

SOIL CHARACTERISTICS OF AN ARCTIC CITY: MINERALOGICAL AND CHEMICAL COMPOSITION, POLLUTION RISKS AND TOXICITY ASSESSMENT (NOVY URENGOY, RUSSIA)

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ABSTRACT. Urbanization leads to multi-component environmental pollution, so it is especially important to conduct a comprehensive screening of transformations of vulnerable Arctic soils. An assessment of urban soil pollution in Novy Urengoy was conducted, providing a detailed geochemical characterization of the study areas. Electron microscopy confirmed the presence of both rock-forming mineral inclusions and heterogeneous solid particles of various origins: ore minerals (sphalerite, galena, cinnabar, cassiterite, argentite, atacamite), finely dispersed silver and gold particles, Cu-Ni-Zn and Fe-Cr-Ti-Mn alloys, titanium plates, and microplastics. The content of petroleum and polycyclic aromatic hydrocarbons (PAHs) is predominantly low, except for several sites near transport infrastructure, where petroleum hydrocarbon content reaches 2200–2400 mg/kg and the sum of 15 PAHs achieves 84 µg/kg. Natural factors remain the leading drivers of soil chemical composition. Local exceedances of Russian regulatory standards for Zn were detected in transport and residential areas. The Cd-Pb-Zn-Cu-Ni association indicates pollution derived from motor vehicle emissions. In urban areas, residential development acts as an additional source of Ca-Mn-Co-Sr-Zn compounds. Calculation of the mean effects range median quotient (MERMQ) for contaminated soils revealed low and moderate risk levels. Biotesting using *Daphnia magna*, *Chlorella vulgaris*, and *Lepidium sativum* demonstrated acute toxicity in soils contaminated with PAHs and petroleum hydrocarbons. The integrated landscape total pollution index (*LTP*), based on the Harrington desirability function, confirmed that motor vehicles are the primary source of urban pollution.

KEYWORDS: pollution, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, metals, soil toxicity, biotesting

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INTRODUCTION

The high resource and raw material potential of the Arctic region is driving an increase in anthropogenic impact on the natural-territorial complexes (NTCs). Mining and transport system development contributes to the creation of settlements and social infrastructure (Kumpula et al. 2011). While environmental assessments in the Arctic typically focus on studying the impact of oil and gas production on the NTCs (Moskovchenko and Moskovchenko 2018; Opekunova et al. 2022; Zamotaev et al. 2015), urbanization remains a persistent and powerful factor in environmental transformation. It leads to the pollution of all components of NTCs, permafrost degradation, and altered migration of chemical elements (Khrebtchenko et al. 2025; Moskovchenko

and Moskovchenko 2018; Mukhartova et al. 2025; Opekunova et al. 2026a; Schuur et al. 2022; Tesic et al. 2022; Turetsky et al. 2020). Therefore, studying the impact of urban development, transportation networks, industrial zones, and waste landfills is of particular importance¹.

Urbanization in the Arctic is predominantly driven by the extractive industries, specifically mining and hydrocarbon production. Soil formation in cities of the Far North is associated, on the one hand, with cryoturbation and stagnant moisture typical of the tundra and, on the other hand, with the development of humus horizons, which is accompanied by an increase in soil pH, enrichment with metals and metalloids (especially Pb, Cu, Ni, Cd, Ba, Zn, As) and petroleum products. The highest degree of pollution is recorded in organic horizons (Abakumov et

¹National report "Global climate and soil cover of Russia: the Arctic zone, permafrost soils – for the future of Russia (agriculture and forestry)". (2024). Ivanov A.L. Goryachkin S.V., Lapteva E.M. [et al.], 4, Moscow: Dokuchaev Soil Institute (in Russian)

al. 2023; Korneykova et al. 2022; Perryman et al. 2020). Organic matter, clay minerals, and newly formed Fe and Mn hydroxides participate in the fixation of metals in the upper soil layer (Orlov et al. 2002).

In Arctic cities, replantozems (quasizems), urbostratozems, and technogenic surface formations are widespread; in urban parks over 50 years old, recreazems with a series of buried rat horizons are formed; the soil cover is significantly fragmented, with inclusions of municipal and construction waste². A significant portion of the soil is sealed or recompactd during urban development (Szymanski et al. 2019). Urbanization leads to the replacement of poorly developed natural organic horizons with umbric, plaggic, and urbic horizons with thicknesses ranging from 5 to 10 cm. In the cities of Salekhard, Nadym, and Novy Urengoy, the thickness of the humus horizon in parks exceeds 20 cm due to the introduction of fill soils² (Abakumov et al. 2023). Organic matter content varies widely, reaching, for example, 10% in the organic horizon in Murmansk and up to 1% at a depth of 80 cm. In artificial soils in Vorkuta, organic carbon content reaches 20%, and in Magadan, 6.9–9.0%. In Apatity (Murmansk Region), carbon reserves in urban soils are twice as high as in forested areas (Korneykova et al. 2022).

Parent rocks play a fundamental role in shaping the chemical composition of Arctic soils, determining their physicochemical properties such as pH, texture, cation exchange capacity, and elemental composition. This, in turn, determines the total metal content, their mobile forms, and the mechanisms of their radial and lateral migration within the catena geochemical structure³.

The level of metal contamination of urban soils in the Arctic varies widely. Pollution spreads from smelting plants extending within a radius of 2–5 km, from mines and thermal power plants within a radius of 1–2 km, from boreholes within a radius of up to 0.5 km, and from highways within a strip of 0–50 (100) m. In addition, long-range transboundary transport from industrial regions of mid-latitudes is an important source of contaminants in the northern regions (Opekunova et al. 2026b). For example, in the impact zone of Pechenganikel and Severonikel on the Kola Peninsula, enrichment factors (EFs) for Zn, Mn, Fe, Co, Pb, and Cd were 1.6–10.8; for Ni and Cu, EFs were 18.4 and 24.7, respectively, with maximum EF values of 75 and 92 within the industrial complex. In Alaska, geochemical anomalies of As, Cr, Hg, Ni, and Pb exceeding the background values for soils by two times or more recorded in areas affected by mines (Perryman et al. 2020). At the same time, as shown in the example of Longyearbyen on Svalbard, despite a small population and the absence of a clear pollution source, pollutant concentrations in the soils of northern cities can correspond to background levels (Szymanski et al. 2019).

Northern ecosystems are characterized by high levels of biogenic polycyclic aromatic hydrocarbons (PAHs) in peatlands. Pollution of urban soils is associated with a variety of anthropogenic sources (Lifshits et al. 2021; Opekunova et al. 2022). Spills of drilling waste and their discharge onto the terrain lead to soil contamination with petroleum hydrocarbons and low-molecular-weight PAHs, including fluorene, acenaphthene, fluoranthene, phenanthrene, and anthracene. Emissions from heavy-duty vehicles are characterized by benzo[ghi]pyrene and benzo[a]pyrene. Indicators of diesel fuel combustion include indeno[123-cd]pyrene and acenaphthylene. Increased concentrations of petroleum products, benzo[a]anthracene, benzo[b]

fluoranthene, chrysene, pyrene, and phenanthrene have been observed in soils as a result of combined pollution from exhaust gases and drilling waste spills (Opekunova et al. 2026b).

The microbiome in Arctic urban soils undergoes significant changes due to the high diversity of environmental conditions, the presence of easily degradable substrates (waste, compost, petroleum products), soil compaction, and increased soil temperatures compared to natural ecosystems (Korneykova et al. 2022). Invasive bacteria and micromycetes, including those producing organic acids into the environment, are actively dispersing. At the same time, the indigenous microflora in urbanized areas is significantly suppressed⁴.

The aim of the study is to examine the characteristics of urban soils in the Arctic zone using the example of the Novy Urengoy municipality by analyzing their mineralogical and chemical composition, assessing pollution risks, and determining toxicity.

The specific objectives of the study were:

1. To study the physicochemical properties of soils: pH, soil texture, and organic matter content;
2. To identify mineral inclusions in soils;
3. To determine the content of total petroleum hydrocarbons (TPHs), and PAHs, as well as the isomeric ratios of PAHs;
4. To determine the total content of metals and the concentrations of their mobile forms; to identify factors determining the distribution of metals in soils;
5. To assess soil toxicity using biotesting;
6. To present an integrated assessment of soil pollution using the Harrington desirability function.

MATERIALS AND METHODS

The study area

Is the Novy Urengoy municipality, located in the Yamalo-Nenets Autonomous Okrug. It is a rapidly developing oil and gas production center with a population of approximately 118,000. The city's economy is driven by enterprises directly involved in gas, condensate, and oil production, all of which are subsidiaries of Gazprom PJSC. The city is located on the banks of the Yevo-Yakha River, a tributary of the Pur River. The Tamchara-Yakha and Sede-Yakha rivers flow through the city, dividing it into two districts: Northern and Southern.

Geologically, the study area is located in the northern part of the young Epi-Hercynian West Siberian Plate, covered by Mesozoic and Cenozoic horizontal strata (Biske 2019). The Quaternary succession is represented by late Neopleistocene alluvial-marine deposits of the fourth marine terrace, as well as modern alluvial sediments of floodplain terraces (Larin et al. 2004).

The climate in Novy Urengoy is sharply continental with harsh, long winters and short, cool summers. The soil cover is predominantly represented by Gleysols and cryometamorphic soils, which are characterized by low self-purification capacity and high sensitivity to anthropogenic impacts (Goryachkin 2010). The studied soils include Entic Podzols (sandy and loamy), Albic Podzols and Histic Albic Podzols (sandy to loamy sand), and complexes of Histic Cryosols and Histic Gleysols. Some areas feature combinations of Histic Podzols (light loamy) and Histic Gleysols (light to heavy loamy). In green zones of the municipality, the soil cover is dominated by complexes of Alfhumic Abrazems, Entic Podzols, and Albic Podzols

^{2,3,4}National report "Global climate and soil cover of Russia: the Arctic zone, permafrost soils – for the future of Russia (agriculture and forestry)". (2024). Ivanov A.L. Goryachkin S.V., Lapteva E.M. [et al.], 4, Moscow: Dokuchaev Soil Institute (in Russian)

(ranging from sand to medium loam). Industrial and transport zones are characterized by Technic Arenosols (anthropogenically disturbed), while landfill sites consist of Abralites and Lithostrats (sandy). The urbanized areas are represented by mosaics of Urbiquasizems, Lithostrats (Technosols), and remnants of Alfehumic Abrazems (Podzols) and Albic Podzols, primarily of sandy and loamy sand texture. These soils are characterized by an acidic reaction. The light texture of most soils accounts for the low concentrations of most studied metals, as well as their high mobility within the soil profile. It is known that the mobility of metals rises within complex compounds and with an increase in the physical clay fraction content (Motuzova 2009; Orlov et al. 2002). Conversely, the accumulation of semi-decomposed organic matter and the formation of a peat horizon act as a geochemical barrier, impeding both lateral and radial migration of airborne pollutants (Opekunov et al. 2022; Opekunova et al. 2026a). The spatial distribution of different soils correlates well with changes in mesorelief, microclimate, and water regime. The thickness of the seasonally thawed layer varies from 0.4–0.7 m in peat-oligotrophic soils to 1.0–1.5 m in Gleysols and over 2 m in Illuvial-Iron Podzols.

Novy Urengoy is located in the southern part of the forest-tundra zone, in the Srednepurovsky district of the Nadym-Purovsky northern province of flat-hilly bogs in combination with riverine larch sparse forests and lichen tundra (Larin et al. 2004). Outside urbanized areas, sparse larch forests and larch-spruce sparse woodlands predominate. The herbaceous-shrub layer is formed by boreal and hypoarctic shrubs – *Empetrum subholarcticum* V.N. Vassil., *Ledum palustre* L., *Vaccinium vitis-idaea* L., and *V. uliginosum* L. (Khozyainova 2008). Vegetation in the urban area is fragmented and is represented by ruderal-mixed herb communities with birch-larch sparse forests. There are birch plantations and lawns with a grass mixture dominated

by *Festuca rubra* L., *Poa pratensis* L., and *Bromopsis inermis* (Leyss.) Holub (Pismarkina et al. 2022).

The study area experiences substantial atmospheric pollution load due to transportation, extensive oil and gas operations, and urban expansion (Opekunova et al. 2025). Nevertheless, PM10 concentrations remain low, despite being enriched with Sb and Zn (Khrebtchenko et al. 2025).

The studies were carried out in July 2025 at 42 monitoring stations (MSs) in Novy Urengoy (Fig. 1). In compliance with geoecological research standards, MSs were distributed uniformly across the municipality, targeting maximum contrast in environmental conditions. This strategy ensured coverage of various functional zones—ranging from residential districts and green spaces to industrial areas and waste disposal sites—at varying distances from transportation hubs (roads, railways, and the airport). By accounting for diverse pollution sources, soil types, and plant communities with different degrees of disturbance, this sampling design enables a comprehensive analysis of environmental transformation across both natural and urbanized NTCs.

At each MS, soil samples were taken from the organic and illuvial horizons (totaling 82 samples). For a comparative analysis of changes in the chemical composition of soils in the study area, data obtained during work on the territory of the municipality in 2022–2024 were used (Opekunov et al. 2024, 2025; Opekunova et al. 2022, 2025).

Based on extensive long-term research (Opekunov et al. 2024, 2025; Opekunova et al. 2019, 2022, 2025, 2026a, b) and a review of the references⁵ (Goryachkin 2010; Khrebtchenko et al. 2025; Moskovchenko 2010; Mukhartova et al. 2025; Schuur et al. 2022; Suleymanov et al. 2022), the most representative indicators were selected to assess soil pollution in the municipality: basic soil properties, concentrations of potentially toxic metals, TPHs, and PAHs, as well as soil toxicity determined by biotesting.

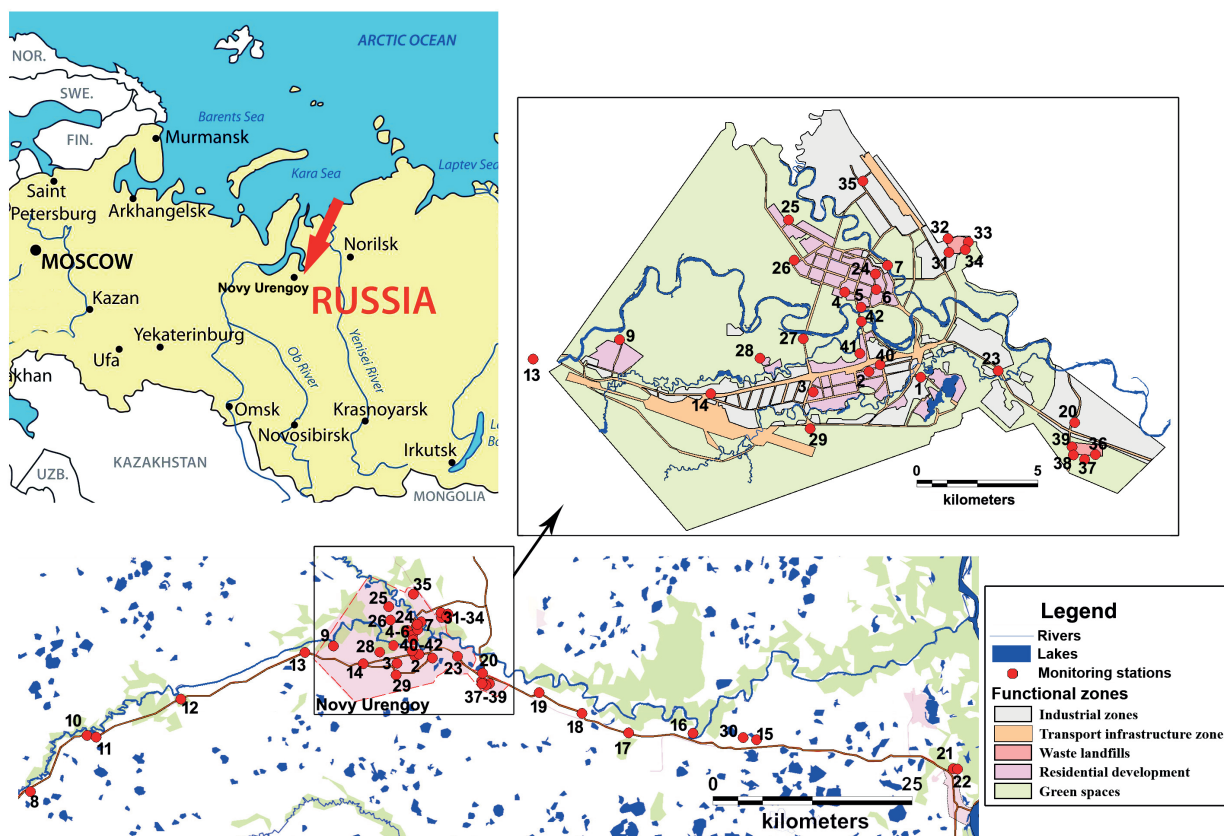


Fig. 1. Map of the location of monitoring stations and soil sampling in the Novy Urengoy

⁵National report "Global climate and soil cover of Russia: the Arctic zone, permafrost soils – for the future of Russia (agriculture and forestry)". (2024). Ivanov A.L. Goryachkin S.V., Lapteva E.M. [et al.], 4, Moscow: Dokuchaev Soil Institute (in Russian)

The soil pH was measured using the potentiometric method with an "Expert-001" device. The organic matter content of the soils was determined using loss on ignition in a muffle furnace at 900°C. Particle size distribution was determined using the sieve methods without rinsing with water, in accordance with GOST 12536-2014 (Russian National Standard for soil grain-size analysis). The mineralogical composition, as well as secondary formations and anthropogenic inclusions (including microplastics) in the organic soil horizons (fractions 0.2–1 mm; 0.2–0.1 mm; <0.1 mm) was studied using optical (Leica M205C stereomicroscope) and scanning electron microscopy (SEM; HITACHI TM 3000) at the Resource Center for Microscopy and Microanalysis at St. Petersburg State University.

The content of TPHs was determined by a fluorimetric method, while concentrations of 15 priority polycyclic aromatic hydrocarbons were analyzed using high-performance liquid chromatography at the RPA "Taifun" laboratory.

The analysis of the total content of metals (Me: Na, Ca, K, Mg, Sc, Fe, Mn, Cd, Cr, Zn, Sr, Cu, Ni, Ba, Pb, Co, V) in soil samples was performed at the Central Laboratory of the Karpinsky All-Russia Geological Research Institute via ICP-MS (ELAN-6100 DRC). Soil samples underwent total acid digestion according to the Russian Standard PND F 16.1: 2.3: 3.11-98. The concentrations of Me mobile forms (extracted with ammonium acetate buffer, pH=4.8) were determined by the ICP-AES using an ICPE-9000 Shimadzu spectrometer at the Resource Center for Methods of Analysis and Materials Research of St. Petersburg University. Biotesting using *Daphnia magna* Straus and *Chlorella vulgaris* Beijer was carried out according to PND FT 14.1:2:3:4.12-06, 16.1:2:3:4.10-04. Phytotoxicity testing with *Lepidium sativum* L. (eluate and application methods) was used to determine seed germination, as well as root and shoot growth effects (Terekhova et al. 2022).

Data processing and statistical analysis

Factor analysis using the principal component analysis (PCA) (rotation: Equimax with Kaiser normalization for total concentration, and Varimax normalized for mobile forms of Me) and cluster analysis were performed using the STATISTICA 26.0 (StatSoft) software package. The normality of the distribution was assessed based on skewness (threshold < 1) and kurtosis (threshold <5) (Nasledov 2013). Log-transformation was applied to data that did not meet these criteria. The sanitary condition of residential soils was evaluated using the total pollution index (Zc), calculated relative to regional background concentrations (RBC) (Opekunova et al. 2019).

The total content of 15 PAHs was determined. These included 3-ring: acenaphthylene (Acy), acenaphthene (Ac), fluorene (Fl), phenanthrene (Phen), anthracene (An); 4-ring: fluoranthene (Fln), pyrene (Py), benzo[a]anthracene (BaA), chrysene (Chr); 5-ring: benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), dibenzo[a,h]anthracene (DahA), benzo[a]pyrene (BaP) and 6-ring: benzo[g,h,i]perylene (BghiP) and indeno[1,2,3-cd]pyrene (InP). The sum of high-molecular (HMW 5–6 rings) and low-molecular (LMW 3–4 rings) PAHs, the sum of petrogenic (Petr – Ac, Fl, Phen, Py, Chr, BghiP) and pyrogenic PAHs (Prg – Acy, An, Fln, BaA, BbF, BkF, BaP, DahA, InP) were calculated.

The Enrichment Factor (EF) was calculated using Eq. 1:

$$EF = \frac{(Metal/RE)_{soil}}{(Metal/RE)_{background}} \quad (1)$$

where *RE* is the value of metal, adopted as Reference Element. In this research it was Sc. There are five classes of soil quality state: $EF \leq 2$ – deficiency to minimal enrichment; $2 \leq EF < 5$ – moderate enrichment; $5 \leq EF < 20$ – significant enrichment; $20 \leq EF < 40$ – very high enrichment; $EF \geq 40$ – extremely high enrichment (Barbieri 2016).

Ecotoxicological risk assessment. To assess the risk of soil contamination with PAHs, the Contamination Severity Index (CSI) (Pejman et al. 2015) was calculated using a formula adapted for PAHs (Opekunova et al. 2022) (Eq. 2):

$$CSI = \sum_{i=1}^n w_i \left(\left(\frac{C_i}{ERL} \right)^{\frac{1}{2}} + \left(\frac{C_i}{ERM} \right)^2 \right) \quad (2)$$

where C_i is the content of substances of the PAH group in a particular soil sample; w_i is the weighted toxicity coefficient; *ERL* is the content, below which biological effects are seldom; *ERM* is the value, above which effects are often or constant.

The toxicity equivalent (TEQ) (USEPA 1993) was determined for each sample to assess the ecotoxicological risk (Eq. 3):

$$TEQ = \sum_{i=1}^n (TEF_i \times C_i) \quad (3)$$

where TEF_i is the benzopyrene equivalent of the toxicity of the *i*-th polycyclic aromatic hydrocarbon (USEPA 1993); and C_i is the content of the *i*-th polycyclic aromatic hydrocarbon in soil, µg/kg. The weight coefficient of toxicity (w_i) was calculated by the Eq. 4:

$$w_i = \frac{TEF_i}{\sum_{i=1}^n TEF_i} \quad (4)$$

To assess the toxicity of soil samples, the mean effects range median quotient (MERMQ) was calculated using the Eq. 5 (Kowalska et al. 2018):

$$MERMQ = \frac{\sum_{i=1}^n \frac{C_i}{ERM_i}}{n} \quad (5)$$

where C_i is the concentration of the analyzed Me; ERM_i is the median value of the metal concentration above which biological effects are frequently or always observed (Long et al. 1995); *n* is the number of Me used in the calculation for which the *ERM* value has been established (Ni, Cu, Cr, Zn, Pb, Cd) (Long et al. 1995). Additionally, Ba was included using an *ERM* value of 2800 mg/kg (Carlon 2007). The MERMQ value was categorized into four toxicity risk levels: < 0.1 – low (9% probability of toxicity); 0.1–0.5 – moderate (21%); 0.5–1.5 – high (49%); > 1.5 – very high (76%) (Long et al. 2000).

To conduct a comprehensive assessment of soil pollution, an integrated landscape total pollution index *LTP* (Landscape Total Pollution) was calculated based on the Harrington desirability function (Opekunov and Opekunova 2014). First, the normalized values (y') for each indicator were calculated relative to the conditional background. Subsequently, the partial indices (y) were derived using the following Eq. 6:

$$y = -0.94 \times \ln(y') + 1.523 \quad (6)$$

The partial pollution indices (d) for various indicators were then calculated as Eq. 7:

$$d = \exp[-\exp(-y)] \quad (7)$$

Finally, the *LTP* values were determined using the geometric mean (Eq. 8):

$$LTP = \sqrt[q]{\prod_{i=1}^q d_i} \quad (8)$$

This index takes into account total metal content exceedances; concentrations of their mobile forms, TPHs, and PAHs in soils; and biotest toxicity (mortality of *D. magna* after 48 hours of cultivation, deviations in optical density (OD) of *C. vulgaris*, and germination energy of *L. sativum* seeds using the applicate and eluate methods) relative to the local background.

RESULTS AND DISCUSSION

Basic Soil Properties

The soil pH varies from acidic in forest-tundra NTCs and peatlands (pH = 3.91–5.80 in organic horizons and 4.25–5.83 in illuvial horizons) to neutral in residential areas (5.60–7.58 and 5.06–7.91), industrial (4.28–6.14 and 4.72–5.83) and transport (4.43–7.17 and 4.26–6.54) zones due to the alkalizing effect of building materials and the addition of fill soils. In urban conditions, an indicator of aerotechnogenic impact is an increase in acidity deeper into the soil profile, which is in good agreement with the literature data (Khrebtchenko et al. 2025; Opekunov et al. 2025; Opekunova et al. 2025; Suleymanov et al. 2022).

Loss on ignition for organic horizons varies, on average, from 7.3% (ranging from 0.45% to 45%) in filled soils of residential areas to 22% (1.3–78%) in automorphic soils under open larch forests, 32% (22–56%) in peat-gley soils, and up to 85% (81–92%) in peatlands. In illuvial horizons, the organic matter content decreases to 1.7% in Technosols (with individual samples ranging from 0.04% to 5.2%) and to 3.4% in Podburs and Podzols (0.58–11.0%).

The soil texture is diverse, ranging from sands to heavy loams. Sands and loamy sands predominate, with an average sand fraction of 98%, of which 79% is fine sand (0.05–0.25 mm). Loams are characterized by high sand content (over 80%), with the fine sand fraction exceeding 65%. This is in good agreement with published data on the sand content in soils of Novy Urengoy, reported as 87% (Nizamutdinov et al. 2021). On average, the fractional composition for the majority of the studied soils is as follows: 39.5% (0.10–0.25 mm fraction; fine sand) > 30.7% (0.056–0.10 mm; fine sand) > 18.6% (0.25–0.50 mm; medium sand) > 6.0% (0.050–0.056 mm; fine sand) > 3.3% (0.5–1.0 mm; coarse sand) > 1.6% (<0.02 mm; silt, clay, and colloids) > 0.42% (0.02–0.05 mm; coarse silt).

Mineralogical and geochemical composition

The samples contain common rock-forming minerals: quartz, feldspars (plagioclases, potassium feldspars), micas (including biotite, muscovite, phlogopite), apatite, sylvite, halite, monazite, zircon, wad, iron oxides and hydroxides, gypsum, calcite, pyrite, rutile, and cobaltite (Fig. 2).

Morphologically, these are well-rounded aggregates consisting of detrital, spherical, and pseudospherical grains. The framework grains are predominantly sand-sized (psammitic) and silt-sized, while the matrix consists primarily of pelitic (clay-sized) minerals and, to a lesser extent, silts.

An increase in the number of barite grains is an indicator of contamination from the drilling fluids. Sphalerite, galena, cinnabar, cassiterite, argentite, atacamite, and finely dispersed particles of silver and gold, which are typically represented by submicron-sized crystal or a scattering of small grains, were found in urbanized and industrial zones. Cassiterite, silver, and gold particles may be present in alluvial deposits used for road construction. In the eastern part of the Nadym-Purovsky interfluvium, the presence of Zn, Cu, Ni, Pb, and pyrite is associated, among other things, with the impact of the Norilsk industrial region (Opekunov et al. 2024). The following technogenic materials were identified: Fe-Cr, Fe-Ti-Mn, and Ti-Fe systems; Cu-Zn and Cu-Ni-Zn alloys; and titanium plates (Fig. 2).

White microplastic threads were found in all samples. A high concentration of polymer particles was specifically observed in the 0.2–1 mm fraction (Fig. 3). Waste landfills and local dumps serve as primary sources of polymers, with atmospheric transport facilitating their long-range distribution. Preliminary assessments indicate that the concentration of microplastic inclusions in the microscope field of view increases in proximity to municipal solid waste landfills. Its presence in soils serves as an indicator of anthropogenic impact on the study area; furthermore, the integration of polymers into food chains may pose risks to living organisms, including the synergistic effects of microplastics and other pollutants (Yu et al. 2022).

Content of TPHs and PAHs

The content of TPHs in background areas varies from 24 to 90 mg/kg with an average value of 47 mg/kg (Fig. 4). At most MSs, concentrations are also low: 13–160 mg/kg. However, in the zone of impact of the airport transport infrastructure (MS 14) and highways (MSs 14 and 42), the concentrations of pollutants increase to 2200 and 2400 mg/kg, respectively. At these sites, the content of PAHs expectedly increases: the sum of 15 priority PAHs is 84 µg/kg at MS 14 and 47 µg/kg at MS 42 and exceeds the background (4.9 µg/kg) by 17 and 9.6 times, respectively. This results from an increase in individual PAH concentrations by 1.7–117 times relative to the background, with the exception of Acy, DahA, and InP. All MSs are characterized by Fl_n levels 1.7–30 times above the background, which is typical for pollution within the city (Kosheleva et al. 2024; Opekunova et al. 2022). The Russian standard for BaP was not exceeded in any sample.

Isomeric ratios

The LMW/HMW and An/(Phen + An) ratios indicate a petrogenic source of PAHs at all studied MSs, with the exception of MS 42, where the source of contamination is pyrogenic. PAH emissions from motor vehicles are confirmed by BaP/BghiP ratios >0.6 (MSs 3, 4, 6, 14, 23, 28) and Fl_n/(Fl_n + Py) >0.5 (MSs 26, 35, 40 pointing to contamination from urban air pollution, wood combustion, including bush fires).

Low molecular weight compounds predominate in most of the studied samples (except for MS 42), with their content in background areas reaching 83.8–97.1%. Phenanthrene accounts for the largest share of the total PAH content at most MSs: 19.9–44.6% in the city and 40.4–50.0% in background areas. At MS 42, its contribution decreases to 12.1%, while the share of BghiP increases to 30.4% and BaP to 12.5%, respectively; these serve as indicators of vehicle pollution.

⁵National report "Global climate and soil cover of Russia: the Arctic zone, permafrost soils – for the future of Russia (agriculture and forestry)". (2024). Ivanov A.L. Goryachkin S.V., Lapteva E.M. [et al.], 4, Moscow: Dokuchaev Soil Institute (in Russian)

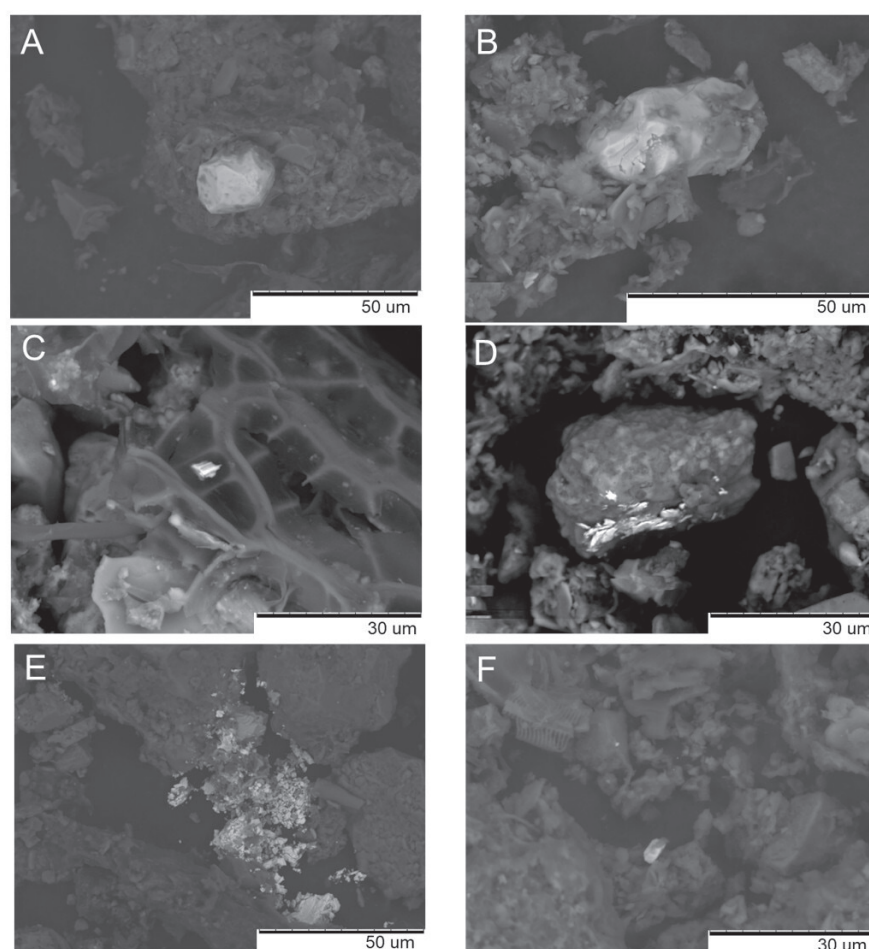


Fig. 2. Mineral inclusions in organic horizons of the soil (SEM-BSE images, reflected electrons): A – pseudospherical aggregate of monazite (MS 26, fraction 0.1–0.2 mm); B – zircon grain (MS 26, fraction <0.1 mm); C – titanium plate (MS 8, fraction 0.2–1 mm); D – Cu, Zn crystals on a quartz grain (MS 40, fraction <0.1 mm); E – galena (MS 28, fraction <0.1 mm); F – barite (MS 19, fraction 0.2–1 mm)

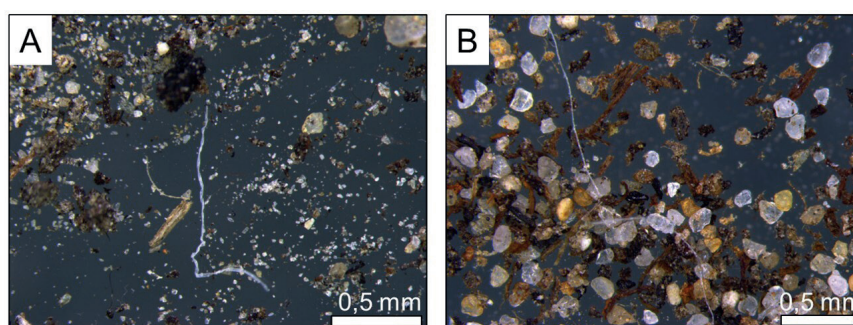


Fig. 3. Microplastic inclusions in organic soil horizons: A – MS 42 (fraction 0.2–1 mm); B – MS 28 (fraction 0.1–0.2 mm)

Toxicity and environmental risk assessment

The CSI is 0.01–0.03 in most of the samples studied, which is similar to the background level (CSI=0.01–0.02); for samples MSs 14 and 42, the contamination severity index is characterized as low (CSI=0.07).

According to the scale (Opekunova et al. 2022), TEQ and CSI indicate safe loads at most MSs, including background (CSI is 0.01–0.03; TEQ from 0.11 to 0.65, at background sites – from 0.04 to 0.18). At MSs 14 and 42, pollution is at the threshold effect level with a low hazard level (CSI=0.07; TEQ values are 8.0 and 6.8, respectively).

Total content of metals

A comparative analysis of metal concentrations against the RBC (Opekunova et al. 2019) indicates that the soils are depleted in most of the determined elements (Tables 1, 2). In all functional zones – except for roadside areas – the

average contents of Mn, Fe, Sc, V, Cr, Co, Ni, Cu, Zn, Sr, and Pb in the organic and illuvial horizons are either at the RBC level or up to 4.3 times lower. In the transport infrastructure zones, the chemical composition of the illuvial horizons matches background values. However, concentrations in the organic horizons exceed the RBC by an average of 1.6–1.8 times for Fe, Cr, Co, and Ni; 2.1–2.2 times for Mn, V, and Zn; and 3.4 times for Cu. Locally, along highways, these deviations from the RBC in organic horizons reach 2.4–3.8 times for Fe, Cr, Co, and Ni; 3.4–5.2 for Mn, V, and Zn; and 8.7 for Cu. A 14.6-fold excess of Ba in the organic horizon was observed at the Ecotechnology waste disposal site (MS 34), near the drilling mud processing unit. Pb and Cd levels remain below or comparable to the RBC across all sites.

Significant exceedances of Russian standards for Zn were observed in the organic and illuvial horizons at site MS 3 (Tundrovyy district): 6.2 and 2.0 times, respectively. This site is located 250 m from the roadway and 50 m from residential buildings. Similarly, Cu and Zn levels in

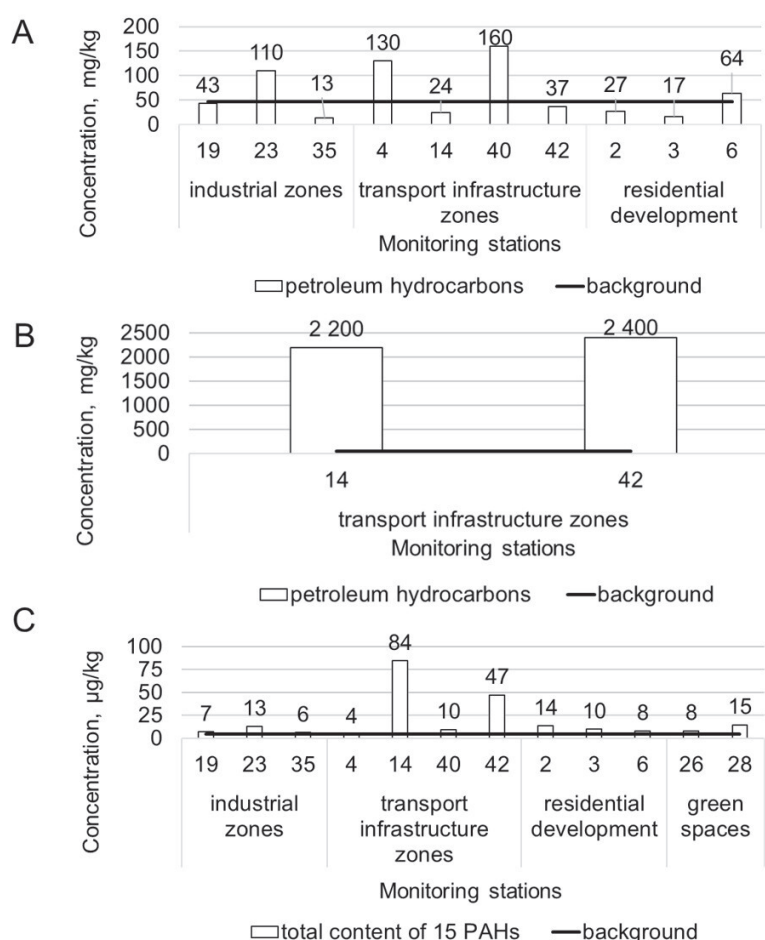


Fig. 4. Concentrations of TPHs (A, B) and PAHs (C) in organic soil horizons

the organic horizon at MS 14 exceeded the standards by 2.1 and 3.3 times, respectively; the site is situated near the airport, the Surgut-Salekhard road, and a railway crossing (150 m). These elevated levels are primarily associated with motor vehicle emissions (Tescic et al. 2022).

The Zc index indicates a low hazard level for most samples, except for organic layer soils at MS 14 ($Z_c = 27$) and 42 ($Z_c = 20$), which represent a moderate hazard. According to the adopted scale, the vast majority of the samples showed low contamination levels. Samples from the organic horizons at MS 42 (a forest area in the valley of the Tamchara-Yakha и Sede-Yakha rivers on the outskirts of Novy Urengoy, 100 m from the paved road) and MS 14 (the airport area) are classified as moderately dangerous.

MERMQ values range from 0.02 to 0.26 in organic horizons and from 0.02 to 0.18 in the illuvial horizons, indicating low to moderate toxicity (with a probability of $\leq 21\%$) and confirming the weak nature of soil pollution. Values of 0.11–0.17 are typical for residential areas (MS 3) and green spaces (MSs 7, 26, 29), while the ranges of 0.11–0.26 characterize roadside areas (MSs 5, 14, 27, 42); for the waste landfills (MS 34), MERMQ is 0.22.

The EF values confirmed a low soil pollution level: for 73% of the measured parameters, no metal enrichment was observed. No samples reached the “extremely high enrichment” threshold. In one sample from a residential area, the EF for Zn in the illuvial horizon reached 31, which corresponds to “very high enrichment”. “Significant enrichment” was identified in 2.8% of the cases: sporadic deviations for Ca, Mn, Fe, Zn, Cu, and Ba were found in organic horizons, and for K, Ca, Mn, Cu, Zn, Sr, Ba, and Pb in illuvial horizons at MSs in residential areas, parks, and waste disposal areas. The local nature of the pollution, the trends of which are described above, is further supported by the

EF values: EF ranging from 2 to 5 was obtained for 24.2% of the measurements for Na, Mg, K, Ca, Mn, V, Cr, Cu, Zn, Sr, and Ba in organic horizons and for Na, Mg, K, Ca, Mn, Fe, V, Co, Cu, Zn, Sr, Cd, Ba, and Pb in illuvial horizons.

The PCA associates the first factor ($V_{86}Cr_{84}Sc_{83}Fe_{77}Ni_{67}$), explaining 26.5% of the sample variance, with the composition of alluvial-marine parent rocks of late Neopleistocene age located in the northern and western parts of the municipality. A distinctive feature of marine sediments is the high content of siderophile and lithophile elements. This factor reflects natural soil-forming conditions. The second component (25.0% of variance) characterizes urbiquasizems (Technosols) formed on the fill areas of Novy Urengoy. This is confirmed by the aluminosilicate association ($K^{91}Ba^{87}Sr^{82}Na^{68}Mn^{65}$), represented by metals within aluminosilicate minerals, which primarily constitute the mineralogical composition of sands. Cd^{33} shows a significant negative loading on this factor, which allows for differentiation of peaty soils from anthropogenic fill. High negative factor values are observed in the peat soils of the study area. The third component ($Pb_{80}Zn_{78}Cd_{62}Cu_{59}$), accounting for 18.0% of variance, reflects the impact of transport (Opekunov et al. 2025).

Exhaust gases are a source of Pb and Zn; road marking paint contributes Cd and Pb; tire wear provides Cd, Pb, and Zn; and brake pads are sources of Cd, Cu, Pb, and Zn (Muller et al. 2020). The fourth factor, accounting for 17.8% of the variance ($Ca_{85}Co_{64}Cd_{58}$), characterizes the impact of the construction industry on the chemical composition of soils. This sector significantly contributes to the city's infrastructure development, with a maximum loading of Ca as an indicator of the use of calcareous materials. The reliability of the component interpretation is supported

Table 1. Mean total contents of metals in organic horizons of soils of various functional zones of the municipality of Novy Urengoy, mg/kg

Functional zones/ Horizons Metals	Industrial zones	Transport infrastructure zones	Waste landfills	Residential development	Green spaces	Local background		RBC (Opekunova et al. 2019)	
	organic n=5	organic n=6	organic n=10	organic n=5	organic n=6	organic n=9	peatlands n=6	organic	peatlands
Na	1500±500*	3100±800	1700±700	2000±600	3400±2700	1700±800	1200±500	–	–
Mg	900±250	8350±5000	850±350	1500±1000	1350±1050	800±700	600±300	–	–
K	4700±1700	6100±1400	5700±1600	6600±1500	6900±3000	3200±1500	3100±1300	–	–
Ca	2400±2300	8800±4800	1200±600	3800±3700	2200±2100	2100±800	1600±700	–	–
Mn	137±80	515±227	120±66	222±190	413±400	77±33	61±29	240	49
Fe	23400±23000	13900±4500	4600±2900	6500±3500	8100±5500	8900±2700	9000±4600	8790	4890
Sc	1.8±0.10	6.7±3.3	2.0±0.77	2.3±0.62	3.1±1.9	1.9±0.63	4.6±2.3	3.76	0.90
V	18.8±5.0	46±13.7	18.6±9.7	20±5.1	30±20	13.5±5.5	32±19.3	20.7	7.84
Cr	16.2±4.9	38±16.8	13.0±5.1	16.1±4.8	21±13.4	13.3±4.6	30±17.2	18.6	7.92
Co	2.5±0.70	6.5±2.4	1.4±0.68	2.9±1.4	3.2±2.2	4.1±1.7	4.5±3.2	4.09	2.07
Ni	5.0±0.89	16.8±7.3	3.6±1.6	6.6±3.6	7.2±4.6	6.4±1.7	10.9±4.7	8.89	6.34
Cu	13.0±9.7	33±20	4.7±1.9	6.4±2.5	8.7±4.3	8.1±5.4	9.9±4.8	7.92	6.24
Zn	26±9.7	79±45	21±6.9	92±90	29±17.7	23±7.1	12.1±3.7	34.9	17.4
Sr	37±14.2	74±18.6	40±11.8	65±38	62±40	38±14.0	24±5.4	72.6	20.5
Cd	0.09±0.07	0.14±0.09	0.07±0.03	0.06±0.04	0.08±0.06	0.19±0.05	0.15±0.05	0.352	0.248
Ba	291±139	338±146	562±560	285±63	299±111	165±53	153±32	224	65.1
Pb	9.9±2.9	16.3±7.7	8.1±3.0	11.3±5.5	12.8±7.1	8.5±2.0	5.4±3.0	13.5	4.93

*confidence interval (p = 0.05)

Table 2. Mean total contents of metals in illuvial horizons of soils of various functional zones of the municipality of Novy Urengoy, mg/kg

Functional zones/ Horizons Metals	Industrial zones	Transport infrastructure zones	Waste landfills	Residential development	Green spaces	Local background	RBC (Opekunova et al. 2019)
	n=5	n=5	n=8	n=4	n=6	n=5	
Na	1900±1000*	5500±3300	1800±800	1300±300	5100±3400	3800±3100	–
Mg	1000±800	2200±1350	700±650	550±100	2400±1800	2000±1900	–
K	6800±2600	11200±3300	5700±1700	4900±800	9300±4300	7400±4700	–
Ca	800±500	1600±800	800±400	700±200	1600±1100	1900±1400	–
Mn	138±85	177±69	79±20	81±19.5	156±85	136±102	183
Fe	6300±4000	13700±8100	7000±2500	3600±300	18000±11900	16100±12300	12400
Sc	2.4±1.6	4.8±2.6	2.4±0.96	1.4±0.06	6.4±4.0	5.4±4.0	6.16
V	22±13.5	49±26	26±9.5	12.9±0.85	62±39	51±42	37.4
Cr	22±15.6	33±17.8	18.1±7.7	10.4±0.42	47±32	41±33	26.1
Co	3.0±2.5	4.6±2.9	2.2±0.94	1.7±0.11	6.1±4.0	5.4±4.5	4.68
Ni	4.2±3.1	10.1±6.5	5.2±2.5	3.2±0.52	13.5±8.5	9.9±8.6	7.05
Cu	3.7±1.6	8.2±3.5	3.0±1.5	3.6±1.7	11.4±7.1	13.6±10.5	5.54
Zn	13.2±6.4	23±11.8	18.2±4.2	34±33	26±14.2	19.5±15.0	19.7
Sr	46±15.3	83±33	35±9.3	34±5.8	69±38	57±36	110
Cd	0.02±0.01	0.04±0.02	0.03±0.02	0.02±0.01	0.05±0.05	0.07±0.06	0.049
Ba	327±87	396±84	211±44	223±25	316±123	293±148	379
Pb	6.7±1.8	9.8±3.4	5.2±1.2	5.5±2.7	9.9±5.3	5.4±6.0	8.13

*confidence interval (p = 0.05)

by the results of factor analysis of metal concentrations in the solid phase of snow cover, which yielded similar factors (Opekunov et al. 2024).

Cluster analysis revealed a division of MSs based on both NTCs and soil types (peatlands and sands), as well as land use (waste landfills, transport infrastructure, residential and green spaces in the city, and industrial zones). As pollution levels increase, the clustering distance grows, and MSs with the highest contamination levels act as outliers, being effectively separated from the identified groups.

In the illuvial horizons, the influence of the underlying rocks is more pronounced than in the organic horizons. Hierarchical clustering clearly differentiates the samples into two groups: soils formed on alluvial-marine deposits (north and west of the city) and those on alluvial strata (south and east).

The content of mobile forms of metals varies widely due to variations in pH and total metal content (Table 3). The significant heterogeneity of the samples is confirmed by the calculations of the coefficients of variation: for Ba, Cd, Cr, Fe, and Sr, they reach 104–581% in organic horizons and 41–219% in illuvial horizons. A decrease in sample heterogeneity and metal mobility in illuvial horizons is consistent with published data (Enchilik and Semenov 2022).

On average, metal mobility decreases in the following series: Ca (99% in the organic horizons and 63% in the illuvial) > Cd (59% and 92%) > Mn (45% and 7.9%) > Zn (32% and 13.0%) > Mg (22% and 9.0%) > Pb (16.0% and 8.9%) > Co (13.9% and 7.3%) > Ba (11.6% and 5.2%) > Ni (10.9% and 7.8%) > Cu (6.4% and 7.9%) > K (3.8% and 1.0%) > Cr (2.1% and 3.1%) > Fe (1.8% and 3.2%) > Na (1.3% and 0.41%) > V (0.28% and 0.67%). Cd and Ca are highly mobile, with mobile forms accounting for up to 99% of their total content. In

urban areas, despite the atmospheric anthropogenic input, the bioavailability and the toxicity of cationic elements are reduced due to their lower mobility at neutral pH (Glazovskaya 2007; Kabata-Pendias 2011). Conversely, unlike in undisturbed NTCs, metal mobility in urbanized areas increases in illuvial horizons due to a downward decrease in pH.

Exceedances of Russian standards were detected only at MS 14 (near the airport) and MS 16 (the highway), where the concentration of Zn mobile forms in the organic horizons was 2 times the limit, and in the Tundrov microdistrict (MS 3), with surpasses of 3.6 times in the organic horizon and 2 times in the illuvial horizon.

According to the PCA results, the structure of factors determining the content of mobile forms of Me in soils is dominated by the lithogenic (parent rock) factor, characterized by the association $V_{98}Cr_{97}Fe_{96}Co_{95}Mn_{95}Cu_{94}K_{92}Ca_{92}Ni_{91}Mg_{83}Pb_{35}$ (41.6–43.9% of variance), and acid-base conditions ($Ni_{94}Co_{84}Fe_{83}K_{69}Cu_{53}Cr_{49}Sr_{37}Mg_{32}$), which determine the mobility of Me in soils (9.7–24.9%).

Another natural factor is organic matter, associated with the accumulation of $Cd_{85}Sr_{66}$ in peat and Ba^{49} in sands (6.8–8.6%). Anthropogenic impact is manifested through the input of $Ba_{95}Sr_{93}Ca_{82}Pb_{63}pH_{43}$ via alkalizing dust compounds (9.3–17.0%) and motor vehicle emissions ($Zn_{98}Pb_{64}Ba_{64}$; 8.4–11.5%). In organic horizons, the role of anthropogenic factors is higher than in illuvial ones.

According to **biotesting results**, 63% of samples were classified as moderately toxic (Fig. 5), while two samples (14O and 37B) exhibited acute toxicity. Organic horizons exhibit higher toxicity than illuvial horizons due to both aerotechnogenic contamination and lower pH levels. Exceptions include soils with sandy or fragmentary organic horizons, which facilitate the active migration of pollutants through the soil profile.

Table 3. Mean contents of mobile forms of metals in organic and illuvial horizons of soils of various functional zones of the municipality of Novy Urengoy, mg/kg

Functional zones/ Horizons Metals	Industrial zones		Transport infrastructure zones		Waste landfills		Residential development		Green spaces		Local background	
	O	B	O	B	O	B	O	B	O	B	O	B
	n=6	n=6	n=11	n=10	n=10	n=10	n=5	n=4	n=7	n=7	n=3	n=3
Na	20±10.6*	10.0±6.3	55±24	56±37	78±24	67±24	17.0±16.8	8.3±3.0	34±22	14.7±11.3	32±16.2	8.5±8.3
Mg	157±135	62±32	1767±1372	101±50	99±44	45±3.7	221±195	76±15.5	304±234	59±23	167±75	73±38
K	126±105	53±22	232±86	80±34	183±65	82±28	98±52	87±14.0	229±131	57±15.4	264±98	78±59
Ca	530±124	385±171	791±78	673±478	562±146	299±25	691±148	599±171	631±143	391±161	766±346	485±277
Mn	25±22	6.2±3.6	231±230	13.8±11.5	76±74	5.8±5.6	137±130	11.9±6.8	623±620	3.2±1.0	22±20	16.3±16.0
Fe	4166±4100	90±27	50±41	632±630	33±25	79±42	40±39	87±44	87±86	464±450	260±250	427±420
V	0.04±0.02	0.08±0.07	0.07±0.03	0.17±0.11	0.05±0.02	0.09±0.05	0.06±0.04	0.11±0.08	0.06±0.03	0.35±0.29	0.07±0.06	0.21±0.15
Cr	0.83±0.80	0.43±0.14	0.27±0.11	0.69±0.33	0.19±0.11	0.49±0.24	0.21±0.07	0.28±0.11	0.27±0.16	0.85±0.51	0.31±0.30	0.59±0.70
Co	0.72±0.64	0.19±0.18	0.48±0.46	0.59±0.49	0.14±0.13	0.24±0.14	0.42±0.34	0.26±0.24	0.68±0.67	0.31±0.28	1.1±1.0	0.39±0.37
Ni	1.0±0.90	0.29±0.13	0.81±0.29	0.76±0.57	0.31±0.07	0.45±0.14	0.32±0.09	0.34±0.14	0.62±0.30	0.46±0.21	0.73±0.59	0.37±0.35
Cu	1.1±1.0	0.39±0.18	0.56±0.31	0.33±0.23	0.17±0.10	0.19±0.09	0.30±0.07	0.29±0.12	0.17±0.06	0.23±0.12	0.25±0.15	0.36±0.52
Zn	6.5±6.3	1.2±0.40	16.8±9.5	1.4±0.52	4.5±2.7	2.1±0.76	23±22	12.8±12.0	10.9±6.2	1.0±0.29	6.1±0.90	1.3±1.2
Sr	5.2±2.9	4.1±2.4	8.0±2.4	4.4±1.3	14.5±1.4	3.0±0.18	13.3±13.1	4.1±0.73	7.7±3.9	4.3±1.7	8.1±3.2	5.3±2.7
Cd	0.03±0.01	0.03±0.01	0.06±0.05	0.04±0.03	0.04±0.01	0.05±0.04	0.10±0.09	0.02±0.01	0.15±0.14	0.04±0.03	0.18±0.17	0.05±0.04
Ba	34±29	19.5±19.4	43±35	14.3±5.1	34±29	8.1±1.7	16.5±5.7	13.9±7.0	29±16.1	15.1±5.6	21±4.4	15.7±9.7
Pb	1.9±1.7	0.53±0.50	2.0±0.92	0.63±0.29	1.1±0.98	0.19±0.13	1.5±0.98	0.88±0.98	2.3±1.2	0.66±0.25	1.8±0.83	0.48±0.39

*confidence interval (p = 0.05)

While biotesting results across different test objects are comparable, *D. magna* shows higher sensitivity to TPH and PAH contamination ($r=0.61-0.83$; $r_{cr}=0.58$ at $p=0.05$). *L. sativum* (applicator method) proved particularly responsive to BbF ($r=0.58$), BkF ($r=0.60$), BaP ($r=0.68$) and BghiP ($r=0.75$), as well as to the total content of Mn, Co, Ni, Cu, and Sr ($r=0.36-0.64$; $r_{cr}=0.33$, $p=0.05$).

Phytotesting using the eluate method showed that changes in OD of *C. vulgaris* correlated weakly with pollutant concentrations. Nevertheless, a statistically significant response was observed for DahA ($r=0.62$; $r_{cr}=0.58$, $p=0.05$), as well as for the total content and mobile forms of Fe, Mn, Cr, Co, Ni, and Sr ($r=0.34-0.43$; $r_{cr}=0.33$, $p=0.05$).

Integrated assessment of soil contamination

Based on the *LTP* calculation results, the soil contamination level at numerous MSs is assessed as low (Fig. 6). Significant deviations from background levels were recorded at MS 14 ($LTP=0.11$) and MS 42 (0.18). Such low values are due to the substantial exceedance of reference standards by pollutant concentrations (up to 36-fold for certain parameters) in the organic horizons.

Pollution levels are minimal at 10 MSs, representing local background sites and green spaces. This category includes MSs 21, 32, 36, and 39 despite their proximity to landfills. MSs 21 and 32 are situated in larch forests, 150–200 m away from roads and landfill sites, resulting in an insignificant emission impact. At MSs 36 and 39, the soil cover consists of Technosols (abrasives and abralites); these predominantly sandy soils are characterized by low accumulative capacity.

The primary contribution to the decrease in *LTP* is driven by partial indicators of TPHs and PAHs content, as well as biotesting results, as test objects respond sensitively to such pollution. In urbanized areas, these parameters serve as reliable indicators of environmental change. The impact of motor vehicles – the main pollution source in Novy Urengoy – is confirmed by both partial indicator calculations (which are lower in transport infrastructure areas than in other functional zones, with *LTP* ranging from 0.11 to 0.77) and by literature data (Khrebtchenko et al. 2025; Opekunov et al. 2025). In industrial zones, the *LTP* variation (0.62–0.77) corresponds to a low pollution level. In residential areas, *LTP* values (0.51–0.80) indicate moderate transformation, resulting from highways and the use of fill soils.

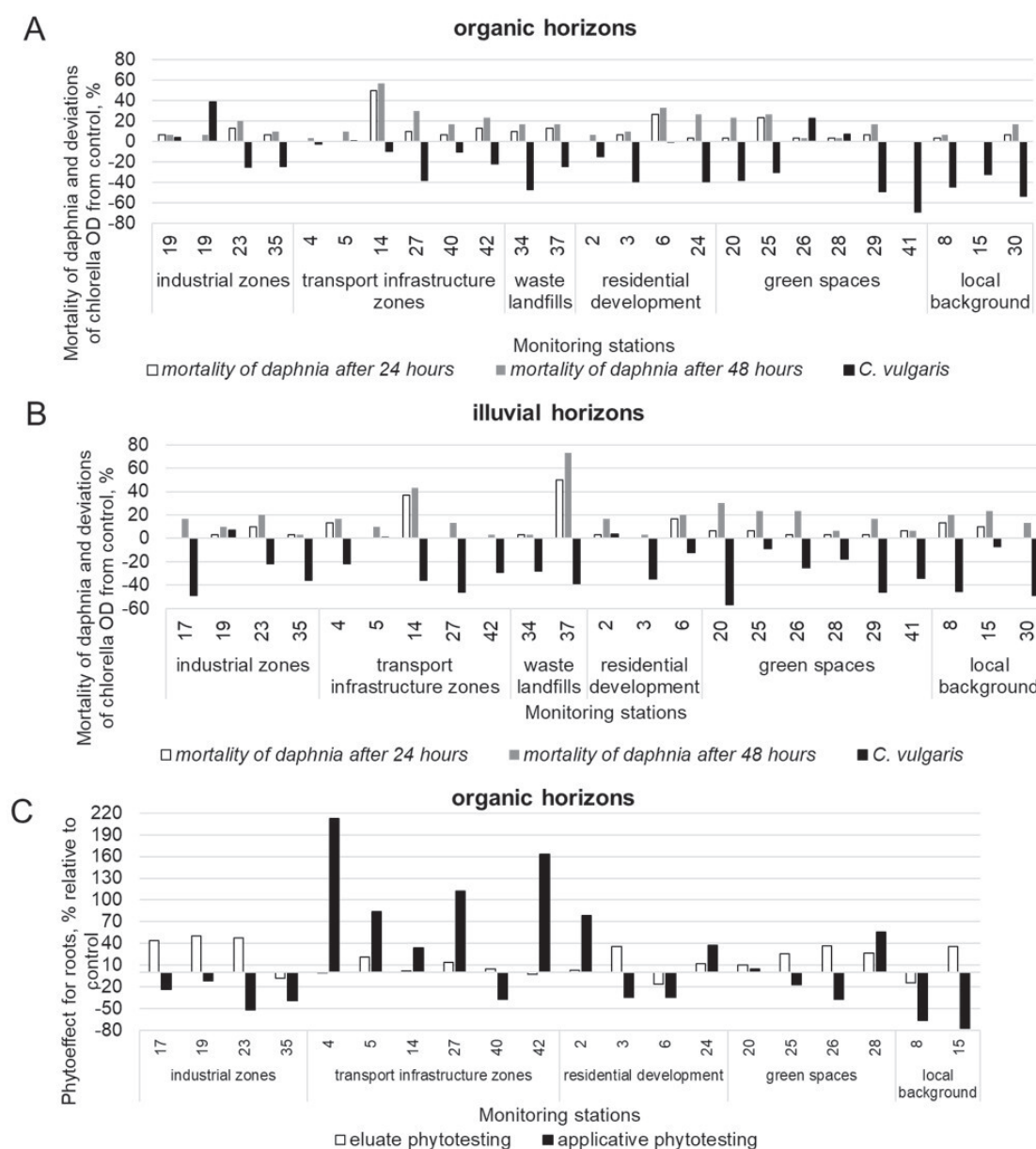


Fig. 5. Results of soil biotesting: A, B – with *D. magna* and *C. vulgaris*; C – with *L. sativum*

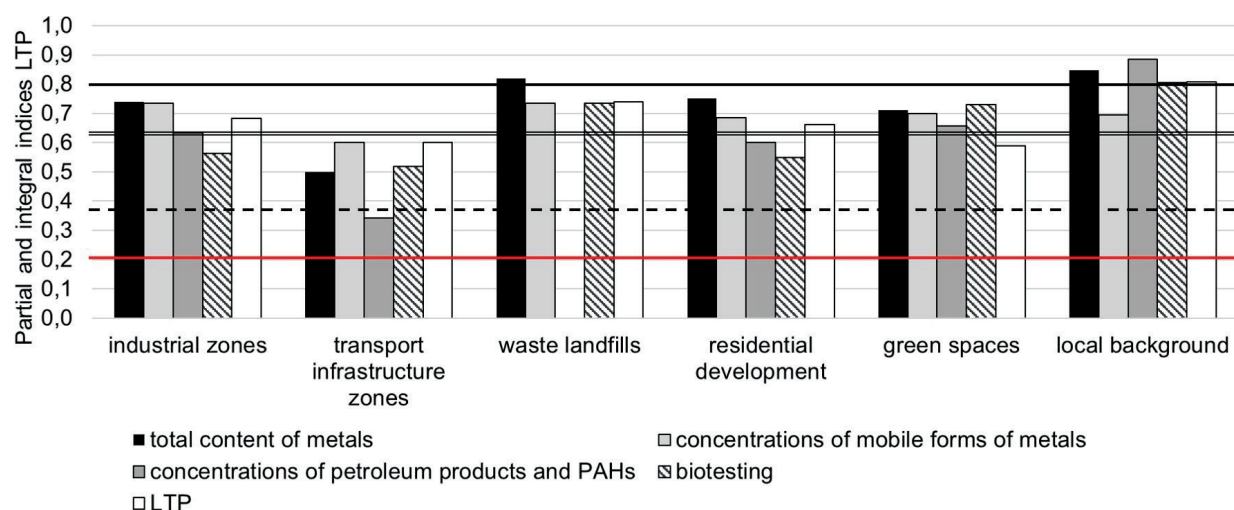


Fig. 6. The value of the integrated landscape pollution index LTP at the MSs in Novy Urengoy. Legend, gradation of pollution levels of environmental components: extremely high ($LTP < 0.20$); high ($0.20 \leq LTP < 0.37$); moderate ($0.37 \leq LTP < 0.63$); low ($0.63 \leq LTP < 0.80$); $LTP \geq 0.80$ – extremely low

CONCLUSIONS

Soil pollution in Novy Urengoy municipality is low and localized. Motor transport is the primary source of anthropogenic pollution. Due to the simultaneous impact of oil and gas production, urbanization, and atmospheric transport, the soil composition contains inclusions of rock-forming and accessory minerals. Additionally, technogenic components such as barite (from drilling) and minerals associated with Arctic mineral development (including sphalerite, galena, cinnabar, argentite, and atacamite) are present. Various alloys (Fe-Cr, Fe-Ti-Mn, Ti-Fe; Cu-Zn, Cu-Ni-Zn) and titanium plates, resulting from vehicle emissions and industrial activities, have also been identified.

The content of TPHs and PAHs concentrations at most sites remain within safe limits, corresponding to background levels. Concentrations associated with transport infrastructure have reached threshold effect levels, indicating a potential environmental hazard.

The total metal content is below the RBC. While the overall potential for metal contamination remains low, biotests revealed significant soil toxicity. This toxicity is attributed to elevated levels of PAHs, TPHs, and specific elements including Mn, Fe, Cr, Co, Ni, Cu, Sr, and Pb. Deviations from baseline values were observed in samples across all functional zones.

A combined analysis of the geochemical environment, anthropogenic impact sources, and soil pollutant levels indicates a low overall level of environmental pollution; most indicators generally align with background values and Russian regulatory standards. Transport infrastructure zones are characterized by contamination with Fe, Cr, Co, Ni, Mn, V, Zn, and Cu, as well as PAHs and petroleum products. In waste disposal areas, Ba emission is observed due to the dusting of drilling waste. The highest levels of soil contamination with TPHs, PAHs, and metals – exceeding background values by 1.5–117 times – were recorded in the airport's impact zone and along the highway between the Northern and Southern utility zones in the forest area of the Tamchara-Yakha and Sede-Yakha river valleys.

The addition of fill soils leads to a decrease in the overall level of urban pollution, while the alkalization of soils by dust from construction materials reduces metal mobility and bioavailability to plants. However, sandy fills increase the risk of radial migration of pollutants. This, combined with seasonal thawing of permafrost, poses risks of pollutant redistribution within the soil profile and subsequent accumulation in underlying horizons. Roadside areas are particularly vulnerable to these risks due to the constant presence of pollution sources and active lateral migration of contaminants from the roadway. Notably, the chemical composition of urban soils can change significantly due to the application of fill soils to lawns and construction sites.

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Appendices

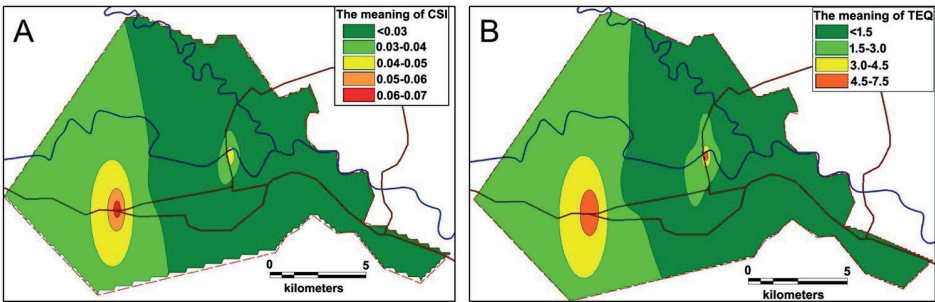


Fig. A.1. Schemes of spatial distribution of CSI (A) and TEQ (B) values

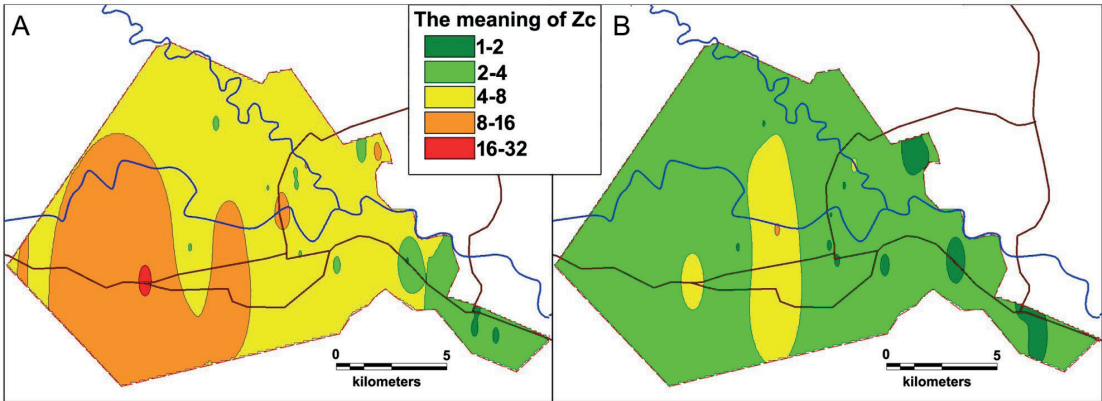


Fig. A.2. Schemes of spatial distribution of Zc values in organic (A) and illuvial (B) horizons

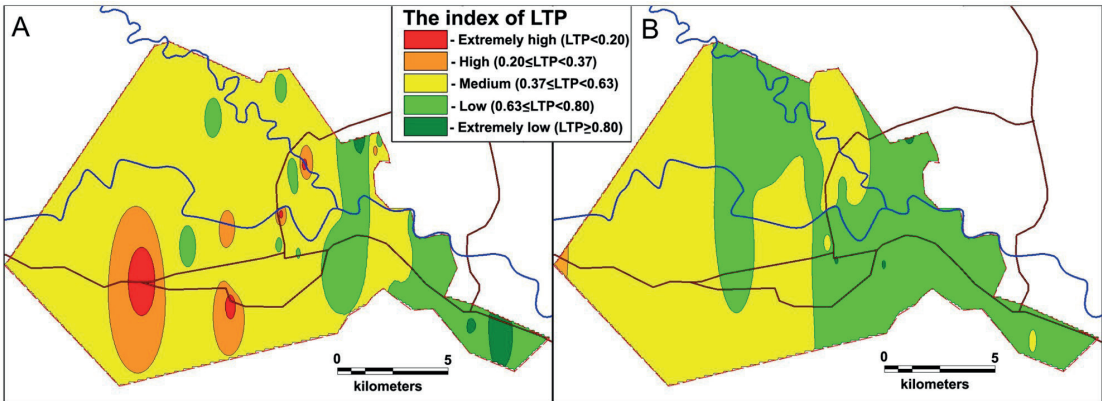


Fig. A.3. Schemes of spatial distribution of LTP values in organic (A) and illuvial (B) horizons