacent to highways and winter roads with metals. The research objectives included:

— assessment of the chemical composition of parent rocks;

— study and characterization of acidic-basic properties and chemical composition of soils;

— statistical modeling and assessment of soil pollution levels caused by motor vehicles in the study area;

— determination of the status of indicator plant species in areas affected by motor vehicle traffic.

OBJECTS AND METHODS

The study objects included the Surgut—Novy Urengoy—Salekhard motorway within the Nadym-Pur interfluve, and the former special-purpose winter road (i.e., a road laid on snow without a hard surface) that had been in operation about ten years ago within the Tazovsko-Zapolyarnoye license area situated in the Pur-Taz interfluve (northern section). The study was conducted on a 100 km section of the motorway: more than 50 km to the west (western section) and about 45 km to the east (eastern section) of Novy Urengoy, as well as within the city itself (urban section) (Fig. 1). While there are no official data on traffic intensity in the studied sections of the motorway, visual observations and the logistical importance of these directions suggest higher traffic loads in the eastern section. The special-purpose winter road had been used for several years to transport drilling equipment and support geophysical and drilling operations. The research was conducted in 2021—2022.

Within the study area, a continuous layer of Quaternary deposits covers the eroded surface of Paleogene continental sediments. The upper part of the section is divided into the Middle and Upper Neopleistocene and the Holocene. In the western section of the motorway and in the winter road area, the Quaternary sediment is represented by alluvial-marine deposits of the fourth marine terrace of the Upper Neopleistocene (am^4III), composed of sandy and silty (motorway) as well as silty and clayey (winter road) sediments. In the eastern section, the parent materials are alluvial deposits of the second fluvial terrace, Upper Neopleistocene in age (a^2III), represented by sands, silt, peat, and modern alluvial (aIV), mostly sandy deposits of the Evo-Yakha River [1].

The predominant soils in the study area are podburs (typical and iron-illuvial), Entic Podzols, loamy sands and sandy loams with poorly developed subsoil, peat gley podburs, Histic Podzols, medium and clay loams with well pronounced organic surface horizons involved in peat formation (up to 0.2 m thick), and iron-illuvial podzols, Albic Podzols, predominantly loamy sandy. The depth of the seasonally thawed layer (STL) is over 2 m. Poor drainage and low evaporation lead to the development of bogging and the formation of typical tundra gley soils, Stagnic Gelic Gleysols, and clay loamy peat gley soils, Histic Gleysols. The depth of the STL varies greatly: in the southern part of the study area, it can be 1.5 m or more, while in the northern background areas, it ranges from 1.0 to 1.5 m. Peat oligotrophic soils, Histosols, are widespread, ranging from 0.4 to 0.7 m in depth. Surface horizons are characterized by varying degrees of peat decompo-

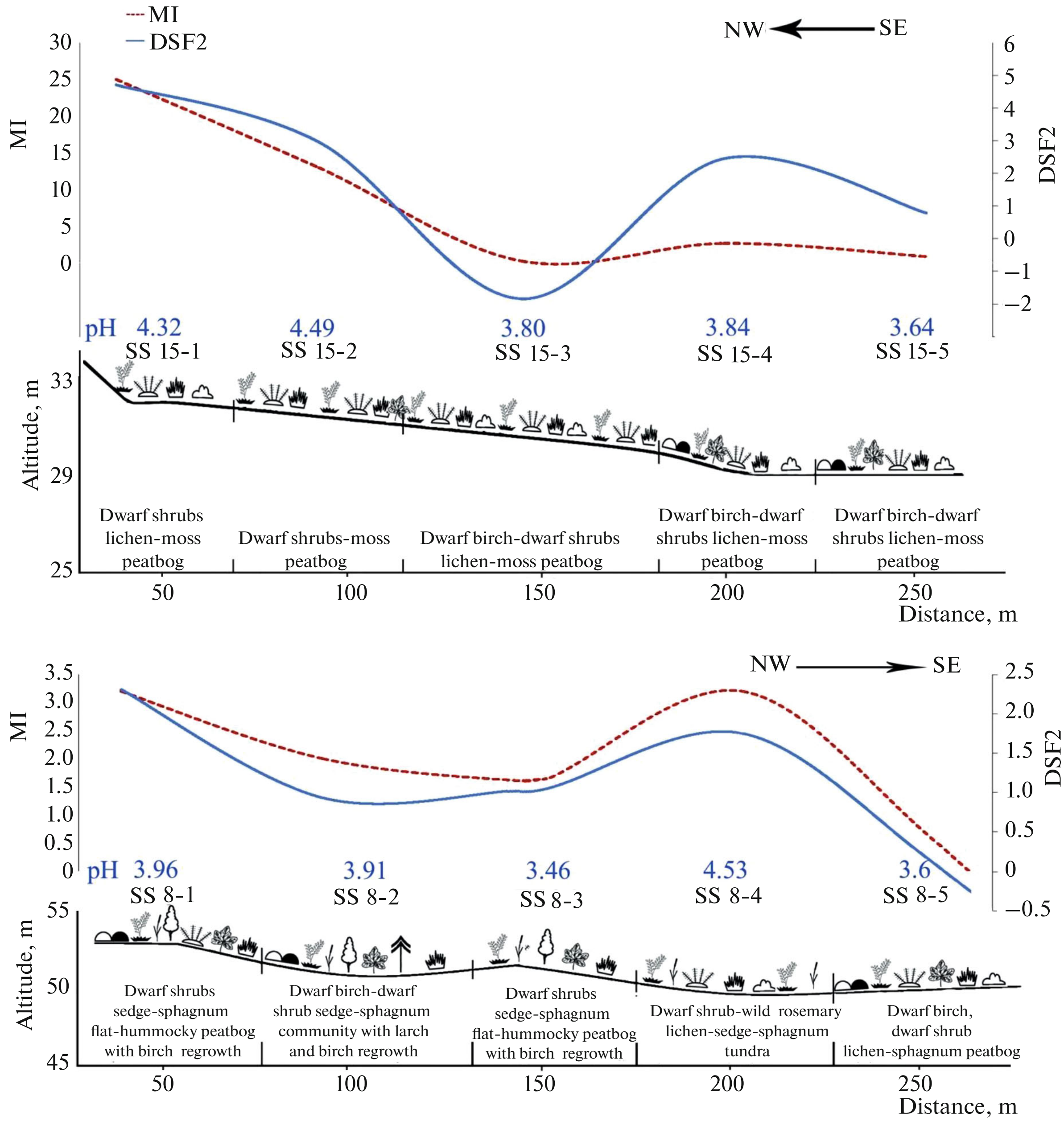

Fig. 2. Ecological geochemical characterization of the organic soil horizon (pH, multiplier index (MI), discriminant scores of the function (DSF2) at sampling sites) at transects 15 (eastern section) and 8 (western section). MI is the multiplier index of Pb and Cd content in the organogenic soil horizon; DSF2 stands for the discriminant scores of function 2 (pollution by motor vehicle traffic).

sition. Cryoturbation processes are observed. A common characteristic of the soils is their mosaic microrelief. Urbikvazizems predominate in urban areas.

Peat oligotrophic soils are found in three study areas (except for the urban area). In the north, there are also typical tundra gley soils. The western section is characterized by podburs (typical, peat, and peat-gley) and iron-illuvialpodzols. Podzols are found in the eastern section, and psammozems along the river banks.

Soil samples along the motorway, winter road, and within the city of Novy Urengoy were taken from all genetic horizons (O, B, and C) in accordance with the requirements of GOST standard 17.4.3.01-2017. Along the motorway, soil samples were taken at 50 m from the road shoulder. Transects consisting of five sampling sites were laid out in the western and eastern sections at 50 m intervals perpendicular to the road (Fig. 2). The sampling sites within the city are located in different microdistricts in areas affected by road and rail transport. Within the Tazovsko-Zapolyarnoye license area, sampling was carried out along two transects crossing several typical tundra natural complexes: one

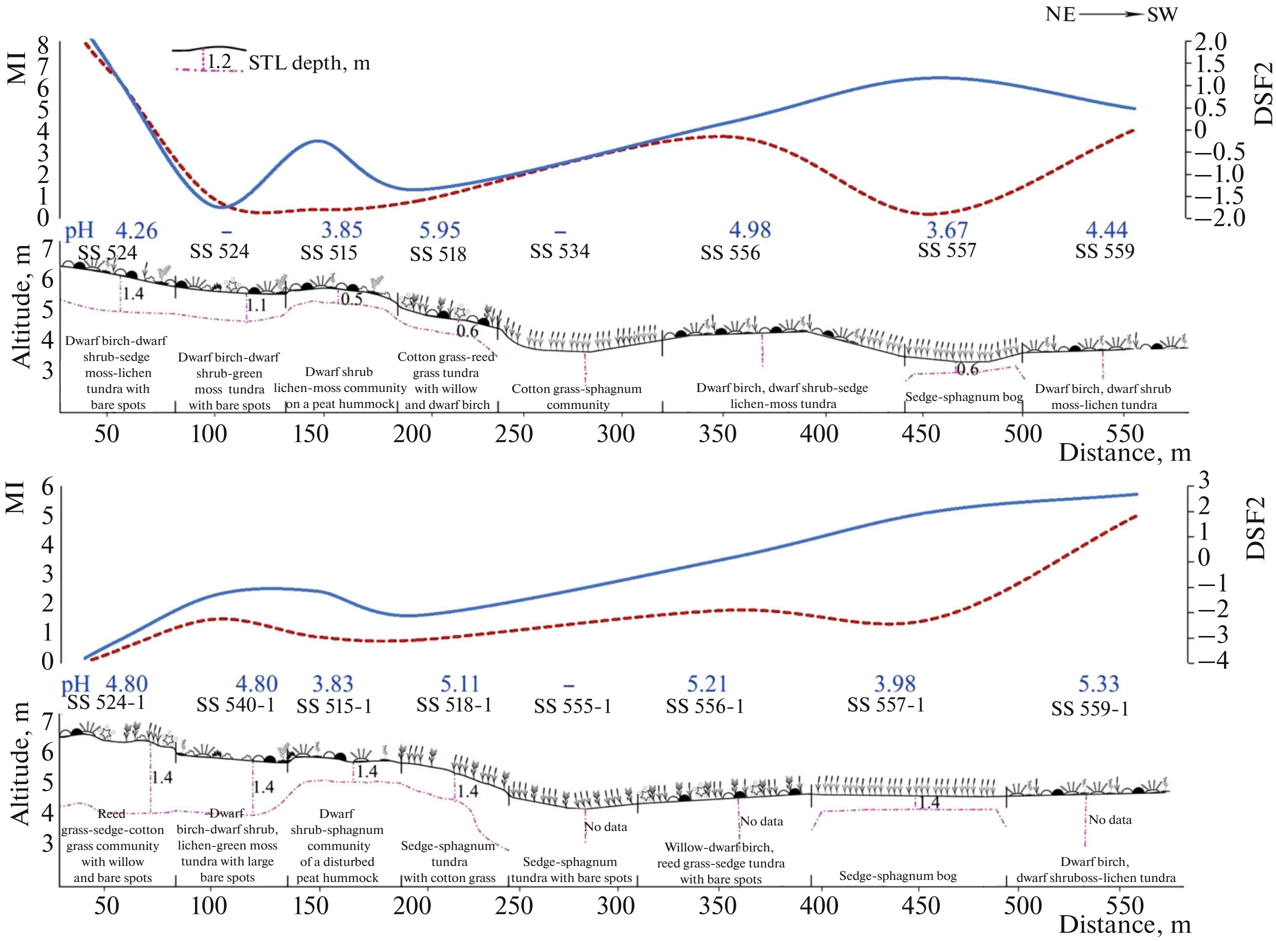

Fig. 3. Ecological and chemical characterization of the organic soil horizon (pH, MI, DSF2) at the sampling sites on the transects of the northern section: winter road (below) and the conventional background (above).

along the route of an overgrown winter road, and the other parallel to it at a distance of 50–100 m. Soil samples were taken using a coupled sampling method from natural environments and genetic horizons (Fig. 3).

A total of 60 samples were collected from different genetic horizons along the Surgut–Novy Urengoy–Salekhard route (including the city of Novy Urengoy), and 61 samples were collected along the winter road. Along with soil sampling, samples of indicator plant species were taken: 19 samples of wild rosemary *Ledum decumbens* (Ait.) Lodd.ex Steud. and 16 samples of lichen *Cladonia stellaris* (L.) Rubh. The representativeness of the material selection was ensured by obtaining an average sample of the above-ground vegetation (10–25 plants) from sampling plots 20 × 25 m in size.In April 2021 and 2022, a total of 28 snow samples were collected at soil sampling sites in the city and along the motorway using a VS-43 snow gauge. The number of cores ensured that a total volume of approximately 2.0 L of meltwater was obtained. The snow was melted at room temperature, and the mineralization and pH of the water were recorded. The meltwater was filtered through membrane filters (0.45 μm) to separate the dissolved and solid phases, and acidified with HNO_3. The metals load and the total dissolved and solid phases of metals (μg/(m^2 day)) were determined in the snow cover [9].

The analysis of metal content (Na, Ca, K, Al, Sc, Fe, Mn, Cd, Cr, Zn, Sr, Cu, Ni, Ba, Pb, Co, and V) in soils, in indicator plant species, and in the solid phase of snow cover was done at the Central Laboratory of the All-Russian Geological Research Institute of A.P. Karpinsky using the ISP-MS method on an ELAN-6100 DRC device (USA). Samples of snow and its solid phase were subjected to complete acid digestion according to Federal Environmental Regulations 6.1:2.3:3.11-98.

Geochemical data were statistically processed (descriptive statistics, factor, cluster, discriminant, and dispersion analyses) using the *Statistica* 28.0 software package (StatSoft). The criteria for normal distribution in the sample were asymmetry (<1) and excess (<5) [7]. If the data did not meet these criteria, logarithms of element content were used in statistical calculations.

Previous tests on metal content in snow samples collected near roads suggested that traffic does not exert a significant impact on the condition of soils in the Urengoy tundra [11], i.e., pollution is mild. However, this conclusion requires further substantiation based on soil studies. To qualify mild soil pollution, the following criteria can be used: pollutant content of 0.5–0.9 MPC, or in the absence of MPC, a concentration factor (CF) based on the background value ranging from 1.2 to 2.0 [9].

To obtain reliable results despite significant natural variations in the chemical composition of parent rocks and mild contamination, a statistical model was developed. At the first stage, we performed factorization of geochemical data based on the principal component method, and obtained and interpreted the factors influencing the chemical composition of the studied soils. Based on the results, we performed preliminary data grouping and used discriminant analysis to create a predictive model for assigning objects to nonoverlapping groups [7].

In a comparative analysis of soil contamination, a multiplier index was used, which is product of the content (mg/kg) of indicator elements. The index is used in exploration geology to amplify weak geochemical anomalies. In our case, we consider the multiplier index of Pb and Cd, indicator metals of pollution from motor vehicles.

To assess the toxicity of soil samples, the toxicity probability index (mean effects range median quotient, or MERMQ) was calculated using formula [21]:

$$\mathrm{MERMQ} = \frac{\sum_{i=1}^{n} \frac{C_i}{\mathrm{ERM}_i}}{n},$$

where C_i is the concentration of metals analyzed; ERM_i is the median of metal concentration above which biological effects are observed frequently or always [23]; and n is the number of metals used in the calculation.

The MERMQ value was assessed at four levels of toxicity risk: <0.1 is low risk (the probability of the sample's toxicity is 9%); 0.1–0.5 is medium risk (21%); 0.5–1.5 is high risk (49%); and >1.5 is very high risk (toxicity probability is 76%) [22].

RESULTS

The chemical composition of the parent rocks in the studied sections varies in terms of their macro- and microelement content. A comparison of the mean metal content using the *t*-test for independent samples showed that the maximum concentrations are characteristic of alluvial-marine deposits (am^4III) on the winter road, while the minimum concentrations were recorded in alluvial sediments (a^2III–aIV) in the eastern section of the motorway. It was previously noted that alluvial-marine sediments of the third and fourth marine terraces of the Nadym-Taz interfluve display high concentrations of siderophiles (Ni, Co, and V) and chalcophiles (Cu and Pb) [13]. Compared to marine sediments, alluvial deposits have statistically significant lower concentrations of all studied chemical elements. That is, in marine sediments, the content of Na, Ca, Al, Sc, V, Cr, Mn, Fe, Co, Ni, and Cu is 3.3–6.4 times higher than in alluvial sediments, while for Cd, Ba, and Pb these values are 1.6–1.8.

These features of the Quaternary rock composition are confirmed by the cluster analysis (hierarchical clustering) of observations using the between-groups linkage method. The degree of similarity was determined using Pearson's correlation coefficient. Based on the analysis, soil samples from the surface and middle horizons, as well as parent rocks, were grouped into four clusters (Table 1). The first cluster includes mineral soil horizons formed on alluvial-marine deposits of the fourth marine terrace in the western and northern sections (intraclass correlation coefficient is 0.994, and intraclass correlation coefficient is 0.985). This highlights the similarity of the geochemical specialization of marine sediments, which have common sources of sediment input but were formed in different marine environments (facies control). Higher concentrations of metals around the winter road are due to soils forming on clay loams, while to the west of Novy Urengoy, the am^4III deposits are primarily loamy sands and sands. The second cluster comprises mineral horizons of soils on alluvial deposits (intraclass correlation coefficient is 0.987, and interclass correlation coefficient, 0.985). Two more clusters are represented by organic horizons (0.989 and 0.987) and peatbogs (0.983 and 0.981).

The analysis of the content showed a noticeable excess of metal concentrations in marine sediments compared to alluvial sediments, with the exception of Cd and Pb. High microelement content is known to be typical for marine sedimentation [17]. Note the indicator role of Ca, found in high concentrations in marine clay sediments in the northern section, indicating deeper water deposition conditions compared to the western section in the Nadym-Pur interfluve.

The acidic-basic properties of soils are characterized by low pH values, a typical feature of northern landscapes. In the western section, pH in the surface organic and peat horizons varies from 3.46 to 4.90. In the middle horizons, pH usually goes up to 3.39–5.56. In the eastern section, the soil cover is mainly composed of oligotrophic peat with pH of 3.28–5.16. In the middle horizons, a weakly acidic environment (5.28–5.85) is observed. In the winter road section, pH in the organic horizons is 3.55–5.84, while in the middle horizons, and especially in the parent rocks, the values are higher, ranging from 5.11 to 6.69, with a clearly pronounced alkalization down the profile, resulting from the marine conditions of rock forma-

Table 1. Mean contents of metals in the identified clusters of the studied soils, mg/kg

Metal	Mineral horizons (B and C) over am^{4}III sediments		Mineral horizons over a^{2}III and aIV sediments (n = 11)	Organic horizons (n = 26)	Peatlands (n = 31)
	northern section (n = 40)	western section (n = 13)			
Na	17500 ± 300*	6100 ± 900	3900 ± 1100	3600 ± 500	1200 ± 140
Al	69400 ± 1700	41200 ± 4400	20000 ± 4700	19100 ± 2800	9800 ± 1300
K	21600 ± 450	10900 ± 1100	8300 ± 1500	6700 ± 850	2100 ± 220
Ca	13000 ± 600	3800 ± 500	3700 ± 1100	7600 ± 3100	3600 ± 460
Sc	12.5 ± 0.3	7.59 ± 0.79	3.01 ± 0.74	3.35 ± 0.50	2.71 ± 0.39
V	120 ± 2	72 ± 9	32.3 ± 8.7	30.6 ± 5.1	20.3 ± 3.2
Cr	79 ± 1	57 ± 7	24.3 ± 5.5	25.9 ± 3.5	16.5 ± 2.5
Mn	728 ± 49	232 ± 38	178 ± 48	316 ± 79	80 ± 10
Fe	34600 ± 800	21000 ± 2300	8700 ± 2200	12500 ± 2800	8200 ± 1000
Co	16.5 ± 0.5	8.9 ± 1.0	4.21 ± 1.33	5.49 ± 0.75	4.08 ± 0.45
Ni	37.7 ± 1.2	15.8 ± 1.8	5.93 ± 1.81	9.9 ± 1.2	8.1 ± 0.9
Cu	22.0 ± 1.0	12.9 ± 2.1	5.69 ± 1.48	10.0 ± 1.1	7.1 ± 0.8
Zn	58 ± 2	28.1 ± 3.0	23.6 ± 7.1	35.1 ± 4.4	16.7 ± 1.7
Sr	196 ± 5	90 ± 11	74 ± 16	78 ± 14	31.8 ± 2.4
Cd	0.07 ± 0.01	0.09 ± 0.02	0.04 ± 0.02	0.21 ± 0.02	0.16 ± 0.01
Ba	595 ± 8	421 ± 40	366 ± 54	353 ± 39	115 ± 10
Pb	14.9 ± 0.1	12.3 ± 1.1	9.2 ± 2.1	16.6 ± 2.7	4.67 ± 0.45

* Standard error of mean.

tion. In the urban area, the physicochemical indicators of urban quasi-soils differ from those of tundra soils by higher pH values, corresponding to slightly acidic and neutral pH (5.20–6.94).

The chemical composition of soils was studied in two horizons: the organic and the middle-profile ones (Table 2). Overall, the maximum metal content was observed in the soils of the urban and northern sections. The urban soils have a statistically significant excess of Zn and Ba in the organic horizon compared to the soils of other sections, with elevated levels of Al, K, Ca, V, Cr, Mn, and Sr. The soils of the northern section are characterized by high concentrations of Ni and Na.

The elemental composition of the middle-profile soil horizons largely depends on the chemical composition of the parent rock. The highest metal concentrations in the middle horizon are found in the soils of the northern section, which lies on am^{4}III clay deposits. Similar metal contents in the middle soil horizons of the western and urban sections are attributed to the common genesis of their parent rocks (am^{4}III deposits, sandy and loamy sandy). In the soils of the eastern section on alluvial deposits, the lowest concentrations of metals were found.

A comparison of the chemical composition of the organic and middle-profile soil horizons gave the following results. In the western section, a statistically significant excess of Na, Al, K, Sc, V, Cr, Mn, Fe, Sr, and Ba was found in the middle horizon, while Cd accumulates in the organic horizon. In the northern section, all metals studied, except for Cd, are concentrated in the middle-profile horizon. The opposite situation is observed in the eastern section, with higher concentrations of Al, Ca, Sc, V, Cr, Co, Ni, Cu, and Cd in the organic horizon. In the urban section, the differences in the composition of the two horizons are insignificant, due to the particularities in urbikvazizems formation. Of all the metals studied, only Cd shows a consistent trend, accumulating in the organic horizon.

The statistical modeling of soil conditions in the studied areas followed the algorithm proposed above. At the first stage, factor analysis was performed using the principal component method for metal content in soils. The factors were interpreted based on the values of the components. The first factor, explaining 34.5% of the sample variance, is considered to be rock-related. The maximum factor loadings belong to Sc–V–Cr–Ni–Al, which include an association of siderophilic and lithophilic metals, most pronounced in alluvial-marine sediments (Table 3). The second factor (weight 28.0%) is represented by metals with positive and negative impacts on the component. The association of metals with positive impacts (K–Ba–Na–Sr–Al–Mn) reflects the composition of aluminosilicates (feldspars and clay minerals) and corre-

Table 2. Mean contents of metals in the organic and middle-profile soil horizons in the studied sections, mg/kg

Metal	Section							
	urban		western		eastern		northern	
	organic ($n = 6$)	middle-profile ($n = 7$)	organic ($n = 14$)	middle-profile ($n = 9$)	organic ($n = 17$)	middle-profile ($n = 5$)	organic ($n = 24$)	middle-profile ($n = 13$)
Na	5800 ± 1100*	5900 ± 1300	2300 ± 510	6000 ± 780	1800 ± 160	1200 ± 390	2900 ± 770	12900 ± 1600
Al	32500 ± 4600	33400 ± 5800	15700 ± 2700	36700 ± 4200	12000 ± 1400	5900 ± 1200	14100 ± 3100	49800 ± 5900
K	11300 ± 1150	11650 ± 1450	4300 ± 820	11100 ± 1100	3150 ± 320	3450 ± 550	3900 ± 950	15500 ± 1900
Ca	19100 ± 9900	5700 ± 1300	2800 ± 240	3600 ± 360	2300 ± 200	1000 ± 160	4800 ± 440	9200 ± 600
Sc	5.8 ± 0.9	5.1 ± 1.0	3.1 ± 0.5	6.7 ± 0.9	3.1 ± 0.5	0.9 ± 0.2	3.5 ± 0.7	9.4 ± 1.1
V	55 ± 10	57 ± 12	24.6 ± 5.0	64 ± 10	25.5 ± 4.0	7.6 ± 1.5	27.9 ± 6.0	92 ± 11
Cr	43 ± 6	42 ± 8	22.4 ± 3.8	48 ± 8	22.5 ± 2.9	9.2 ± 2.0	19.1 ± 4.3	63 ± 7
Mn	595 ± 212	242 ± 57	104 ± 19	248 ± 33	97 ± 38	48 ± 12	223 ± 47	422 ± 76
Fe	15400 ± 2500	15600 ± 3000	9500 ± 1200	18100 ± 2400	12200 ± 3300	2100 ± 560	9200 ± 1700	25600 ± 2700
Co	7.8 ± 1.5	7.5 ± 1.7	5.8 ± 0.8	7.7 ± 1.0	3.3 ± 0.4	0.66 ± 0.19	4.9 ± 0.8	12.0 ± 1.1
Ni	14.9 ± 2.6	12.2 ± 2.8	10.2 ± 1.1	12.1 ± 1.9	6.9 ± 0.7	1.1 ± 0.5	11.9 ± 1.8	25.7 ± 2.9
Cu	15.3 ± 2.1	10.2 ± 2.0	8.7 ± 0.9	9.9 ± 2.4	8.1 ± 0.9	1.7 ± 0.3	8.7 ± 1.0	14.4 ± 1.7
Zn	56 ± 10	33 ± 9	23.6 ± 3.0	23.5 ± 3.1	18.8 ± 2.4	15.5 ± 7.7	21.2 ± 3.1	42 ± 3
Sr	146 ± 35	102 ± 16	47 ± 7	96 ± 10	31.5 ± 2.8	27.1 ± 4.7	53 ± 9	154 ± 15
Cd	0.15 ± 0.02	0.08 ± 0.03	0.18 ± 0.02	0.06 ± 0.02	0.20 ± 0.03	0.04 ± 0.02	0.19 ± 0.01	0.10 ± 0.02
Ba	493 ± 56	473 ± 41	224 ± 35	446 ± 37	212 ± 35	193 ± 27	159 ± 36	471 ± 52
Pb	22.5 ± 7.5	13.5 ± 2.4	8.9 ± 1.3	11.5 ± 1.1	24.8 ± 15.4	3.2 ± 0.6	7.4 ± 1.2	13.1 ± 1.3

* Standard error of mean.

Table 3. Factor loading matrices of the soil and snow chemical composition in the studied sections of the Surgut–Novy Urengoy–Salekhard motorway (maximum likelihood estimation; Varimax with Kaiser normalization)

Metal	Soil ($n = 95$)				Metal	Snow ($n = 28$)			
	factor					factor			
	I	II	III	IV		I	II	III	IV
Na	0.48	0.76			Na	0.94			
K	0.37	0.90			K	0.86			
Ca		0.39	0.82	0.25	Ca		0.90		
V	0.87	0.43			V	0.64	0.69		
Cr	0.86	0.46			Cr	0.49	0.42	0.64	
Mn	0.30	0.59	0.66		Mn	0.63	0.75		
Fe	0.77		0.28	0.31	Fe	0.73	0.59		
Co	0.68		0.58	0.30	Co	0.59	0.78		
Ni	0.78		0.42	0.41	Ni		0.53	0.49	
Cu	0.72		0.34	0.47	Cu			0.82	
Zn		0.35	0.48	0.53	Zn		0.59	0.56	
Sr	0.30	0.75	0.56		Sr	0.75	0.56		0.34
Cd		–0.33		0.83	Cd		0.45	0.64	
Ba	0.26	0.89	0.27		Ba				0.87
Pb		0.56		0.75	Pb			0.94	
Al	0.76	0.61			Factor weight, %	28.0	27.9	21.0	7.8
Sc	0.92	0.31							
Factor weight, %	34.5	28.0	15.5	13.0					

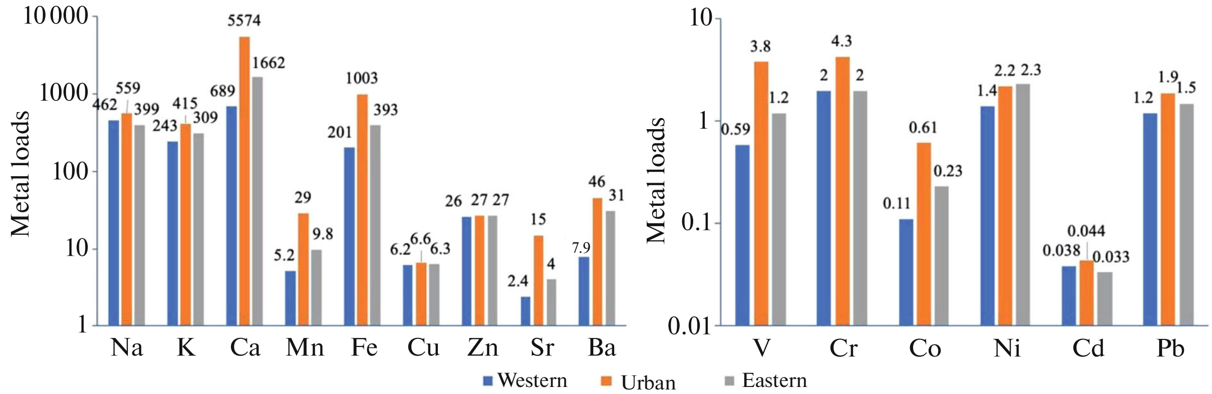

Fig. 4. Mean metal loads in the snow cover at the sampling sites, μ/(m^2 day).

sponds to the mineral and organomineral horizons. An alternative (negative loading) to this association is Cd as an indicator element of peat soils [13]. The third factor (15.5%) is represented by a paragenesis of metals typical for surface soil horizons in the Novy Urengoy area: Ca–Mn–Co–Sr–Zn. The fourth factor (13.0%) characterizes pollution from motor vehicles. The indicator of pollution is an association of Cd–Pb–Zn–Cu–Ni. Thus, the third and fourth factors are technogenic, characterizing the main sources of pollution.

The reliability of factor interpretation can be demonstrated by the results obtained from the study of metals associativity in the solid phase (dust) of snow cover. Factor analysis of the chemical composition of dust from soil sampling sites showed almost complete identity of geochemical associations with those of soil samples. Four factors were identified, the first of which (Na–K–Sr–Fe–V–Mn) corresponds to the second factor in soils and characterizes the mineral component of the snow cover. The validity of this interpretation is confirmed by numerous studies of the solid phase of snow, composed mainly of minerals of soil origin (60%), with quartz accounting, on average, for 40–50%. The remaining mineral phases are feldspars: albite (Na), microcline (K, Al), muscovite (K, Al), and others [18, 32]. Microscopic studies of snow dust samples from sampling sites confirmed the presence of feldspars, clay minerals, micas (Na, K, Sr), and accessory minerals, iron hydroxides, and slag (Fe and Mn) in the samples [11].

The association of Ca–Co–Mn–V–Zn–Fe (second factor) is similar in composition to the paragenesis of the third factor in soils (Ca–Mn–Co–Sr–Zn) and is found in the city of Novy Urengoy. The leading position of Ca (and partly Sr) in the paragenesis is explained by the widespread use of calcareous materials in residential building. The construction industry is one of the most important and actively developing sectors in the city economy, which lacks large-scale industrial production, while power is gas-generated.

Another paragenesis, Pb–Cu–Cd–Cr–Ni–Zn (the third factor), as noted above, is seen as technogenic, pointing to pollution of soil and snow cover by motor vehicles. Indeed, when studying snow cover contamination, the metals included in the association are most often interpreted as resulting from motor traffic [34, 35]. So, exhaust gases are a source of Ni, Mn, Fe, Pb, and Zn; road marking paint is a source of Cd and Pb; tire wear contributes Cd and Pb; brake pads release Cd, Cu, Pb, and Zn; asphalt pavement contributes to Ni input; and engines and car bodies are sources of Cr and Ni [2, 18, 24, 28, 34].

The calculated snow load reflects the intensity of traffic in the studied sections of the Surgut–Novy Urengoy–Salekhard motorway. The maximum mean value of the total load was recorded in the settlement area (7690 μg/(m^2 day)), with a statistically significant excess of Ca, V, Mn, Sr, and Co (Fig. 4), i.e., metals included in the urban metal association. The minimum total load was observed in the western section (1650 μg/(m^2 day)); in the eastern section, it grew to 2850 μg/(m^2 day) as traffic intensity increased.

Significantly, in the city of Novy Urengoy and on adjacent sections of the motorway, only sand is used to control ice in winter, and almost no road salt is applied. This is reflected in low concentrations of Na (0.647 mg/L) and K (0.437 mg/L) in the snow cover, compared to the results from areas where salt mixtures are widely used as deicing agents [33]. For example, in a residential area of Novi Sad (Serbia), the average Na content in meltwater from a low-traffic road was 1924 mg/L, and K was 10.7 mg/L [24], which is by 2–4 orders of magnitude higher than the concentrations measured in the study area.

Based on the results of factor analysis of metal content in soils, samples can be divided into four groups: (1) mineral and organomineral soil horizons, (2) peatbogs, (3) urban soils, and (4) soils subject to pollution by motor vehicle traffic outside the settlement area. The first two groups are outside the zone of technogenic impact. Values of the relevant factors were used as criteria for assigning samples to groups. A total of 73 out of 95 samples were grouped. The remaining 22 samples did not show any significant loading by any of the factors. Statistical modeling was performed using discriminant analysis with stepwise selection by Wilks' Lambda. The results of the analysis allowed us to perform a complete classification of the samples. Four distinct groups were used as dependent variables in the analysis. The metals analyzed were considered independent variables. According to the results of the calculations, Pb, Ba, Cd, Sc, Al, Ca, Sr, and Ni served as discriminating (participating in the separation of groups) elements. These metals show high loadings in the associations that indicate the groups under consideration. Among the predictors, Pb, Ba, Cd, and Sc contributed most to intergroup differences. The results of the analysis showed that 95.7% of the 95 initial observations were classified correctly, proving the high reliability of the geochemical identity of the groups.

Based on the discriminant functions in the group centroids, we can describe the groups. The first function, explaining 62.7% of the sample variance, acts as a regression of metal content with positive values in mineral and organomineral horizons and negative values in peatlands, i.e., it describes the background state of the soils. The main impacts on this function are borne by Al, Ba, and Sr, and for peat soils, by Cd. The second function (26.2% of the variance) groups the characteristics of soils affected by motor vehicle traffic. Pb and Cd have the maximum effect on the discriminant function. The third discriminant function (11.1% weight) provides a solution for the distribution of metals in urban soils. Ca is the main loading on the function. The last two discriminant functions, reflecting the regression dependence of metal distribution under the influence of anthropogenic factors, have a total weight of 37%, which, once again, points to the low level of soil contamination within the studied sections.

Based on the results of the discriminant analysis, a cross-classification matrix of samples was obtained, part of which is shown in Table 4, and it includes only samples exposed to "urban" (third group) or "motor vehicle" (fourth group) pollution. In the matrix, the second most significant group is indicated for each sample according to the nature of metal associativity. The discriminant scores for the second (motor vehicle pollution) and third (urban pollution) functions are shown, as interpreted above. These scores reflect the magnitude of the canonical discriminant function, i.e., the degree of correlation between the chemical composition of the corresponding sample and the functions. Based on the scores of the second and third regression functions, soils can be compared according to the level of impact from the corresponding sources of pollution on their elemental composition.

A distinctive feature of the chemical composition of soils in two transects in the winter road area (northern section) is the absence of statistically significant differences for all studied elements, as determined by the *t*-test for independent samples. The modeling showed that out of 37 samples from the surface and middle horizons, only three were contaminated by traffic: 524A, 559A, and 559-1A. The most significant sign of damage to the winter road itself relative to the roadside (nominally background) transect is thawing with the growing depth of the seasonal thaw layer. Thus, within the sedge-sphagnum bog in the adjacent area, the STL is 0.6 m thick; it is more than 1.0 m thick on the winter road; 1.4 and more than 2.2 m, respectively, in the dwarf birch tundra; and about 1.3 m and more than 1.5 m, respectively, in the same place on a spot of bare ground.

The condition of indicator plant species is one of the elements used to assess the impact of motor vehicles on roadside landscapes. For this reason, a study was conducted to determine the chemical composition of plants in the western and eastern sections of the motorway. When compared with background metal contents in *C. stellaris* and *L. decumbens* [4, 12], it was found that concentrations in lichens in the western section were lower than background levels, while in the eastern section they were higher. In wild rosemary, the content of Na, K, Ca, V, Cr, Ni, Cu, Cd, and Pb in both sections is below background values.

A comparison of the mean metal content in plants using the *t*-test for two independent samples (eastern and western sections) showed that in the eastern section, *C. stellaris* had a statistically significant excess of Ca, Sc, V, Cr, Fe, Co, Ni, Cu, and Ba; and in *L. decumbens* it was Sc, V, Fe, Co, Cu, Zn, and Ba (Fig. 5). At the same time, higher concentrations of K and Mn were observed in wild rosemary in the western area.

These data contradict to some extent to the results of soil chemical composition studies, which showed higher metal concentrations in the soils of the western section. Therefore, the contrast in plant chemical composition is not related to the influence of soils. As noted above, the eastern section of the route differs in terms of more intense traffic flow. The discrepancy can be explained mainly by the foliar uptake of metals by plants.

DISCUSSION

The results of the modeling helped us to identify two main sources of impact. In urban areas, chemical pollution is compound, reflecting the influence of both the construction industry and motor vehicle traffic. The scores for the second and third functions describing these types of pollution are close, and the maximum contribution of traffic to urban soil pollution is observed at the sampling site (SS) located in close proximity to a busy bypass road (SS 4). Ca, Zn, and Mn are typical elements of urban pollution. Their mean concentrations are significantly higher than

Table 4. A fragment of the cross-classification matrix of soil samples from the studied areas subject to contamination (groups 3 and 4) and the probability of toxicity (MERMQ) of soils

Sample	Soil characteristics: soil name, state of organic matter decomposition, thickness	Primary group*	Second most significant group	Discriminant scores**		MERMQ
				function 2	function 3	
		Urban section				
$1UR_1$	Urbikvasizem, a small amount of organics, loamy sand	3	4	1.36	3.25	0.06
$1UR_2$	Urbikvasizem, loamy sand	4	1	1.65	–1.62	0.03
$2UR_1$	Urbikvasizem, dark gray with an admixture of loamy sand	3	1	0.22	6.58	0.15
$2UR_2$	Urbikvasizem, stratified dark gray sand	3	1	2.30	2.11	0.15
4O	Iron-illuvial podbur, poorly decomposed organics, charcoals, 3–2 cm	3	4	2.71	2.58	0.14
5O	Iron-illuvialn podzol, poorly decomposed organics	3	1	2.37	4.59	0.17
7T	Gley peat podbur, well decomposed organics, up to 5 cm	4	1	1.87	–0.62	0.11
		Western section				
8-1T	Gley peat podbur, weakly decomposed peat, up to 20 cm	4	1	2.31	–2.00	0.08
$8\text{-}2T_1$	Peat gley soil 0–10 cm, weakly decomposed peat	4	1	0.93	–2.16	0.06
$8\text{-}2T_2$	Peatgley soil, brown well decomposed peat, 10–25 cm	4	2	–0.23	–1.94	0.12
8-4O	Gley soil, poorly pronounced; predominance of yellowish grey loamy sand	4	1	1.75	–1.71	0.09
12O	Iron-illuvial podbur, 3–5 cm, weakly decomposed organics	4	1	2.28	–0.70	0.08
13T	Gley peat podbur, up to 20 cm, peat formation	4	2	2.41	–1.85	0.09
		Eastern section				
$15\text{-}1TO_1$	Peat oligotrophic, weakly decomposed peat, up to 20 cm	4	2	4.71	–1.00	0.30
$15\text{-}1TO_2$	Peat oligotrophic, well decomposed peat, brown, 50 cm	4	2	2.25	–2.45	0.03
15-2TO	Peat oligotrophic, weakly decomposed peat, O horizon up to 5 cm	4	1	2.96	–1.23	0.11
15-4TO	Peat oligotrophic, weakly decomposed peat, up to 10 cm, O horizon 5 cm	4	2	2.45	0.10	0.04
15-5 TO	Peat oligotrophic, weakly decomposed peat, up to 10 cm	4	2	0.79	–1.09	0.04
16O	Anthropogenically disturbed psammozem, O horizon practically absent	4	3	3.49	0.64	0.05
17TO	Peat oligotrophic, 5–7 cm, weakly decomposed peat	4	3	4.51	0.04	0.06
18C	Poorly pronounced psammozem, O horizon practically absent. Coarse-grain sand predominates	4	2	2.53	–0.93	0.03
19O	Iron-illuvial podzol, 3–5 cm, weakly decomposed organics	4	3	2.94	0.99	0.06

Table 4. (Contd.)

Sample	Soil characteristics: soil name, state of organic matter decomposition, thickness	Primary group*	Second most significant group	Discriminant scores**		MERMQ
				function 2	function 3	
Northern section (winter road)						
524T	Peat gley soil, peat horizon is weakly pronounced, up to 5 cm	4	2	1.38	–0.89	0.09
559-1T	Peaty gley soil, peat horizon is very weakly pronounced, up to 3 cm	4	1	2.68	–1.08	0.14
559T	Peat gley soil, peat horizon is very weakly pronounced, up to 2–3 cm	4	1	0.48	–1.21	0.14

* Actual or predicted group based on the four groups described in the text.
** Discriminant scores characterize the degree of connection between the sample's chemical composition and functions.

those in other groups (Table 5). High concentrations of Cu and Sr are also typical for urban soils. The leading role of Ca and Sr in the contamination of urban soils leads to their alkalization, as suggested by the measured pH values of 5.20–6.94.

Outside the urbanized area, roadside soils in the eastern section are subject to high loads due to higher traffic intensity. This is indicated by higher mean values of the discriminant score of the second function (2.96). In the western section, their mean value is 1.58, and not all soils studied along the road fall into the motor vehicle pollution group (SS 9, 10, and 11). The typomorphic elements of transport pollution include Pb and Cd. In the eastern section, for samples taken on the outskirts of the city (SS 19), near the Nartovo station (SS 16), and close to the chemical plant (SS 17), the second most significant is the third group (urban pollution).

A comparison of the mean metal contents in contaminated soils and soils unexposed to anthropogenic impact outside urban areas using the *t*-test showed a statistically significant ($p = 0.05$) increase in the concentration of Ca, Ba, Zn, Cd, and Pb in the first of these two samples. Chalcophiles are included in the anthropogenic association based on the results of the factor analysis. The high content of alkali-earth metals in roadside soils is due to their presence in the sandy material transported by air currents from the road fill and used as a deicing agent in winter. However, the alkalizing effect of dust on the soil is weak, as evidenced by the low pH values of 3.28–5.56. Only a slight increase in pH is noted at the sampling sites closest to the motorway.

The findings from the transect studies in the western and eastern sections allow us to draw preliminary conclusions about the nature of lateral migration of metals originating from motor vehicles flow. Despite differences in traffic intensity and pollution levels, there are common patterns in metal migration. As contamination was detected at a distance of up to 200 m from the road, it can be assumed that 200 m is the maximum distance over which solid aerosols can be carried by the wind. This is consistent with the research showing that the maximum transfer of pollutants from roads by atmospheric flows is 250 m [35]. Pollutants enter the soil when water is splashed from the road to a distance of about 10 m [20]. Given the

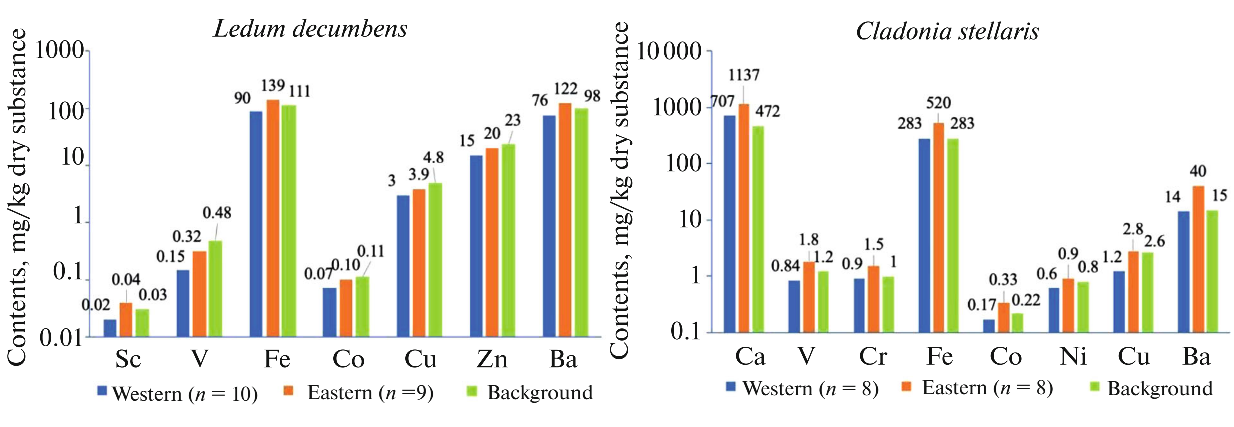

Fig. 5. Mean content of metals in indicator plant species in the western and eastern sections of the Surgut–Novy Urengoy–Salekhard motorway, mg/kg dry substance.

Table 5. Mean contents of metals in the soil samples grouped based on the modeling results, mg/kg

Metal	Background area		Impact zone	
	mineral and organomineral horizons ($n = 31$)	peatlands ($n = 39$)	traffic pollution ($n = 20$)	urban pollution ($n = 5$)
Na	9300 ± 900*	1300 ± 250	3500 ± 600	5000 ± 900
Al	42900 ± 3100	9800 ± 1400	17000 ± 2500	28900 ± 5000
K	13600 ± 900	2200 ± 300	5900 ± 800	9800 ± 1150
Ca	6200 ± 600	3300 ± 300	3400 ± 400	23000 ± 11300
Sc	7.8 ± 0.6	2.7 ± 0.4	3.1 ± 0.5	5.3 ± 1.0
V	78 ± 6	20 ± 3	28 ± 5	48 ± 10
Cr	55 ± 4	15 ± 2	24 ± 3	40 ± 6.3
Mn	330 ± 40	93 ± 13	215 ± 54	710 ± 235
Fe	21500 ± 1700	7100 ± 800	12800 ± 2900	14900 ± 3200
Co	9.5 ± 0.8	3.5 ± 0.4	5.4 ± 0.7	9.3 ± 2.3
Ni	19 ± 2	8.2 ± 0.8	9.6 ± 1.5	16 ± 3.3
Cu	12 ± 1	7.3 ± 0.7	8.5 ± 0.8	17 ± 2
Zn	34 ± 3	15 ± 1	29 ± 3	68 ± 11
Sr	124 ± 9	32 ± 3	60 ± 8	147 ± 41
Cd	0.08 ± 0.01	0.15 ± 0.01	0.24 ± 0.02	0.16 ± 0.03
Ba	473 ± 21	110 ± 10	330 ± 38	478 ± 68
Pb	13 ± 1	4.6 ± 0.4	27 ± 13	26 ± 9

* Standard error of mean.

high mobility of metals in acidic environments, lateral migration can be expected in the surface layer of the soil. Along the transects, its extent is limited by relief and does not exceed 100 m.

Radial migration of pollutants is very weak. Only at two sites (SS 8-2 and 15-1), closest to the motorway, there is a transfer of pollutants to lower horizons. In both cases, the discriminant score of the second function in the middle horizon is significantly below the mean value. The peat horizon in the studied soils acts as a complex geochemical barrier (alkaline, biogeochemical, and sorptive), and is responsible for the low lateral and radial migrations of metals even in an acidic environment [3, 6, 15]. The barrier's effectiveness was noted in tundra and northern taiga soils when studying the migration of metals [30] and petroleum hydrocarbons [8, 14] during hydrocarbons extraction. In addition, cryogenic conditions neutralize to a certain extent the radial migration of substances by upward water flows during seasonal thawing of permafrost [31].

In the northern section within the winter road, the soil cover was found to be disturbed, and soil thawing was clearly evident together with an increase in the thickness of the STL. The remaining traces of chemical contamination are localized. Since the end of its operation, the runoff down the slope has led to a decrease in metal content in the surface horizon to background levels. Significantly, contamination was found in the lower positions of the catena at SS 559-1 and 559. At the northeastern edge of the transect (SS 524), high scores for the discriminant second function and the multiplier index of Cd and Pb content may be due to the proximity of the Urengoy–Tazovsky motorway. Analysis of the mobile forms of Co, Ni, Cu, Zn, and Pb in this area showed no excesses of MPCs in the soils, while the total content of Cd, Mn, Ni, Cu, Zn, and Pb was below the TPC values, and V was below the MPC values. At the same time, the maximum Cd (0.22–0.30 mg/kg), mobile forms of Pb (3.5–4.4 mg/kg) and Zn (12.6–19.3 mg/kg) were recorded at three sites selected based on contamination levels, confirming the adequacy of the used model for the identification of low-level contamination.

The toxicity index (MERMQ) calculated for a group of metals included in the Cd–Pb–Zn–Cu–Ni association and indicative of pollution from motor vehicles showed a low probability of toxicity (9%). In individual samples, mainly taken within the city and at two transect sites closest to the motorway, an average probability of toxicity (21%) was found. In the eastern and western sections, a decrease in MERMQ values was observed in the surface soil layer with distance from the motorway. In the northern section, the probability of toxicity of three soil samples exposed to contamination varies between 0.09 and 0.14, corresponding to low and medium toxicity risk levels, with the highest values in the subaquatic position.

The conclusion regarding the predominantly foliar pathway of metal uptake by plants, obtained through the study of the chemical composition of indicator plant species, is confirmed by other authors' research conducted in heavily polluted landscapes [29]. However, according to the present data, this route of pollutant accumulation by plants plays a significant role even under low contamination levels. This result is relevant for assessing the mechanisms of metal input into soils via air or lateral migration. At low levels of contamination and high buffering capacity of the peat horizon, aerotechnogenic transfer becomes the leading mode.

CONCLUSIONS

Studies have shown that in the Russian Arctic zone, with low-intensity vehicle traffic, metal contamination of roadside soils is very weak; there are no exceedances of MPCs and TPCs; and the soil toxicity index is low to moderate. For the identification of contamination under low impact, statistical modeling was tested based on the successive application of multivariate statistical methods, namely, factor and discriminant analysis.

The leading technogenic association of metals in motor vehicle pollution, both in soil and in the solid phase of snow, is mainly represented by chalcophiles Cd–Pb–Zn–Cu–Ni. In Novy Urengoy, urban construction plays a decisive role in the pollution of the territory, along with motor vehicle traffic, the influence of which is indicated by the association with priority of Ca (Ca–Mn–Co–Sr–Zn). The similarity of technogenic associations in snow and soil points to the decisive role of aerotechnogenic metal transfer in the environmental pollution of natural and urban areas.

A study of the soil at one of the winter road's sections 10 years after the end of its operation revealed a disturbance of the soil cover and an increase in the STL thickness. Local chemical contamination of the soil with metals was found mainly in superaquatic positions.

The nature of soil contamination in the studied sections of the Surgut–Novy Urengoy–Salekhard route suggests a low potential for metal migration, despite the acidic environment. Lateral migration does not exceed 100 m, and radial migration hardly ever goes beyond the upper peat horizon of the soil. This is due to the barrier function of peatlands, reducing the migration potential of pollutants and increasing the resistance of tundra landscapes to chemical pollution. Aerotechnogenic transfer has an impact at a distance of up to 200–250 m from the road.

The study of indicator plant species in roadside landscapes has revealed changes in their chemical composition, caused mainly by aerotechnogenic transfer of metals from motor vehicles and road surfaces. Of the two indicator plants, the most pronounced signs of chemical pollution in the given conditions are found in *C. stellaris*.

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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 authors of this work declare that they have no conflict of interest.

REFERENCES

1. *Atlas of the Yamalo-Nenets Autonomous Okrug* (FGUP Omsk. Kartograficheskaya Fabr., Omsk, 2004).
2. *A. A. Ganina*, Candidate's Dissertation in Technical Science (Irkutsk, 2021).
3. I. V. Zamotaev, I. V. Ivanov, P. V. Mikheev, and A. N. Nikonova, "Chemical contamination and transformation of soils in hydrocarbon production regions," *Eurasian Soil Sci.* **48** (12), 1370–1382 (2015).
4. N. V. Kuz'menkova, N. E. Kosheleva, and E. E. Asadulin, "Heavy metals in soils and lichens of the tundra and forest-tundra zones (northwest of the Kola Peninsula)," *Pochvovedenie,* No. 2, 244–256 (2015). https://doi.org/10.7868/S0032180X14100062
5. A. V. Levanchuk, "Pollution of the environment by products of operational wear of the road complex," Gig. Sanit., No. 6, 17–21 (2014).
6. E. D. Lodygin, "Sorption of Cu^{2+} and Zn^{2+} ions by humic acids of tundra peat gley soils (histic reductaquic cryosols)," *Eurasian Soil Sci.* **52** (7), 769–777 (2019).
7. A. D. Nasledov, *IBM SPSS Statistics 20 and AMOS: Professional Statistical Data Analysis* (Piter, St. Petersburg, 2013) [in Russian].
8. *National Report "Global Climate and Soil Cover of Russia: Arctic Zone, Permafrost Soils—the Future of Russia (Agriculture and Forestry)"*, Ed. by R. S.-Kh. Edel'geriev and A. L. Ivanov (Pochv. Inst. im. V. V. Dokuchaeva, Moscow, 2024), Vol. 4 [in Russian].
9. A. Yu. Opekunov and M. G. Opekunova, "Integral estimation of landscape pollution using Harrington's desirability function," Vestn. S.-Peterb. *Univ. Ser. 7* **4**, 101–113 (2014).
10. A. Yu. Opekunov, M. G. Opekunova, S. Yu. Kukushkin, S. Yu. Yanson, I. Yu. Arestova, N. A. Sheinerman, V. V. Spasskii, E. E. Papyan, and E. Yu. Elsukova, "Mineralogical–geochemical characteristics of the snow cover in areas with mining and ore-processing facilities," *Geochem. Int.* **59** (7), 711–724 (2021).
11. A. Yu. Opekunov, M. G. Opekunova, S. Yu. Kukushkin, and S. Yu. Yanson, "Mineralogical and geochemical peculiarities of snow cover in anthropogenically dis-

turbed areas of the Nadym-Purovsky interfluve (north of Western Siberia)," Vestn. Mosk. Univ. Ser. 5, *Geogr.* **79** (3), 17–31 (2024).

12. M. G. Opekunova, A. Y. Opekunov, S. Y. Kukushkin, I. Y. Arestova, and S. A. Lisenkov, "Background concentrations of chemical elements in plants inhabiting the northern part of Western Siberia and changes they undergo under the impact of oil and gas production," *Contemp. Probl. Ecol.* **17** (2), 314–324 (2024).
13. M. G. Opekunova, A. Yu. Opekunov, S. Yu. Kukushkin, and A. G. Ganul, "Background contents of heavy metals in soils and bottom sediments in the north of Western Siberia," *Eurasian Soil Sci.* **52** (4), 380–395 (2019).
14. M. G. Opekunova, A. Yu. Opekunov, S. Yu. Kukushkin, S. A. Lisenkov, S. V. Vlasov, and V. V. Somov, "Soil pollution with polycyclic aromatic hydrocarbons and petroleum hydrocarbons in the north of Western Siberia: spatial pattern and ecological risk assessment," *Eurasian Soil Sci.* **55** (11), 1647–1664 (2022).
15. O. D. Tregubov, "Geochemical barriers in soils and landscapes of the Anadyr tundra," Vestn. Mosk. Univ. Ser. 5, Geogr., No. 3, 70–79 (2017).
16. N. V. Shatalova, "Road communication of the Arctic zone of the Russian Federation," in *Modernization and Scientific Studies in Transport Complex* (2014), Vol. 1, pp. 539–542.
17. Ya. E. Yudovich and M. P. Ketris, *Geochemical Indicators of Lithogenesis (Lithological Geochemistry)* (Geoprint, Syktyvkar, 2011) [in Russian].
18. E. Adamiec, R. Wieszała, M. Strzebońska, and E. Jarosz-Krzemińska, "An attempt to identify traffic related elements in snow," *Geol. Geophys. Environ.* **39**, 317–329 (2013).
19. A. Goth, A. Michelsen, and K. Rousk, "Railroad derived nitrogen and heavy metal pollution does not affect nitrogen fixation associated with mosses and lichens at a tundra site in Northern Sweden," *Environ. Pollut.* **247**, 857–865 (2019).
20. B. Kluge, M. Werkenthin, and G. Wessolek, "Metal leaching in a highway embankment on field and laboratory scale," *Sci. Total Environ.* **493**, 495–504 (2014).
21. J. B. Kowalska, R. Mazurek, M. Gasiorek, and T. Zaleski, "Pollution indices as useful tools for the comprehensive evaluation of the degree of soil contamination – a review," *Environ. Geochem. Health* **40**, 2395–2420 (2018). https://doi.org/10.1007/s10653-018-0106-z
22. E. R. Long, D. D. Macdonald, C. G. Severn, and C. B. Hong, "Classifying probabilities of acute toxicity in marine sediments with empirically derived sediment quality guidelines," *Environ. Toxicol. Chem.* **19**, 2598–2601 (2000).
23. E. R. Long, D. D. Macdonald, S. L. Smith, and F. D. Calder, "Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments," *Environ. Manage.* **19**, 81–97 (1995).
24. S. Meland, PhD Thesis (Norwegian University of Life Sciences, 2010). https://nmbu.brage.unit.no/nmbu-xmlui/handle/11250/2431910.
25. A. Mihailović, M. Vučinić-Vasić, J. Ninkov, S. Erić, N. M. Ralević, T. Nemeš, and A. Antić, "Multivariate analysis of the contents of metals in urban snow near traffic lanes in Novi Sad, Serbia," *J. Serb. Chem. Soc.* **79**, 265–276 (2014). https://doi.org/10.2298/JSC130311052M
26. D. Moskovchenko, R. Pozhitkov, A. Zakharchenko, and A. Tigeev, "Concentrations of major and trace elements within the snowpack of Tyumen, Russia," *Minerals* **11**, 709 (2021). https://doi.org/10.3390/min11070709
27. I. H. Myers-Smith, B. K. Arnesen, R. M. Thompson, and F. S. Chapin III, "Cumulative impacts on Alaskan arctic tundra of a quarter century of road dust," *Ecoscience* **13**, 503–510 (2006).
28. A. Müller, H. Österlund, J. Marsalek, and M. Viklander, "The pollution conveyed by urban runoff: a review of sources," *Sci. Total Environ.* **709**, 136125 (2020). https://doi.org/10.1016/j.scitotenv.2019.136125
29. P. N. Neitlich, W. Wright, E. D. Meglio, A. E. Shiel, C. J. Hampton-Miller, and M. B. Hooten, "Mixed trends in heavy metal-enriched fugitive dust on National Park Service lands along the Red Dog Mine haul road, Alaska, 2006–2017," *PLoS One* **19**, e0297777 (2024). https://doi.org/10.1371/journal.pone.0297777
30. A. Opekunov, M. Opekunova, S. Kukushkin, and S. Lisenkov, "Impact of drilling waste pollution on land cover in a high subarctic forest-tundra zone," *Pedosphere* **32**, 414–425 (2022).
31. M. Opekunova, A. Opekunov, and S. Kukushkin, "Oil spill pollution in permafrost environments," in *Reference Module in Earth Systems and Environmental Sciences* (2025). https://doi.org/10.1016/B978-0-323-85242-5.00031-2
32. R. Pozhitkov, D. Moskovchenko, A. Soromotin, A. Kudryavtsev, and E. Tomilova, "Trace elements composition of surface snow in the polar zone of northwestern Siberia: the impact of urban and industrial emissions," *Environ. Monit. Assess.* **192**, 215 (2020).
33. D. M. Ramakrishna and T. Viraraghavan, "Environmental impact of chemical deicers—a review," *Water, Air, Soil Pollut.* **166**, 49–63 (2005).
34. A. Vijayan, H. Osterlund, J. Marsalek, and M. Viklander, "Traffic-related metals in urban snow cover: A review of the literature data and the feasibility of filling gaps by field data collection," *Sci. Total Environ.* **920**, 170640 (2024).
35. M. Werkenthin, B. Kluge, and G. Wessolek, "Metals in European roadside soils and soil solution—a review," *Environ. Pollut.* **189**, 98–110 (2014).
36. J. Zhou, "The relationship between soil pH and geochemical components," *Environ. Earth Sci.* **83**, 402 (2024). https://doi.org/10.1007/s12665-024-11711-1

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