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Edaphic Diversity, Polychemical Soil Status of the Prinevskaya Lowland and Prospects for Soils Use

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Abstract: There will be a significant increase in anthropogenic load on the soils of the Prinevskaya lowland in the nearest decade due to the fact that a significant territory is occupied by St. Petersburg. The main objective is a study of the sanitary-hygienic state and soil diversity of the Prinevskaya lowland in case of a high degree of agricultural soil development there and the significant role of the lithological factor. Soils were studied at the following land use and land cover: agricultural and fallow soils of agrolandscapes; forest soils; and soils of industrial areas. Studies were carried out using morphological descriptions and analyses of chemical, physical, and biological properties. The most vulnerable land use are forest and agricultural and fallow zones, where active accumulation of priority toxicants of anthropogenic origin can occur. Geochemical peculiarities of studied soils are deficit of Mn, Cu, Mo, and Zn in soil-forming rock materials and accumulation of strontium and lead in arable horizons. The soils examined show minimal contamination with trace elements, as verified by a range of individual and combined ecotoxicological indicators. Urban development planning, particularly in St. Petersburg, should prioritize the preservation of biodiversity and soil resources.

Keywords: edaphic diversity; soil contamination; pollution status indexes; lowland; anthropogenic impact; soil functioning; land use

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1. Introduction

Urban soils play a crucial role in the urban ecosystem, serving as an essential component of the habitat for humans, plants, and animals, while also underpinning various economic activities [1–4]. The condition of these soils is vital for evaluating the ecological health of a specific area, as they are significant in multiple ways: they act as the primary link in the food chain, serve as a source of secondary pollution for air and water, and provide a consolidated measure of the overall ecological status of the environment [5]. As cities often expand into surrounding agricultural lands, they encounter various agronatural soils and agrozems with distinct agrogenic horizons [6–8].

A significant portion of St. Petersburg is situated on the Prinevskaya lowland plain, a terraced lacustrine–glacial landscape formed from the glaciolimnium of the Baltic glacial lake (Figure 1) [9–11].

This flat region lies between the Gulf of Finland and Lake Ladoga, with its formation history linked to the abrasion and accumulation processes of late- and post-glacial basins, which have contributed to the variety of soil-forming materials present [12–14]. Notably, a large part of the Prinevskaya lowland is occupied by St. Petersburg and its associated industrial and agricultural enterprises, highlighting the significant impact of human activity on the development of lowland soils over the past three centuries.

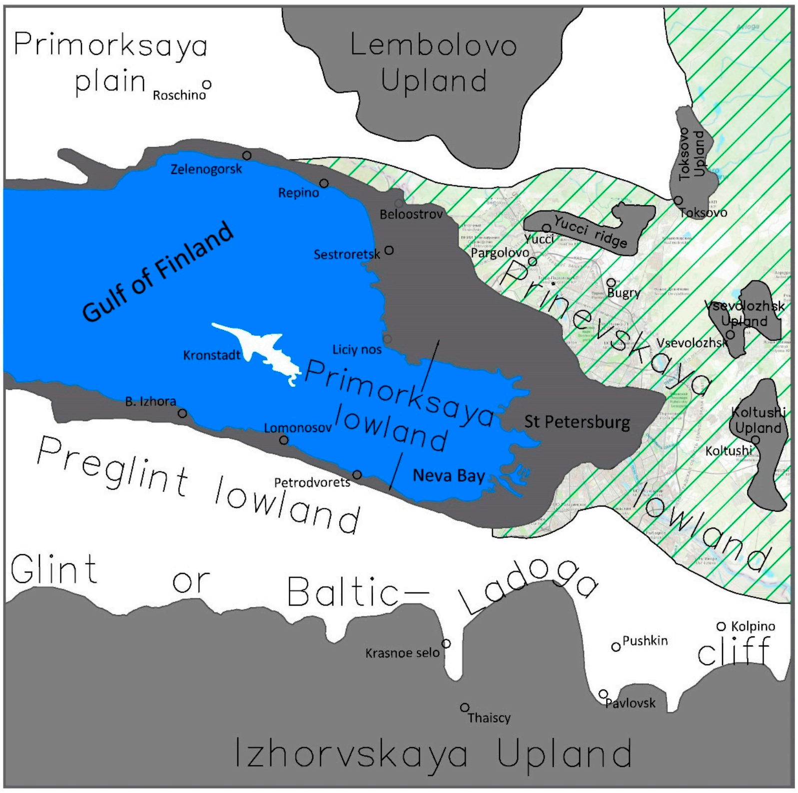


Figure 1. Prinevskaya lowland (marked with green shading).

The peculiarities of the soils of this territory were covered in the works [15–24] and a number of others. The works mentioned above were written in the last century and require updating. Additionally, the diversity of soils and their chemical properties are not well studied. There are challenges in assessing the sanitary and hygienic conditions of soils, as well as gaps in our understanding of soil development dynamics in agricultural landscapes. Furthermore, information regarding the sources of polychemical soil pollution is lacking. The current level of knowledge on the geochemistry of natural and anthropogenic landscapes in St. Petersburg and the Leningrad region is insufficient to address all issues related to the ecological and geochemical conditions of soils in the Prinevskaya lowland. Moreover, large cities such as St. Petersburg are important driving factors of environmental trends due to the increasing proportion of the global population living in urban areas and the high intensity of urban residents' activities. However, as the world urbanizes, people lose touch with the soil and the services it provides to sustain life. As developing cities and countries industrialize, soil pollution continues to increase and reaches a level that requires immediate action. Therefore, conducting a global assessment of the state of urban soils, starting from the local levels, such as the soils of the Prinevskaya lowland, to identify patterns, processes, and unique anthropogenic impacts is quite a relevant objective.

The lowland has a long history of agricultural development. The Prinevskaya lowland is characterized by the prevalence of humus–podzolic–gley soils with a thick peat horizon and drained sphagnum peat bogs [15]. In 1922, a soil survey conducted in the Shusharskaya farm area, situated in the heart of the Prinevskaya lowland, revealed that it can be challenging to reestablish the boundaries of natural soil types after years of cultivation and the application of urban waste and peat [16]. Today, the Prinevskaya lowland serves as the primary region for suburban agriculture, supplying Saint Petersburg with potatoes and vegetables, as well as functioning as a base for livestock feed. The fields were drained, treated with lime, and received large amounts of both organic and mineral fertilizers. Agricultural activities utilize 71–98% of all lowland areas, with over half of this land designated for arable farming (40–65%). A minor portion (ranging from 2 to 18%) is covered by secondary small-leaved forests [25,26].

Data from the third round of soil agrochemical surveys, conducted in the early 1980s during a period of intensive fertilizer application, indicated a significant increase in the average humus content of Leningrad region soils, reaching 3.5%. Additionally, there was a reduction in soil acidity and an enhancement in the levels of essential plant nutrients (the average content of mobile phosphorus and potassium in the region's soils attained average to above-average availability) [27,28]. Moreover, the Prinevskaya lowland stands out as one of the most intensively farmed regions in the Leningrad region. Consequently, areas with low pH, poor humification, and deficiencies in mineral nutrients occupy only a small fraction of their landscape. The practice of intensive agriculture has resulted in the emergence of a new soil component in the Prinevskaya lowland—agrosoils. These soils develop on various parent materials and are characterized by a thick (over 40 cm) organic layer that is well-structured and rich in plant nutrients [6].

Unfortunately, the economic decline in the Russian Federation during the 1990s and early 2000s was marked by inconsistencies in land use, resulting in a decrease in arable land. As a consequence of the changing economic landscape, a substantial portion of arable land in St. Petersburg has been left uncultivated [29–31].

The northwest region of the Russian Federation serves as a distinctive showcase of the diversity found in fallow lands. The quality of these lands, along with their biological characteristics and fertility levels, plays a crucial role in determining the quality of agricultural products, including seeds and grains [32,33].

In addition to the intentional effects of agriculture on the soils of the Prinevskaya lowland, there is also the unavoidable influence of the nearby city of Saint Petersburg, along with its industrial and transportation activities. Heavy metals and other toxic substances are released into the environment through the atmosphere, while sewage and urban waste serve as another major source of pollution. As a result of atmospheric transport, as well as surface and groundwater flow, a substantial suburban area is subjected to contamination. Therefore, the objectives of the study were: (a) to investigate the soil diversity of Prinevskaya lowland and describe the main types of urban, natural, and agrosoils at different land use and land cover (LULC), to determine their morphological features, and taxonomic position; (b) to evaluate the main chemical, physical and biological properties of soils of the different functional zones; (c) to assess heavy metal content and its geochemical distribution, and characterize the soil pollution status. The edaphic diversity and polychemical status of soils in the Prinevskaya lowland were studied on the example of the following objects (LULC):

1. Agricultural and fallow soils of agrolandscapes;
2. Forest soils;
3. Soils of industrial areas.

2. Materials and Methods

The territory of the Prinevskaya lowland is located in the northwest of the East European Plain in the southern part of the Karelia Isthmus. It is limited by the fluvio-glacial hills of the Koltushy upland in the north and by the Izhora upland in the south.

The climate of the Prinevskaya lowland is characterized as moderately cold and humid, influenced by the Atlantic Ocean, the Baltic Sea, and Lake Ladoga. In summer, the thermal regime is primarily affected by solar radiation, while in winter, it is largely determined by heat transfer from the Atlantic. Average temperatures in July range from

16.5 to 17.0 °C, while January sees averages of −8.0 to −8.5 °C, resulting in an average annual air temperature of 2.4 to 2.6 °C [34]. Precipitation patterns are mainly influenced by the topography; for instance, the lowland shores of the Gulf of Finland and Lake Ladoga receive the least rainfall. The average annual precipitation in the area is between 550 and 600 mm, with evapotranspiration rates of 400 to 500 mm, leading to a precipitation ratio of 1.8, indicating excessive moisture [35,36].

In terms of geomorphological zoning, the region falls within the Prinevsky–Estonian district of the Baltic–Valdai region and is part of the North Russian province of the Russian Plain. The Prinevskaya lowland is bordered to the north by the Central (Kotovskaya) Upland of the Karelia Isthmus and to the south by the Baltic–Ladoga escarpment. It features a terraced marshy plain with elevations ranging from 10–15 to 55–60 m [37]. The current landscape is primarily shaped by lake–glacial, glacial, lacustrine, and marine processes that occurred during the late Neopleistocene to Holocene periods. Common landforms include multi-aged lake and lake–glacial plains with coastal ramparts, sand spits, and abrasion scarps, all associated with Late Glacial–Holocene palaeobasins; rock outcrops and remnant uplands are more prevalent in the northern part of the study area. The border of the Prinevskaya lowland in the north is partly the abrasion ledges of the Rantolovsky plateau of the Toksovskaya kame upland.

The Prinevskaya lowland was formed in pre-glacial times. The contemporary landscape began to take shape as the last Valdai glaciation receded. The Prinevsky landscape emerged on sandy hills and loamy moraine deposits that constitute the Prinevskaya lowland, featuring granite boulders and banded clays. Most of the small boulders were removed from the soil during the process of territory development, while large boulders were blasted, crushed, and used in construction (for example, one of the boulders (Grom Stone) was used for the pedestal of the Bronze Horseman).

Moraine covers the bottom of the lowland and the surrounding areas, forming a flat surface (peneplain) and confirming that the lowland was formed before glaciation and is of tectonic origin. The geological column of Quaternary sediments is completed by marine, marsh, and eluvial sediments of the Holocene age.

The study area is characterized by middle-taiga forests, high and lowland swamps, and overgrown lakes. The primary element of the cropping system in the study area has been and continues to be perennial grasses, while annual grasses, vegetables, potatoes, and cereals cover significantly smaller areas.

Ten soil pits within Prinevskaya lowland were made in order to analyze soils of studied LULC (Figure 2).

Morphological soil diversity of the Prinevskaya lowland was studied in August–November 2023. These investigations were conducted utilizing standard soil characterization methods, including soil pits, morphological descriptions, and laboratory analyses focused on examining the chemical, physical, and biological properties of the soils.

Soil samples were collected from various depths of the soil horizons at each sampling location. Soil identification was performed in accordance with the "Classification and Diagnostics of Russian Soils" [38] and the World Reference Database of Soil Resources (FAO, 2015) [39].

All samples were air-dried at room temperature in the Department of Applied Ecology at St. Petersburg State University and subsequently passed through a 2 mm sieve. The analysis of soil properties was conducted on the fine earth fraction. The comprehensive analytical soil characteristics involved assessing chemical, physical, and physicochemical soil indicators through widely recognized methods [40,41].

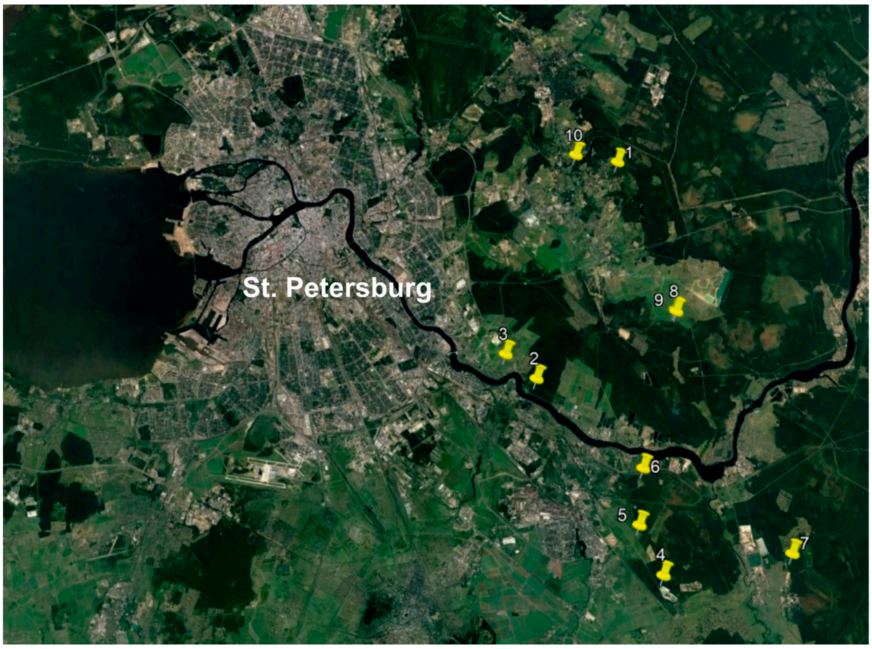


Figure 2. Map of studied plots and soil pits within the Prinevskaya lowland.

The particle size distribution was assessed using the Kachinsky pipette method, which involved the peptization of microaggregates with pyrophosphate. The analysis of mobile potassium compounds was performed following the Kirsanov method, as modified by the Central Scientific Research Institute of Agrochemical Service of Agriculture (CSRIASA) in accordance with Russian National Standard GOST R 54650-2011 [42]. The measurement of basal respiration (BR) was conducted according to the specified method [43]. Basal respiration is based on recording the CO_2 response in native soil. The pH values were determined in water and salt suspensions (soil-to-solution ratio 1:2.5). Substrate-induced soil respiration determined by the SID technique was also evaluated [44]. Carbon content was determined by the Tyurin method [40].

Soil samples in the solid phase were analyzed by X-ray fluorescence method using a portable X-ray spectrometer "Spectroscan" (M-049-P/16, 2016, Ekaterinburg, Russia) for the content of the following metals: Sr, Pb, As, Zn, Cu, Ni, Co, Fe_2O_3, MnO, Cr, V and TiO_2. Spectrometer "SPECTROSKAN" is designed for determination of elemental composition in the range from ^{11}Na to uranium (^{92}U), equipped with a vacuum-assisted scanning crystal-diffraction channel. The range of determinable contents from 0.0001% to 100% without concentrating depends on sample type, analyzed element, and matrix, and from 10^{-6} to 10^{-7}% to several proportions of percent with concentrating. The basic instrumental error does not exceed 0.5%. Calculation from oxide contents to element concentrations was carried out according to standard conversion coefficients [45].

Geochemical soil pollution by heavy metals was assessed by calculating the total soil pollution index Z_c, calculating exceeding the regional background values (single pollution index—*PI*) and maximum permissible concentrations specified in standard SanPiN 1.2.3685-21 [46]. The *PI* values are determined by taking the ratio of heavy metal concentrations (C_n) to their corresponding background regional values (B_n). The overall soil pollution index is computed using the following formula:

$$Z_c = \left(\sum_{i=1}^{n} PI \right) - (n-1) \quad (1)$$

Z_c is classified into four classes (Table 1).

The geoaccumulation index (I_{geo}) (proposed by Muller G. [47]), pollution load index (*PLI*) and potential environmental risk index (*RI*) were used to fully assess the pollution status of potentially toxic metals in soils of the Prinevskaya lowland.

The geoaccumulation index I_{geo} is used to determine the degree of contamination by trace metals relative to natural regional background values [47,48] and is calculated by the following formula:

$$I_{geo} = \log_2\left[\frac{C_n}{1.5\ B_n}\right], \quad (2)$$

where C_n represents the measured concentration of the element in the soil, B_n denotes the geochemical regional background value. Background values were determined according to Matinyan et al. 2007 [49]. A coefficient of 1.5 is used to minimize possible variations due to lithogenic variations [50]. I_{geo} is classified into seven classes (Table 1).

The Pollution Load Index (*PLI*) is determined as the geometric mean of the Pollution Index (*PI*) values [51–54]. This intricate index is calculated using the following formula:

$$PLI = \sqrt[n]{PI_1 \times PI_2 \times PI_3 \times \ldots PI_n} \quad (3)$$

PLI is divided into six categories (see Table 1).

The Potential Ecological Risk (*RI*) Index assesses the level of ecological risk associated with the harmful effects of trace metals [53,55,56]. This index is computed using the following formula:

$$RI = \sum_{i=1}^{n} E_r^i = \sum_{i=1}^{n} T_r^i \times P \quad (4)$$

where n represents the number of heavy metals, E_r^i indicates a single ecological risk factor index, and T_r^i refers to the toxicity response coefficient for each metal (As-10; Ni, Pb, Co-5; V, Cr-2; Zn-1) [55]. *PI* is calculated values for the Single Pollution Index. *RI* is categorized into five classes (Table 1).

All the indices utilized have their own evaluation scales, which are detailed in Table 1.

Table 1. Classification of pollution status indexes.

The Total Soil Pollution Index (Z_c) [46]		
1	<16	Permissible pollution
2	16–32	Moderately dangerous pollution
3	32–128	Dangerous pollution
4	>128	Extremely dangerous pollution
Geoaccumulation index (I_{geo}) [57]		
0	$I_{geo} \leq 0$	Absence of pollution
1	$0 < I_{geo} \leq 1$	From unpolluted to moderately polluted
2	$1 < I_{geo} \leq 2$	Moderately polluted
3	$2 < I_{geo} \leq 3$	From moderately to highly polluted
4	$3 < I_{geo} \leq 4$	Highly polluted
5	$4 < I_{geo} \leq 5$	From highly to extremely high polluted
6	$I_{geo} > 5$	Extremely high polluted
Pollution load index (*PLI*) [53,58]		
0	PLI < 1	Absence of pollution
1	PLI = 1	Baseline levels of pollution
2	$1 < PLI \leq 2$	Low pollution
3	$2 < PLI \leq 3$	Moderate pollution
4	$3 < PLI \leq 5$	High pollution
5	PLI > 5	Strong pollution

Table 1. *Cont.*

Potential ecological risk (*RI*) [55,56]		
1	RI < 90	Low potential ecological risk
2	90 ≤ RI < 180	Moderate potential ecological risk
3	180 ≤ RI < 360	High potential ecological risk
4	360 ≤ RI < 720	Strong potential ecological risk
5	RI ≥ 720	Very strong potential ecological risk

The vertical electrical resistivity sounding (VERS) method, which enables the vertical division of soil layers into genetic layers with distinct properties and characteristics [59,60], was conducted using the portable LandMapper device (ERM-03, Landviser, LLC, League City, TX, USA). Measurements of apparent electrical resistance in the soil and strata were taken with electrode spacings of MN 10 and AB/2 at distances of 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150, 200, 300, 400, and 500 cm. This approach allowed for the determination of apparent soil electrical resistance values at the corresponding depths.

The statistical data processing and analysis were performed using methods with the software packages MS Excel 2016, Past (version 3.20), and Statistica 64 (version 10).

3. Results and Discussion

3.1. Edaphic Soil Diversity of Prinevskaya Lowland

The soil cover of the Prinevskaya lowland was formed within the conditions of flat, poorly drained relief, with insignificant height variations. The cool, humid climate, along with this factor, leads to surface water stagnation and the occurrence of waterlogging processes in the region. The variety of soil-forming rocks in the lowland is a result of glacier and post-glacial water basins, which facilitated the erosion and redeposition of glacial sediments.

In the examined area of the Prinevskaya lowland, the following soil-forming materials were identified: (a) moraine loams and (b) fluvioglacial sands and sandy loams.

Additionally, the region contains banded clays and loams, limnoglacial sands and sandy loams, as well as sands and sandy loams of various origins, all underlain by loams and clays of lacustrine–glacial and moraine types.

The homogeneity of the relief in the Prinevskaya lowland means that soil diversity is largely influenced by lithological factors, which relate not only to the chemical composition and physical properties of the soil but also to their water availability. Additionally, human activities have significantly impacted the development of the soil cover in the study area over the past 200–300 years, leading to the formation of various agronatural soils and agrozems with distinct agrogenic horizons. Initially, this influence could be seen as beneficial—such as through land development and fertilizer application—but as anthropogenic impacts have intensified, their harmful effects have also become evident.

The diversity of soil-forming materials within the Prinevskaya lowland had a significant influence on the nature of soil-forming processes that determine the main soil types (Figure 3). Podzol formation associated with the impact of humus acids on the mineral soil part and further profile migration of decomposition products is most characteristic for soils formed on moraine loams. Gley soils develop on clay materials under conditions of impeded internal drainage and excessive moistening by surface waters. The formation of a lightened horizon in these soils is the result of reduction processes and the removal of elements of variable valence from upper horizons in a horizontal rather than vertical direction. Podzols and podburs (Entic Podzol) with illuvial–iron, and illuvial–humus horizons are formed on sandy rocks under the influence of podzolization and alfehumus processes. The alfehumus process consists of the removal by humus acids of aluminous-iron films from mineral grains and the formation of illuvial horizons with the content of semi-ferrous oxides and incrustive humus [23].

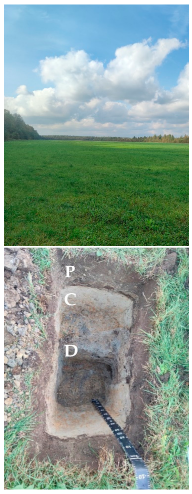
Agricultural and fallow soils of agrolandscapes:

Agrozem redoxymorphous light loamy formed on kama sandy loams (agricultural field) (Stagnic Anthrosol) N°. of study plot–3.

Agrozem texture-differentiated sub-eluvial loamy on cambrian clays (agricultural field) (Plaggic Anthrosol) N°. of study plot–5.

Sod-podzolic postagrogenic redoxymorphic loamy soil on cambrian clays (forest massif) (Umbric Plaggic Albeluvisol) N°. of study plot–7.

Postagrogenic grey humus fallow redoxymorphic sandy loam soil on fluvioglacial sediments (forest massif of the Prikoltushsky part of the Prinevskaya lowland) (Stagnic Anthrosol) N°. of study plot–8.



Agrozem ameliorative deep-turbid redoximorphic sandy loam on fluvioglacial sediments (agricultural field of the Prikoltushsky part of the Prinevskaya lowland) (Irragric Anthrosol) N°. of study plot–9.

Agrozem alfehumus postagrogenic sandy on kama sandy loams (Koltushy uplands nature protected area) (Plaggic Albic Anthrosol) N°. of study plot – 10.

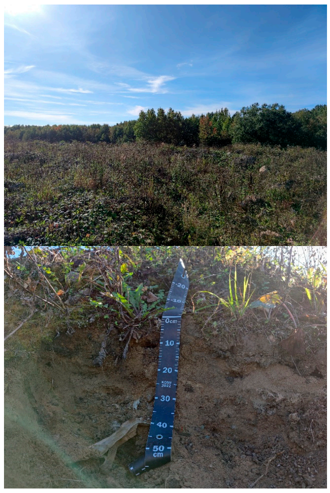
Forest soils:

Soddy podbur podzolized formed on kama sandy loams (border of Prinevskaya lowland and Koltushy upland *) (Umbric Entic Podzol) N°. of study plot–1.

Soddy podbur redoxymorphic sandy loam on kama sandy loams (forest park) (Umbric Entic Podzol) N°. of study plot–2.

Soils of industrial areas:

Lithostrata on cambrian clays (clay quarry) (Nudilithic Leptosol) N°. of study plot–4. Soil horizons were not identified there.



Lithostrata formed on overburden dumps (Spolic Technosol) N°. of study plot–6. Soil horizons were not identified there.

* Koltushy uplands is a unique natural object. This territory was not flooded by any of the seas and lakes that dominated the Prinevskaya lowland, not excluding the First Ioldian Sea—the deepest and largest waterbody: with depth of the First Ioldian Sea at 40–45 m, the Koltushy uplands was an archipelago of islands.

Figure 3. Sampling sites and soil profiles. Number of studying plots is given according to Figure 2.

The soil cover is mainly represented by patches of soddy podzolic soils (Podzol), podburs (Entic Podzol), and agrozems (Anthrosols). Relative microrelief rises, located in spots among the main massif, are occupied by automorphous soddy podzolic soils on moraine loams. Soddy podburs podzolized were found on sands with the thickness of the upper sediments exceeding 60 cm. The weak expression of the podzol process in soils at these plots can be explained by their anthropogenic transformation. Intensive farming leads to the formation of a peculiar component in the soil cover—agrozems. They develop on various types of rock materials and are distinguished by a thick organic layer (over 40 cm) that is well-structured and rich in humus and essential plant nutrients. It is important to mention that despite the long history of development in this region, soils with excessive moisture still cover a substantial area. This indicates the difficulty of soil drainage on clay rock materials in terms of low surface water runoff.

Currently, large areas of the Prinevskaya lowland are drained by an open and closed drainage network (e.g., agrozem ameliorative deep-turbid redoximorphic sandy loam on fluvioglacial sediments at the agricultural field of the Prikoltushsky part of the Prinevskaya lowland; number of study plot–9). In this case, a significant part of the soil cover belongs to soils without or with weak signs of gleization (72%). The water-air soil regime changes due to drainage: the moisture content of the arable horizon decreases by 1.5–2 times, aeration increases, and a zone of active aeration drops below the drainage boundary [61–64]. Amelioration causes the rise of redox potential and, therefore, promotes the oxidation processes in the soil profile: the content of ferrous oxide and mobile manganese decreases, and the content of ferric iron increases [65–67]. The processes of oxidogenesis (landscape geochemical processes of accumulation and transformation of iron oxides and hydroxides in soils and rock materials) are morphologically shown in the pronounced accumulation of ferruginous-manganese nodules in the upper horizons and heterogeneous color of aggregates [68–70].

Forest soils are characterized by the presence of litter horizon (AO), insignificant thickness, and fluffy structure of humus horizon, which consists mainly of coarse humus and unclear rudiments of podzol horizon—it is dense, whitish, and contains many ferruginous nodules.

Lands of industrial areas are characterized by the widespread distribution of technogenic surface formations—lithostratas.

During field studies measurements of electrophysical soil properties were performed. The measurements were extended to a depth of up to 3 m (Figure 4).

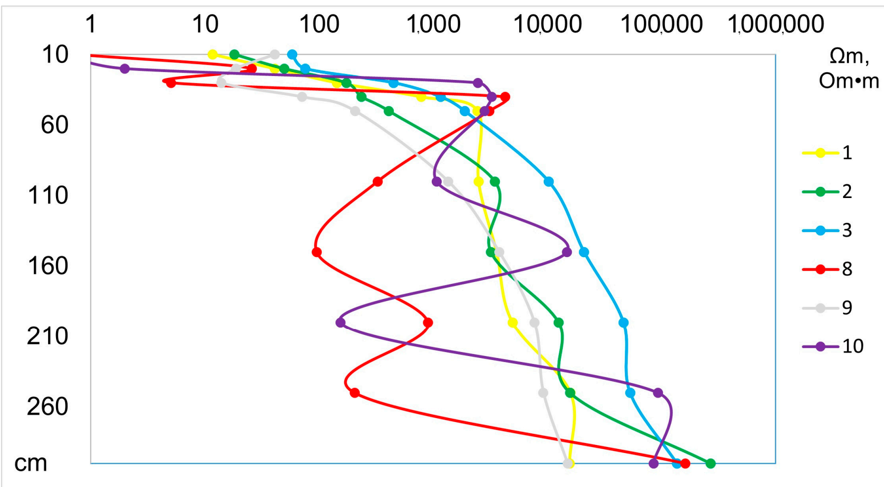


Figure 4. Electrical resistivity (ER, Ωm) of studied soils. Numbers indicate number of soil plots described in Figures 2 and 3.

The primary trend observed was an increase in the value of Ωm with depth, although there were some fluctuations noted at depths of 20–40 cm (Figure 4). This range was recognized as the transition zone between the arable horizon and the underlying layer. The first such fluctuations occur at a depth of 100 cm in non-agricultural soils. These disturbances are probably caused by changes in the structure and composition of the parent rock material. The method of VERS allowed the identification of five to seven heterogeneous layers in studied areas.

Studied soils were characterized by maximum values of temperature in the upper horizons, which smoothly decreased with depth.

3.2. The Physical and Chemical Soil Properties of Prinevskaya Lowland

The data on basic soil properties of studied soils are given in Table 2.

Table 2. Characteristics of studied soils.

LULC	Number of Study Plot *	Horizon, Depth, cm	Soil Moisture Content, %	pH_{H2O}	pH_{KCl}	C_{total}, %	Basal Respiration, μgC-CO_2/g Per hour	K_2O, mg/kg	Particle Size Distribution
Forest	1	AYe 0–10	1.60	6.3	3.9	1.74	1.62	36.9	Sandy loam
		AYe 10–15	1.00	5.6	3.9	1.13	2.55	39.1	Sandy loam
		BF 15–44	1.13	4.9	4.5	0.48	1.14	29.0	Sandy loam
		C 44–80	1.10	6.3	5.8	0.19	-	12.6	Medium-grained sand
Forest	2	AУ 0–18	6.62	5.4	3.5	1.90	2.37	67.1	Coarse sandy loam
		BF 18–40	4.62	5.2	3.7	1.20	1.12	25.2	Coarse sandy loam
		Cff 40–80	3.33	5.5	3.5	0.24	0.73	22.6	Coarse sandy loam
Agricultural and fallow	3	P1 0–25	10.98	5.4	-	2.55	1.28	111.8	Light loam
		P2 25–42	5.79	5.7	5.4	1.12	0.45	206.8	Medium coarse loam
		Cff 42–75	3.03	6.2	5.3	0.05	0.04	177.1	Sandy loam
Industrial	4	0–65	2.50	5.2	-	0.83	1.12	450.1	Medium silty clay
		65–75	0.75	5.8	4.3	0.30	1.18	28.5	Light loam
		75–80	0.22	5.8	4.4	0.07	0.42	26.3	Fine-grained sand
		80–85	0.76	5.4	4.4	0.23	0.87	50.1	Sandy loam
		85–110	1.51	5.3	4.4	1.19	1.24	117.8	Fine clay
		Rock material (cambrian clay)	2.78	5.8	-	0.36	-	571.4	Fine clay
Agricultural and fallow	5	PY1 0–25	4.78	6.2	5.6	2.49	1.37	110.2	Medium coarse loam
		PУ 25–40	4.79	5.9	5.1	2.18	0.69	119.4	Medium coarse loam
		BEL 40–65	4.05	6.1	5.3	0.67	1.54	15.4	Fine loam
		C 65–80	11.15	5.8	4.7	0.12	0.04	46.8	Medium coarse loam
		C 80–110	3.26	6.2	5.5	0.18	0.54	33.1	Light clay
Industrial	6	0–5	3.46	6.0	-	0.44	1.36	426.0	Medium coarse loam
		5–25	1.01	6.2	-	0.30	0.94	79.9	Sandy loam
		25–45	1.04	6.1	-	0.38	1.15	108.6	Sandy loam
Agricultural and fallow	7	AEL 0–20	13.54	6.0	4.9	4.94	1.46	70.4	Medium coarse loam
		EL 20–35	1.79	5.5	3.8	0.57	0.87	79.3	Light clay
		BEL 35–75	2.87	5.1	3.9	0.19	0.41	66.2	Medium silty clay
Agricultural and fallow	8	AYe,pa 0–25	21.68	4.9	3.1	10.61	2.27	112.0	Medium coarse loam
		C 25–60	1.12	6.4	4.2	0.12	0.86	9.1	Medium-grained sand
		D 60–100	10.49	5.8	4.3	0.15	-	12.5	Medium-grained sand
Agricultural and fallow	9	P 0–27	6.76	5.5	4.6	8.07	2.89	58.4	Light loam
		C 27–50	2.88	6.2	4.9	0.13	0.12	8.9	Sandy loam
		D 50–110	0.80	5.8	4.7	0.18	0.04	20.6	Sandy loam
Agricultural and fallow	10	AYpa 0–25	3.62	6.2	4.1	1.49	2.21	94.6	Medium-grained sand
		BF 25–35	0.98	5.9	4.8	0.22	0.08	21.9	Sandy loam
		BC 35–53	1.80	5.8	4.3	0.31	0.67	27.4	Light loam
		C 53–90	1.25	6.1	4.6	0.24	0.46	24.8	Fine loam
Post hoc test Forest–Agricultural–Industrial			0.20	$p << 0.05$	0.14	$p << 0.05$	$p << 0.05$	$p << 0.05$	
Significance of differences			Insign.	Sign.	Insign.	Sign.	Sign.	Sign.	

* Numbers indicate No. of soil plots described in Figures 2 and 3.

Soils of forest areas are characterized by acid pH throughout the soil profile, except for the upper humus horizon, which is close to neutral. The most acidic is the lower part of the soil profile. Postagrogenic and agricultural soils are characterized by higher pH values and have a slightly acidic pH in the lower part of the soil profile, while in the upper part, due to liming, it is close to neutral (pH_{H2O} 6.2).

Humus content in forest soils ranged from 1.9– to 10.61%. The high content of organic carbon in the accumulative part of the soil profile is explained by the time gap of litter decomposition from the intake of plant litter, leading to a significant accumulation of humified substances. At the same time, the qualitative composition of humus in these soils is characterized by a wide C/N ratio, a predominance of fulvic acids, and their mobile fractions [71–73]. The soil profile is divided into two or three parts by humus content. The upper part, the humus accumulative horizon, is characterized by the highest organic carbon content. The underlying horizon contains much less humus than the humus accumulative horizon. The organic matter content in it may either gradually decrease towards the rock material or have more or less close values in the whole profile. In the case of illuvial–humus process development, one more zone of soil profile (illuvial–humus horizon) is distinguished in sandy or sandy loam soils. There, the content of organic carbon is higher than in the neighboring mineral horizons. The humus profile of podburs (Entic Podzol) is characterized by a sharply decreasing distribution of humus. A separation of soil profile into humus-accumulative and mineral parts is very sharply expressed.

Soils of agricultural and fallow areas are characterized by the following features. The humus content in the upper soil profile is lower (4.4% on average), but the total humus stock is higher due to the higher density of the upper horizon and penetration of more significant humus amounts into the depth of the soil profile, i.e., its smoother distribution. Humus is more firmly connected with the mineral part, which is reflected in the crumby structure of the arable horizon (in the formation of which it participates along with calcium) and therefore in the higher content of the corresponding fraction of humic and fulvic acids. The vertical distribution of humus in agrozems is the smoothest. Humus content of 3–5% is maintained in the whole arable stratum, up to a depth of 40 cm.

The potassium distribution in the soil profile is influenced by the mineralogical composition, mainly of the silty fraction. Potassium is represented in clay soils mainly by forms that are difficult to access for plants and microorganisms. Mobile potassium compounds are less than 1% [74,75]. As a result of potassium fertilizer application, potassium accumulation in hard-to-access forms occurs in agrozems. Potassium fixation is also observed below the arable horizon, which is connected with potassium transport by soil colloids and the distribution of mica minerals. Forest soils are characterized by low potassium content (except for one soil at study plot number 8, which was located in a forest, and this forest, according to morphological description, was previously an agricultural field). The distribution of mobile potassium along the soil profile has the following peculiarities. The highest content is observed in the humus-accumulative horizon; the lowest is in the middle horizons. The content of mobile potassium in the rock material in forest soil is 1.1–1.5, and in agricultural soil, it is 3–4 times lower than in the upper soil horizon. It is explained by biogenic accumulation in forest soils, while in arable soils, among other things, it is the result of fertilizer application.

The rate of carbon dioxide release from soils and basal respiration is primarily influenced by two factors: the availability of nutrients and the quantity and physiological condition of the microbial community. The maximum values of basal respiration are characterized for upper humus horizons, where the greatest number of microorganisms and plant roots inhabit, for both forest soils (1.6–2.5 $\mu gC\text{-}CO_2/g$ per hour) and agricultural soils (0.45–2.89 $\mu gC\text{-}CO_2/g$ per hour).

Soils of industrial functional zones showed heterogeneity and the absence of any trend in the distribution of the main physical and chemical properties along the soil profile.

Particle size distribution is determined by rock material features. Studied soils represent all classes of particle size distribution, from sands to clay (Table 2). It could be noted a silt removal from the upper part of the soil profile in loamy soils and, on the contrary, an accumulation of fine particles in the arable layer in sandy soils. Silt is more distributed eluvial–illuvial with a maximum in the middle part of the middle horizon. An absolute predominance of fine sand fraction is observed in sandy soils throughout the soil profile. The arable layer in the agrozems is sandy loam or light loamy.

3.3. The Content of Trace Elements in Soils of Prinevskaya Lowland

Soils of St. Petersburg suburbs widespread at the Prinevskaya lowland have a significant anthropogenic impact. Trace metals are an essential part of the lithosphere [76]. As a result of anthropogenic and technogenic activities of industry and agriculture, the geochemical background of heavy metal content in soils can be changed. Due to the constant input of pollutants into the ecosystem, there is a destabilization of soil functioning, disturbance and change in its basic physical and chemical processes, and, as a consequence, further transformation with the formation of areas with high contents of heavy metals.

The heavy metals content in studied soils is given in Table 3, Figure 5. The average concentrations of trace elements varied, with Cu measuring less than 0.10 mg/kg and MnO reaching up to 591.76 mg/kg. Among all the metals analyzed, Cu exhibited the lowest concentration, often falling below the detection limit in most instances. The mean concentrations of heavy metals were distributed as follows: Sr > Cr > V > Zn > Pb > Ni > Co > As > Cu. Considering significant coefficients of variation in trace element concentrations, which ranged from 23.1% for As to 65.9–66.2% for Ni and Mn, further analysis of trace element concentrations was carried out in the soils of three different sampling sites. The industrial soils are characterized by the maximum heterogeneity, which is confirmed by the high coefficients of variation: from 17.08% for Sr to 67.34% for Co. The forest soils, on the contrary, are characterized by the lowest coefficients of variation.

Table 3. Trace elements content in soils of Prinevskaya lowland, mg/kg.

Trace Element	Mean	Max	Min	CV	SD
Sr	180.0	242.0	16.0	24.8	44.6
Pb	22.5	57.0	1.0	41.8	9.4
As	7.5	13.0	5.0	23.1	1.7
Zn	47.3	132.0	6.0	59.4	28.1
Cu	<0.10	<0.10	<0.10	0.0	0.0
Ni	21.1	72.0	4.0	65.4	13.8
Co	10.0	31.0	0.0	59.9	6.0
Fe_2O_3, %	3.0	6.9	0.9	48.8	1.4
MnO	591.8	1839.0	115.0	66.2	392.0
Cr	65.3	176.0	32.0	46.8	30.6
V	61.1	133.0	6.0	52.9	32.3
TiO_2, %	0.6	1.0	0.2	38.4	0.2

The highest indicators for Sr, As, Co, and Cr are observed among the studied soils. Manganese content is not included in Figure 5 due to high concentrations that did not fit on the graph with maximum coefficients of variation in the range. The MnO levels in forest soils range from 363 to 1839 mg/kg, with one sample exceeding the MPC. In industrial soils, the content varies from 151 to 1319 mg/kg, while agricultural soils show levels between 115 and 1236 mg/kg.

The distribution of heavy metal content is irregular across soil profiles. In industrial soils, there is generally a trend of decreasing content with depth or a fluctuation between high and low concentrations. Conversely, in forest soils, the concentration of trace metals tends to increase with soil depth, likely due to the sorption capacity of clay particles [77] (the increase in clay particles with depth was noted earlier).

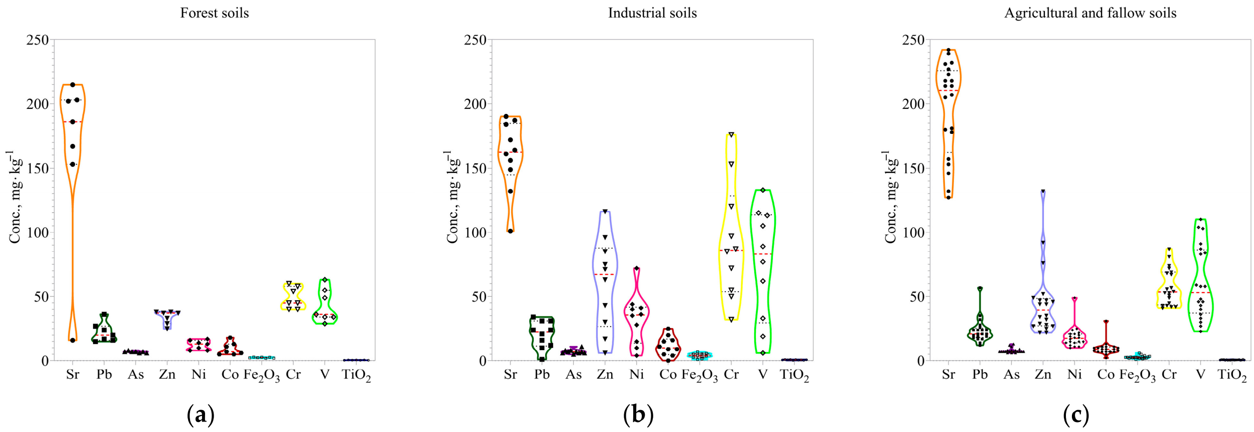


Figure 5. Variation of trace metals concentrations in studied soils s: (**a**)—forest soils; (**b**)—industrial soils; (**c**)—agricultural and fallow soils.

The primary factor influencing the concentration of trace elements in soils is their presence in the soil-forming rock materials. The literature indicates that banded clays have the highest concentration of trace elements among all soil-forming materials, with a total of 937 mg/kg for ten elements. In contrast, fluvioglacial and lake–glacial sands exhibit the lowest concentrations, measuring 626.7 mg/kg and 691.7 mg/kg, respectively. Sands have an increased concentration of strontium in contrast to the low content of other elements. The banded clays have higher concentrations of Cr, Pb, Mn, Zn, Ni, and Co compared to the other rock materials examined.

When comparing the rock materials from the study area to those of the northwest region overall [78], it is evident that clay rocks in this area contain more Ni, while sands have higher levels of Cr. Conversely, the rock materials in the Prinevskaya lowland exhibit lower concentrations of Mn, Zn, and Cu than those found across the northwest region as a whole.

The heavy metals content data were compared with the current standards for the content of trace elements in soil [46], as well as with geochemical background concentrations typical for the northwest of Russia, in particular, the Leningrad region (Figures 6 and 7).

The ecological soil state was assessed by calculating the concentration coefficients of trace elements, or PI (Figure 6). This indicator reflects the accumulation degree of heavy metals relative to their background content in the environment. Excess concentrations over the background content were recorded almost for studied elements, especially for Ni, Co, and Cr. The maximum accumulation was revealed for Ni; its content in all samples exceeds the background content on average from 2 to 7 times.

In general, the contents of trace elements in the analyzed samples were characterized as moderately dangerous (Figure 7) (up to 2 MPC) (for Sr, and separately for Pb, Zn, and Ni) and dangerous (from 2 to 5 MPC) (for As and Co (in case of industrial soils)) levels of soil contamination. An extremely dangerous level of soil contamination with Cr (over 5 MPC) was detected in all investigated soils with an excess of more than 1000 times.

The most polluted soils are found at the base of the quarry complex. This is primarily because the bottom of the quarry serves as a collection point for pollutants carried by rainwater. Elevated levels of these substances may also be linked to the operation of mining equipment, as transport activities were observed in the quarry complex during the material sampling.

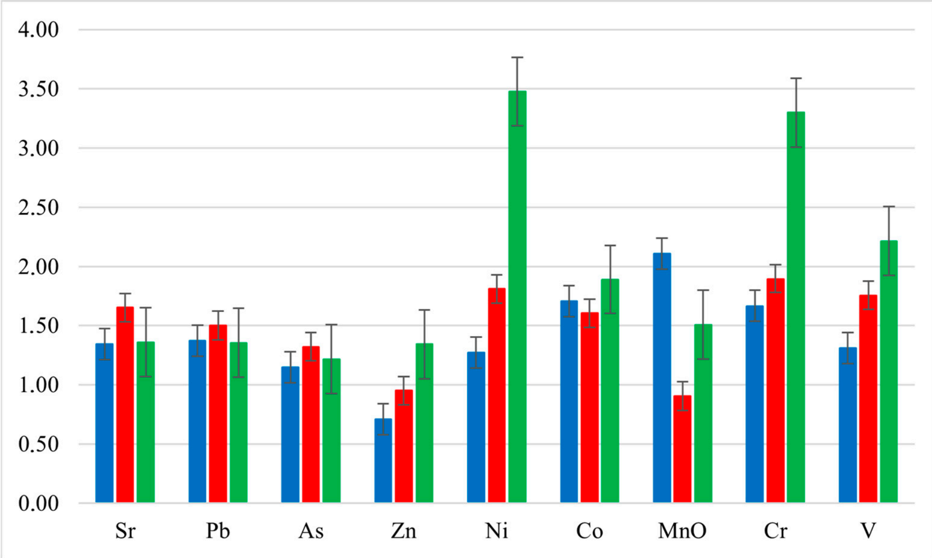


Figure 6. Single pollution index (PI) in studied soils according to LULC: blue color—forest soils; red color—agricultural and fallow soils; green color—industrial soils.

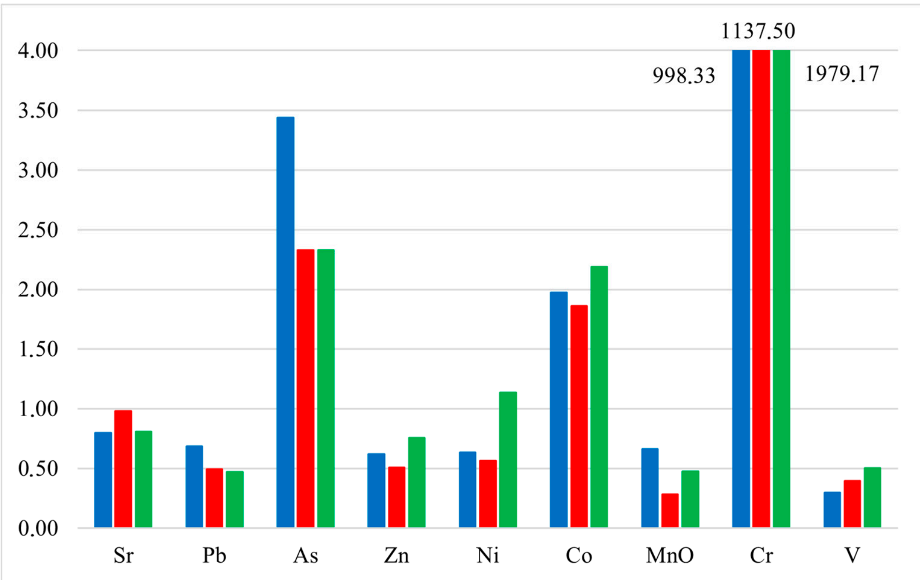


Figure 7. Heavy metal content relative to MPC in studied soils according to LULC: blue color—forest soils; red color—agricultural and fallow soils; green color—industrial soils.

The content of trace elements in arable soil horizon depends on a complex of factors: their content in the rock material, processes occurring in the soil, as well as on anthropogenic impacts. The accumulation of a trace element in the humus horizon relative to its content in the rock material can be explained by both biogenic accumulation and anthropogenic pollution from the surface. At the same time, there are data that biogenic accumulation cannot increase the trace element content more than 1.3–1.5 times in comparison with the rock material [79,80].

Sources of soil contamination by trace metals are as follows. Firstly, heavy metals can penetrate into soils from the atmosphere with emissions from industrial enterprises, transport, and thermal power plants. Secondly, it can be a by-effect of farming intensification. Heavy metals could be in the form of admixtures to chemical fertilizers, ameliorants, and as part of pesticides. Finally, heavy metals can enter the studied soils from solid and liquid urban wastes and through transfer from landfills [accidental or systematic (rubbish as fertilizer)].

Moreover, soil contamination with heavy metals (Pb, Co, Cd, Sr, and Hg) during fertilizer application has been noted by many researchers [81–83]. High doses of manure also contribute to the positive balance of Zn, Pb, Cd, Cu, and Fe [84].

To qualitatively assess the level of contamination of the studied soils with trace metals, the values of several individual and complex indexes were calculated. Its values are presented in Table 4.

Table 4. Qualitative assessment of contamination in studied soils. No. of study plots indicate number of soil plots described in Figures 2 and 3 and correspond to Table 2.

LULC	No. of Study Plot	Z_c		I_{geo}		*PLI*		*RI*	
		Value	**Pollution Status**	**Value**	**Pollution Status**	**Value**	**Pollution Status**	**Value**	**Potential Ecological Risk**
Forest	1	4.49	Permissible	0	Absence	0.99	Absence	36.44	Low
Forest	2	8.41	Permissible	0–1	Unpolluted to moderately polluted	1.63	Low	45.64	Low
Agricultural and fallow	3	8.47	Permissible	0–1	Unpolluted to moderately polluted	1.78	Low	56.80	Low
Industrial	4	16.33	Moderately dangerous	1–2	Moderately polluted	2.00	Moderate	75.59	Low
Agricultural and fallow	5	12.40	Permissible	0–1	Unpolluted to moderately polluted	1.56	Low	63.21	Low
Industrial	6	20.74	Moderately dangerous	1–2	Moderately polluted	2.85	Moderate	90.51	Moderate
Agricultural and fallow	7	7.47	Permissible	0–1	Unpolluted to moderately polluted	1.56	Low	46.53	Low
Agricultural and fallow	8	3.77	Permissible	0	Absence	0.84	Absence	51.09	Low
Agricultural and fallow	9	4.93	Permissible	0	Absence	1.40	Low	39.11	Low
Agricultural and fallow	10	5.09	Permissible	0	Absence	1.43	Low	42.66	Low

In order to assess the sanitary and ecological situation, the total soil pollution index Z_c was calculated. Its values are presented in Table 4. All investigated samples, except for soil samples from industrial areas (moderately hazardous), are characterized by the permissible category of total soil pollution by trace elements.

The contamination degree was also determined using a geoaccumulation index I_{geo}. The I_{geo} pollution degree for soils in industrial areas is characterized by rate No. 2 (moderately polluted); for some agricultural soils-rate No. 1 (from unpolluted to moderately polluted). At the same time, the I_{geo} pollution degree for forests and some agricultural soils was characterized by the rate No. 0 (absence of pollution).

Pollution load index PLI index was used to assess the degree of multiple contamination by toxic elements in studied soils (Table 4). PLI values in soils of three studied LULC ranged from 0.84 (absence of pollution) to 2.85 (moderate pollution).

The RI index provides an estimate of the potential ecological risk of pollution in the studied soils. The RI values ranged from 36.44 to 75.59, indicating a low potential ecological risk overall, except for one soil sample in the industrial zone, which had an RI index of 90.51, reflecting a moderate potential ecological risk.

Calculations of the PLI index reveal that nearly half of the investigated soils are experiencing a decline in soil quality. Despite this deterioration, the RI index remains low for all examined soils, with the exception of the one sample from the industrial area, which is classified as having a moderate environmental risk.

It can be anticipated that over the next decade, there will be a significant increase in anthropogenic pressures on the soils of the Prinevskaya lowland, largely due to the extensive urban area occupied by St. Petersburg. The forest and agricultural zones are the most susceptible LULC types, as they can actively accumulate priority toxicants of human origin. Currently, agricultural lands in St. Petersburg are utilized for crop cultivation and residential purposes, which may have potential implications for the health of the local population. These soils are likely to gather priority toxicants, polycyclic aromatic hydrocarbons, and petroleum products, which can persist in the environment for extended periods due to their low biological activity [85].

4. Conclusions

The Prinevskaya lowland features a complex and varied composition of soil cover components that have developed under various lithological, hydrological, and anthropogenic conditions. The prevailing soil combinations are variations of soddy podzols of different degrees of podzolization and a series of soddy podbur and agrozems. Automorphic soils have limited distribution, and their development is connected with human activity. The variety of soil-forming rock materials in several lowland regions with flat terrain results in complex combinations and mosaics of soddy podzols, exhibiting varying degrees of podzolization and the manifestation of alfehumus processes.

The primary factors driving the diversity of soil cover across different lowland areas differ. In regions dominated by clay, the variation in soil cover is influenced by the redistribution of water in microrelief features, while in areas with fluvio-glacial sandy deposits, it is determined by the level of soil moisture. Additionally, the lithological factor significantly impacts soil structure in regions characterized by a mosaic of soil-forming rock materials.

In comparison to other similar territories in the North-West, the geochemical characteristics of the Prinevskaya lowland are marked by a deficiency of Mn, Cu, and Zn in soil-forming rock materials, alongside an accumulation of Sr and Pb in arable horizons.

The geochemical soil characteristics of agricultural areas are primarily influenced by the underlying rock material from which they originate rather than by the extent of cultivation.

The analyzed soils show minimal contamination with trace elements, as confirmed by various individual and complex soil ecotoxicological indicators. Overall, the potential ecological risk across all areas is considered low, suggesting that the soils are in a good toxicological soil state and are currently suitable for agricultural use. An assessment of pollution status indexes (PI, PLI, RI) indicated that the quarry complex poses the highest level of threat. As anthropogenic impacts on the urban environment grow, industrial and agricultural zones are likely to become the most vulnerable areas of the city, primarily due to the low resilience of these soils to external influences.

According to our view, urban development planning in St. Petersburg should prioritize the principles of maximizing biodiversity conservation and protecting soil resources.

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