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Ecotoxicological Analysis of Fallow Soils at the Yamal Experimental Agricultural Station

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Abstract.
The agricultural use of soils is limited by their contamination with various compounds and low contents of nutrients. We aimed to study the unique soils of the Yamal Experimental Station to determine their contamination with heavy metals and assess their potential fertility.
Established in 1932, the Yamal Experimental Station (Salekhard, Russia) has bred new varieties of vegetable crops in open and protected ground. In August 2021, we made a soil section and 40 pits in a 0–10 cm layer. X-ray fluorescence was used to determine 11 metals and oxides. The qualitative assessment was based on the total soil pollution, soil pollution, and geoaccumulation indexes. Finally, we determined the contents of nutrients.
The metals and metal oxides showed regressive-accumulative distribution along the soil profile. The concentrations of all ecotoxicants (except for arsenic) were within the maximum/approximate permissible values. Since arsenic has a high regional background content, its elevated concentrations make the soil suitable for agricultural use if proper quality control is in place. The total soil pollution index classified the level of pollution as “acceptable”. The geoaccumulation index showed the soils as mostly “unpolluted” with metals. The soil pollution index had values below 1, which indicated the absence of pollution.
The fallow soils of the Yamal Experimental Station have a high level of potential fertility and are suitable for agricultural reuse according to the soil quality indexes applied. They can also serve as a local geochemical standard that has a long history of agrogenic transformation in cryogenic ecosystems. Taking into account increased concentrations of arsenic, we recommend primary quality control of agricultural products to identify its possible migration in the soil-plant system.

Keywords. Ecotoxicological state, soil quality, agrozems, heavy metals, Arctic, polar agriculture

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Почвы залежного поля Ямальской опытной станции: эколого-аналитическая оценка

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Аннотация.
Одним из основных факторов, лимитирующих сельскохозяйственное использование почв, является их загрязненность различными соединениями и низкое содержание элементов питания. Цель работы – исследование уникальных почв Ямальской опытной станции на предмет их загрязненности тяжелыми металлами и оценка их потенциального плодородия. Объектом исследования являлась Ямальская опытная станция (Салехард), на которой с 1932 г. велись опытные работы по выведению различных сортов овощных культур в открытом и закрытом грунте. В августе 2021 г. заложен почвенный разрез и 40 прикопок в 0–10 см слое. Рентген-флуоресцентным методом были определены концентрации 11 металлов и оксидов. Качественная оценка почв осуществлялась с помощью индексов суммарного загрязнения почв (Z_c), загрязнения почв и геоаккумуляции (I_{geo}). Определяли содержание элементов питания.
Распределение металлов и оксидов металлов по почвенному профилю соответствует регрессионно-аккумулятивному типу. Концентрации изученных экотоксикантов (за исключением мышьяка) не превышали ориентировочно допустимые и предельно допустимые. Были зафиксированы повышенные концентрации мышьяка, но, учитывая высокий региональный фон этого элемента, отнесение почвы к классу непригодных не является обоснованным при организации контроля за качеством почв и сельскохозяйственной продукции. Качественная оценка полиэлементного загрязнения почвы, основанная на фоновых региональных концентрациях загрязняющих веществ, показала, что по индексу Z_c уровень загрязнения соответствует допустимому. Применение индекса I_{geo} показало, что почвы «практически не загрязнены» металлами. Значения индекса загрязнения почв менее 1, что свидетельствует об отсутствии загрязнения.
Почвы залежного поля Ямальской опытной агростанции обладают высоким уровнем потенциального плодородия и пригодны для повторного вовлечения в сельскохозяйственный оборот по комплексным показателям качества почв. Они могут служить локальным геохимическим эталоном с долголетней историей наблюдений агрогенной трансформацией почв криогенных экосистем. Принимая во внимание повышенные концентрации мышьяка, рекомендуется проведение первичного контроля качества сельскохозяйственной продукции на предмет его возможной миграции в системе почва – растение.

Ключевые слова. Экотоксикологическое состояние, качество почв, агроземы, тяжелые металлы, Арктика, полярное земледелие

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Introduction

Polymetallic contamination of soil and topsoil is one of the main factors that limit agricultural activity on open ground. Monitoring concentrations of heavy and trace metals is particularly vital if agricultural land is located within urban ecosystems. Anthropogenic load on urban soils has been well studied globally, with researchers repeatedly recording high concentrations of heavy metals [1, 2]. The harmful effects of industrial emissions and products of fossil fuel combustion, as well as illegal waste disposal, degrade topsoil and make it dangerous for human life and health [3–8].

Established in 1932, the Yamal Experimental Station is uniquely located in the city of Salekhard (Yamalo-Nenets Autonomous Okrug, Russia) on the Arctic Circle (Fig. 1). Its fields were first cultivated in 1933 and planted in 1934. Back then, they were fertilized with manure. Later, the station's agriculturists began to test various farming methods and fertilizers (superphosphate, bone meal, potassium salt, and ash) on separate micro-sites. They harrowed and plowed the land to various depths and cultivated various crops, including radish, turnip, potatoes, cabbage, cauliflower, kohlrabi, rutabaga, beetroot, and vetch-oat mixture. Up until early 1990s, the station had done active research, practicing regular crop rotations, using mineral and organic fertilizers, etc. However, the economic and political crisis in the country put an end to all experimental work. No crops were planted for 10 years except for potatoes, and in 2019, the field was completely abandoned [9–12].

The monitoring of agricultural lands located near and within large cities is especially important in terms of their environmental protection and food security. The quality of crop production directly depends on the ecotoxicological state of the soil since toxic substances accumulating in the roots of plants pose a threat to public health [13–16]. Therefore, we aimed to conduct an ecological analysis of the quality of soils at the Yamal Experimental Station in terms of their applicability for agriculture. To achieve this aim, we set the following objectives:

1) determine the concentrations of heavy metals and oxides in the soil;

2) measure pollution levels against the sanitary and hygienic standards of the Russian Federation;

3) examine the ecotoxicological state of soils using complex indices; and

4) assess potential soil fertility based on the content of main nutrients.

Figure 1. Aerial photograph of the Yamal Experimental Station's field

Study objects and methods

For this study, we used a field of the Yamal Experimental Station (Fig. 2) established in the city of Salekhard (Yamal-Nenets Autonomous Okrug, Russia). The station is currently managed by the Tyumen Scientific Center (Siberian Branch of the Russian Academy of Sciences). Salekhard is located on the Arctic Circle (66°31′48″ N 66°36′06″ E) on the border between the subarctic and the temperate climatic zones. Its annual precipitation varies from 220 to 400 mm, mostly falling in spring and summer. The region has low evapotranspiration and constant excess of moisture. Its average temperatures are –23.2°C in January and +14.8°C in July, with +7°C as the annual average. In the warmest months, the temperature of the soil is +13°C at a depth of 10 cm [11, 17].

The soil cover is represented by Plaggic Podzol (Turbic). Long-term agricultural use has formed a unique soil profile (Fig. 3), which is not typical for the background soils of the pristine zones in vicinities of Salekhard city. The upper horizon (Ap) up to 30 cm thick is a brown, clay loamy, agro-light-humus soil permeated with roots. This humus-accumulative horizon gives way to a 45 cm thick illuvial-ferruginous, sandy loamy, gleyic with placic layer horizon (Bs), which gradually turns into sandy, structureless, placic horizons (BCg and Cg@) with redoximorphic features and spots.

The sampling took place in August, 2021, for which we made a soil section and 40 pits in a layer of 0–10 cm. The soil samples were placed in sealed plastic bags and labeled. Laboratory and analytical work was carried out at the Department of Applied Ecology (St. Petersburg State University) and at ITMO University (St. Petersburg). After delivery to St. Petersburg, the soil samples were air-dried in a separate room. Then, they were ground in a porcelain mortar, sieved through a 1 mm mesh sieve, and weighed for further analysis by quartering.

The contents of heavy metals were quantitatively determined by X-ray fluorescence (FR.1.31.2018.32143) using a Spectroscan Max-G spectrometer. The samples were ground in a disk grinder to a particle size of ≤ 71 μm and air-dried (clauses 5.1–5.5, State Standard ISO 11464-2015). Then, they were pressed into a cup of boric acid. For this, we poured boric acid into a

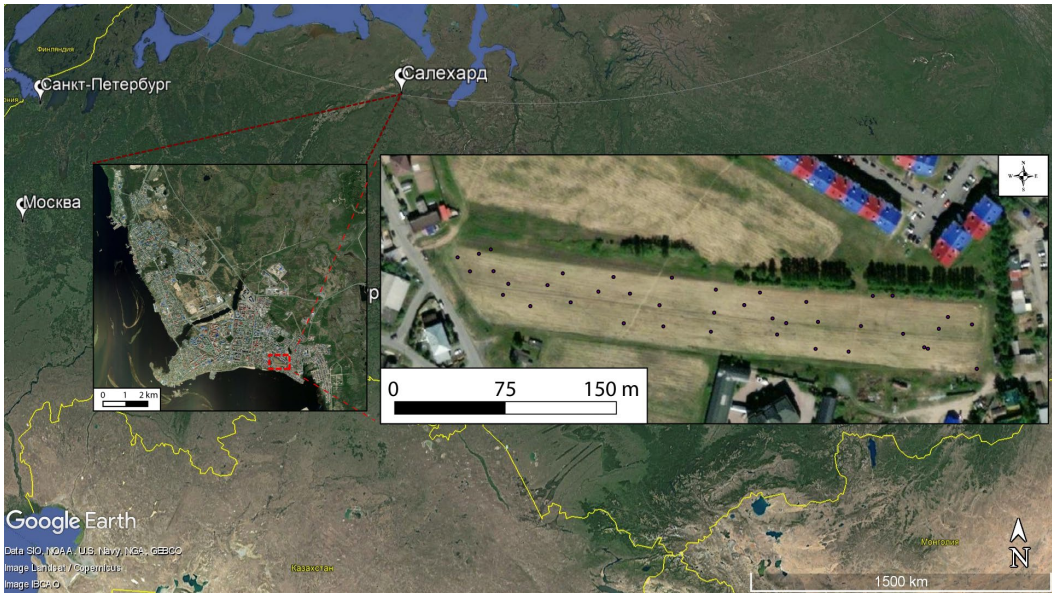

Figure 2. Location of Salekhard and soil sampling sites

mold and formed a cup (at least 3 mm deep) with a figured punch. The sample was then poured into the cup and pressed with a smooth punch and a press. The tablet was placed into the sample holder and then into the spectrometer. The samples were automatically analyzed to determine total contents of 11 elements (oxides): strontium, lead, arsenic, zinc, nickel, cobalt, vanadium, chromium, iron oxide (III), manganese oxide, and titanium dioxide.

Nutrients were determined by standard methods, namely:

– mobile phosphorus and exchangeable potassium: by the Kirsanov method;

Figure 3. Profile of Plaggic Podzol (Turbic)

– ammonium nitrogen: by the Arinushkina colorimetric method; and

– nitrate nitrogen: by the ionometric method [18].

Several complex indices were used to qualitatively assess the ecotoxicological state of the Yamal Experimental Station's soils, namely the total soil pollution index, the soil pollution index, and the geoaccumulation index.

The total soil pollution index (Z_c) was calculated by using formulas 1 and 2 [19].

$$K_c = \frac{C_i}{C_{bi}} \quad (1)$$

where C_i is the actual content of a substance in soil, mg/kg; C_{bi} is the regional background, mg/kg

$$Z_c = \sum (K_{ci} + \ldots + K_{cn}) - (n-1) \quad (2)$$

where n is the total number of substances; K_{ci} is the concentration coefficient of the i-th pollution component.

The soil pollution index (SPI) was based on maximum permissible concentrations (MPC) and calculated by using formula 3. In essence, this index represents the integral level of threshold limit values. The higher it is, the worse the soil's ecotoxicological state. Its values of > 1.0 indicate soil contamination.

$$\mathrm{SPI} = \sum_m^i \left(C_i / C_{\mathrm{MPC}} \right) / n \quad (3)$$

where C_i/C_{MPC} is the ratio of a substance content to MPC at the sampling point; n is the number of substances to be determined.

The geoaccumulation index I_{geo}, which was originally proposed by Müller for bottom sediments and later used to assess the ecotoxicological state of soils, was calculated by formula 4 [20–24]

$$I_{geo} = log_2 \frac{C_n}{1.5B_n} \quad (4)$$

where C_n is the content of an element in soil; B_n is the geochemical background; 1.5 is the compensation factor.

As can be seen from the above formulas, the complex indices were calculated without using generally accepted maximum or approximate permissible concentrations of pollutants. Instead, they were based on the background values of element concentrations, which we calculated by analyzing and averaging those values published in literature. Particularly, we determined element concentrations for the outskirts of Salekhard; Arctic and Southern Yamal, as well as Belyi Island; the Nadym-Pur and Pur-Taz interfluves; the north of Western Siberia, and the Upper Taz Nature Reserve [25–35]. Table 1 shows averaged background concentrations and effective maximum/approximate permissible concentrations (Sanitary Standard 1.2.3685-21).

The current approximate permissible concentrations (APCs) follow Hygienic Standard 2.1.7.2042-06, which was later replaced by Sanitary Standard 1.2.3685-21 with the same APC values. Noteworthily, they were calculated for three main soil groups in Russia: 1) sandy and sandy loams; 2) acidic (loamy and clayey) soils with pH KCl < 5.5; and 3) close to neutral and neutral (loamy and clayey) soils with pH KCl > 5.5. We compared the obtained metal concentrations with the APCs for acidic soils (pH KCl < 5.5) since their textural classes, as well as acidity and alkalinity values, were published earlier [25].

Table 2 shows the scales for the ecotoxicological evaluation of soils, including four pollution categories for the Z_c index, from acceptable to extremely hazardous (Guidelines 2.1.7.730-99), and seven pollution levels for the I_{geo} index, from unpolluted to extremely polluted [21].

Statistical analysis was carried out in the R program.

Results and discussion

The vertical distribution of metal and oxide concentrations in the soil profile is mainly of the regressive-accumulative type and less often of the progressive-eluvial-illuvial type (Table 3). This anthropogenic-differentiated distribution profile, characteristic of most agricultural soil and urban soils, resulted from the long-term (90 years) agricultural use of this land. The upper layer (0–10 cm) of the agrohumus horizon (Ap) contained maximum concentrations of all metals and oxides except for chromium. The transitional illuvial-ferruginous horizon (Bs) showed a sharp decrease in element concentrations, especially iron oxide and cobalt.

Table 1. Current maximum/approximate permissible concentrations and background concentrations of metals and oxides for Yamal-Nenets Autonomous Okrug

Metals and oxides										
Sr	Pb	As	Zn	Ni	Co	MnO	Cr	V	Fe_2O_3	TiO_2
Maximum/approximate permissible concentrations										
600*	65	5	110	40	50*	1500	100*	150	600*	65
Measured background concentrations										
114.3	13.1	6.4	40.2	12.3	5.2	149.5	65.4	33.2	7.1	0.5

* – maximum and approximate concentrations for strontium, cobalt, and chromium were taken from [3, 36] since they were not determined in the standards.

Table 2. Evaluation scales for Z_c and I_{geo} indexes

Z_c		I_{geo}		
Value	Pollution category	Pollution class	Value	Pollution level
Less 16	Acceptable	0	$I_{geo} < 0$	Unpolluted
16–32	Moderately hazardous	1	$0 < I_{geo} < 1$	Unpolluted to moderately polluted
32–128	Hazardous	2	$1 < I_{geo} < 2$	Moderately polluted
Over 128	Extremely hazardous	3	$2 < I_{geo} < 3$	Moderately to strongly polluted
		4	$3 < I_{geo} < 4$	Strongly polluted
		5	$4 < I_{geo} < 5$	Strongly to extremely polluted
		6	$5 < I_{geo}$	Extremely polluted

Table 3. Concentrations of elements, including heavy metals, in the soil profile

Horizon, cm	Sr	Pb	As	Zn	Ni	Co	MnO	Cr	V	Fe_2O_3	TiO_2
	mg/kg									%	
Ap1, 0–10	198	23	16	47	23	5	424	81	113	3.54	0.9
Ap2, 10–20	188	13	16	40	19	4	358	98	104	3.00	0.8
Ap3, 20–30	203	9	13	39	21	5	372	83	97	3.17	0.8
Bs, 30–75	188	9	16	24	16	2	371	63	86	2.28	0.8
BCg, 75–160	166	11	9	15	14	1	295	121	53	1.09	0.5
Cg@, 160–200	159	3	8	15	10	2	178	51	24	0.71	0.3
MPC/APC	600*	65	5	110	40	50*	1500	100*	150	–	–
Background values	114.3	13.1	6.4	40.2	12.3	5.2	149.5	65.4	33.2	7.1	0.5

* – maximum and approximate permissible concentrations (MPC/APC) for strontium, cobalt, and chromium were taken from [3, 36] since they were not determined in the standards.

Table 4. Geoaccumulation index (I_{geo})

Soil horizon, cm	Sr	Pb	As	Zn	Ni	Co	MnO	Cr	V
Ap1, 0–10	0.2	0.2	0.7	–0.4	0.3	–0.7	0.9	–0.3	1.2
Ap2, 10–20	0.1	–0.6	0.7	–0.6	0.0	–1.0	0.7	0.0	1.1
Ap3, 20–30	0.2	–1.1	0.4	–0.6	0.2	–0.7	0.7	–0.2	1.0
Bs, 30–75	0.1	–1.1	0.7	–1.3	–0.2	–2.0	0.7	–0.6	0.8
BCg, 75–160	0.0	–0.8	–0.1	–2.0	–0.4	–3.0	0.4	0.3	0.1
Cg@, 160–200	–0.1	–2.7	–0.3	–2.0	–0.9	–2.0	–0.3	–0.9	–1.1

Arsenic concentrations were above the approximate permissible value of 5 mg/kg throughout the soil profile. They varied from 13 to 16 mg/kg in the agrohumus horizon, decreasing to 8 mg/kg near parent material. The other trace metals showed concentrations below the current MPC/APC values.

Higher arsenic concentrations are quite typical for the Yamal soils, as evidenced by the increased regional background values. Earlier, Tomashunas *et al.* and Alekseyev *et al.* found increased arsenic contents in Yamal, both in its natural and anthropogenically disturbed ecosystems [28, 29]. However, the authors associated these values with the regional features of soil-forming rocks. Consequently, classifying these soils as unsuitable for agricultural use would not be entirely justified. Yet, arsenic belongs to the first hazard class so we cannot ignore its excessive concentrations. Therefore, we strongly recommend further monitoring to identify possible arsenic migration in the soil-plant system. Also, primary agricultural products should be subject to proper quality control to ensure their safety in terms of arsenic content.

Our comprehensive assessment based on the Z_c index (Fig. 4) showed that vertically the soil quality could be classified as "acceptable" ($Z_c < 16$). The polymetallic pollution was of the regressive-accumulative type, with maximum pollution found in the Ap agrohumus horizon ($Z_c = 9.5$, n = 9) and minimum pollution registered in horizon C parent material ($Z_c = 1.8$, n = 3).

Similarly, the SPI index values (< 1 throughout the soil profile) indicated no contamination in the soil (Fig. 5). We measured this index for those elements that had officially established maximum permissible concentrations, namely Pb, As, Zn, Ni, MnO, and V.

The I_{geo} index showed that the soils were mostly "unpolluted" (Table 4). Only its values for arsenic, manganese monoxide, and vanadium classified the soils as "unpolluted to moderately polluted" ($I_{geo} < 2$).

Thus, the three soil quality indices did not reveal a critical level of polymetallic pollution in the soils of the Yamal Experimental Station.

The spatial distribution of polymetallic pollution is not uniform. The contents of elements in the topsoil (0–10 cm) are presented in Table 5. We found that the average contents of heavy and trace metals were within the maximum and approximate permissible values, except for arsenic and chromium. Arsenic concentrations were above the permissible values in all 40 samples, while chromium – only in 9 samples.

Increased element concentrations in the arable horizons of agricultural land may be associated with the application of agrochemicals and manure. Moreover, most pollutants accumulate in the topsoil since this layer is most vulnerable to anthropogenic impact [16].

The spatial heterogeneity of polymetallic pollution could also result from the agricultural experiments of 1932–2007. Every year, the experimental field was divided into many microsections where agriculturists

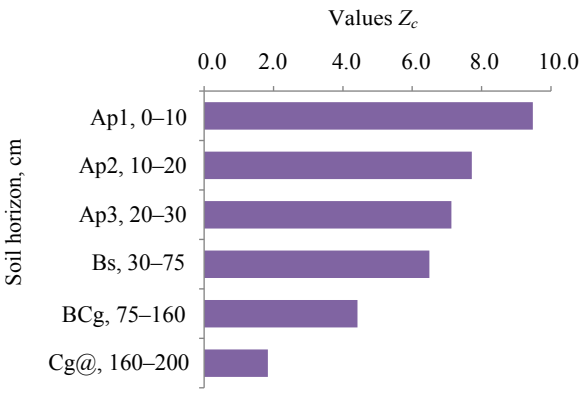

Figure 4. Vertical distribution of the Z_c index values

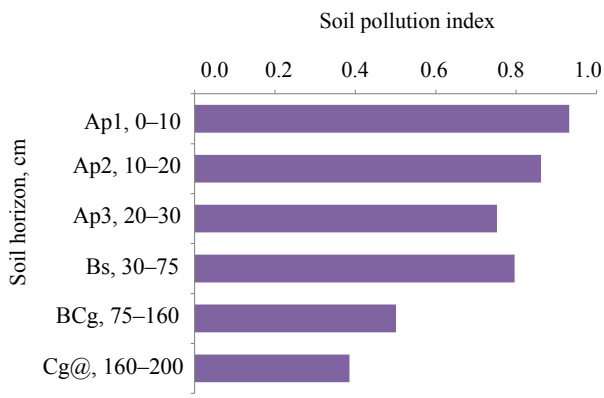

Figure 5. Vertical distribution of the soil pollution index values

Table 5. Contents of elements, including heavy metals, in topsoil (0–10 cm)

Parameter	Sr	Pb	As	Zn	Ni	Co	MnO	Cr	V	Fe_2O_3	TiO_2
	mg/kg									%	
	n = 40										
Minimum	160.0	4.0	7.0	35.0	17.0	0	333.0	71.0	73.0	2.8	0.50
Maximum	247.0	30.0	18.0	80.0	29.0	16.0	499.0	140.0	117.0	4.6	1.00
Average	192.0	15.4	11.5	43.0	21.5	5.6	399.0	90.7	97.8	3.3	0.85
SD	16.3	5.8	2.8	7.4	2.36	3.1	38.4	15.4	10.2	0.3	0.08
MPC/APC	600.0*	65.0	5.0	110.0	40.0	50.0*	1500.0	100.0*	150.0	–	–
Backgrounds	114.3	13.1	6.4	40.2	12.3	5.2	149.5	65.4	33.2	7.1	0.5

* – maximum and approximate permissible concentrations (MPC/APC) for strontium, cobalt, and chromium were taken from [3, 36] since they were not determined in the standards.

Table 6. Concentration coefficient K_{ci} and index Z_c for elements, including heavy metals, in topsoil (0–10 cm)

Parameter	Sr	Pb	As	Zn	Ni	Co	MnO	Cr	V	Z_c
	K_{ci}									
	n = 40									
Minimum	1.4	0.3	1.1	0.9	1.4	0	2.3	1.1	2.2	5.6
Maximum	2.2	2.3	2.8	2.0	2.4	3.1	3.3	2.1	3.5	10.1
Average	1.7	1.2	1.8	1.1	1.7	1.1	2.7	1.4	2.9	7.8
SD	0.1	0.5	0.4	0.2	0.2	0.6	0.3	0.2	0.3	1.1

applied different types of fertilizers and agrotechnical methods, as well as planted different crops. This practice could not fail to affect the nature of heavy metals distribution in the soil.

The qualitative assessment based on the Z_c index (Table 6) classified soil pollution at the Yamal Experimental Station as "acceptable" (Z_c < 16). The Z_c index ranged from 5.6 to 10.1.

According to the complex soil pollution index (Table 7), the humus-accumulative horizon had an insignificant level of spatial pollution.

The spatial analysis of the I_{geo} index (Table 8) revealed the mostly "unpolluted" level of soil contamination with individual heavy metals (I_{geo} < 0). Its maximum values were recorded for cobalt (I_{geo} = 1.0), manganese monoxide (I_{geo} = 1.2), and vanadium (I_{geo} = 1.2), indicating the "moderately polluted" level of soil contamination with these elements (1 < I_{geos} < 2). At n = 40, the average values of the I_{geo} index were above or equal to 1 only for vanadium. For the other elements, they were below 0 or in the range from 0 to 1, indicative of an acceptable pollution level in spatial terms.

The long-term agricultural use of the Yamal Experimental Station contributed to a high content of basic nutrients (Fig. 6). We found a high concentration of mobile phosphorus compounds (up to 450 mg/kg) and exchangeable potassium (up to 60 mg/kg) in the agrolight-humus horizon (Ap). The topsoil also

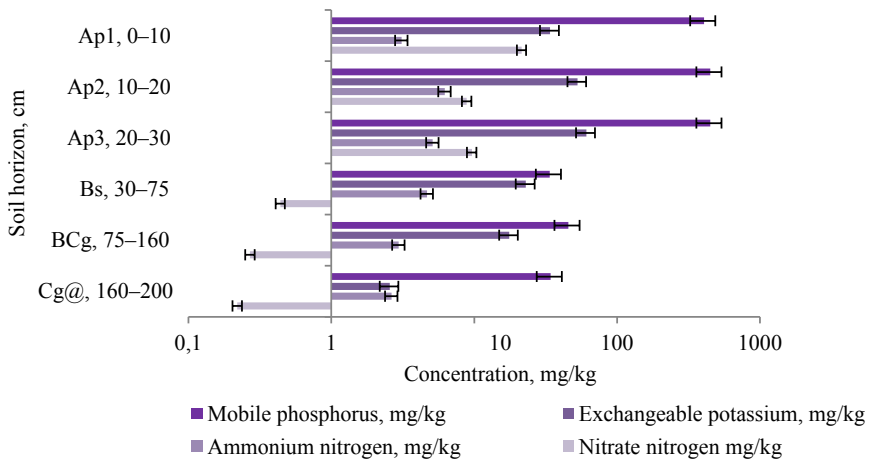

Figure 6. Vertical distribution of nutrients is soil

Table 7. Soil pollution index (SPI) for elements, including heavy metals, in topsoil (0–10 cm)

Parameter	Pb	As	Zn	Ni	MnO	V	SPI
	C_i/C_{MPC}						
	n = 40						
Minimum	0.1	1.4	0.3	0.4	0.2	0.5	0.5
Maximum	0.5	3.6	0.7	0.7	0.9	0.8	0.9
Average	0.2	2.3	0.4	0.5	0.3	0.7	0.7
SD	0.1	0.6	0.1	0.1	0.1	0.1	0.1

Table 8. I_{geo} index values for elements, including heavy metals, in topsoil (0–10 cm)

Parameter	Sr	Pb	As	Zn	Ni	Co	MnO	Cr	V
	n = 40								
Minimum	–0.1	–2.3	–0.5	–0.8	–0.1	–3.0	0.6	–0.5	0.6
Maximum	0.5	0.6	0.9	0.4	0.7	1.0	1.2	0.5	1.2
Average	0.2	–0.5	0.2	–0.5	0.2	–0.6	0.8	–0.1	1.0
SD	0.1	0.6	0.3	0.2	0.2	0.8	0.1	0.2	0.2

Table 9. Contents of main nutrients is topsoil (0–10 cm)

Parameter	Mobile phosphorus, mg/kg	Exchangeable potassium, mg/kg	Ammonium nitrogen, mg/kg	Nitrate nitrogen, mg/kg
	n = 40			
Minimum	165.0	53.0	0.9	0.2
Maximum	1268.0	294.0	10.3	62.8
Average	665.6	106.8	4.8	25.4
SD	235.6	47.9	2.2	19.2

contained maximum concentrations of various forms of nitrogen, namely ammonium nitrogen (up to 6 mg/kg) and nitrate nitrogen (up to 22 mg/kg). We also observed the penetration of nutrients into the mineral horizons (Bs, BCg, and Cg@). At a depth of 160–200 cm, the concentrations of mobile phosphorus, exchangeable potassium, ammonium nitrogen, and nitrate nitrogen were 34, 2.5, 2.6, and 0.2 mg/kg, respectively.

The spatial distribution of nutrient concentrations varied greatly (Table 9). This might be due to the method of applying various doses of fertilizers to the arable horizon.

Conclusion

Our ecotoxicological analysis of fallow soils at the Yamal Experimental Station yielded the following conclusions.

1. The distribution of heavy and trace metals and metal oxides in the soil profile is mainly of the regressive-accumulative type. Their maximum concentrations were found in the topsoil horizon (0–30 cm) with the exception of chromium (75–160 cm).

2. Arsenic exceeded approximate permissible concentrations in the topsoil and in the soil profile. However, literature reveals increased contents of arsenic in the soils of Yamalo-Nenets Autonomous Okrug, even in its anthropogenically undisturbed ecosystems. Therefore, classifying these soils as unsuitable for agriculture is not entirely justified. Yet, we recommend their monitoring to identify potential migration of arsenic into agricultural products. In addition, primary quality control of crops should be in place if these soils are to be used for agriculture.

3. The qualitative ecotoxicological analysis using background regional concentrations revealed insignificant levels of soil pollution both vertically and spatially. The Z_c index classified pollution as "acceptable". The I_{geo} index characterized the soils as "unpolluted" or "moderately polluted". The soil pollution index was below 1, both vertically and spatially, which also indicated an acceptable ecotoxicological state.

4. The contents of the main nutrients in the soils revealed their high potential fertility. Phosphorus, potassium, and nitrogen in the forms available for plants had maximum concentrations in the topsoil horizon. However, we found their downward migration along the soil profile.

Thus, the fallow soils of the Yamal Experimental Station have a high level of potential fertility and can be used for agriculture provided there is proper quality control to monitor arsenic contents.

Contribution

E.V. Abakumov supervised the project. T.I. Nizamutdinov, A.R. Suleymanov, E.N. Morgun, and N.V. Dinkelaker implemented the project.

Conflict of interest

The authors declare no conflict of interest.

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References

1. Guo B, Hong C, Tong W, Xu M, Huang C, Yin H, *et al.* Health risk assessment of heavy metal pollution in a soil-rice system: a case study in the Jin-Qu Basin of China. Scientific Reports. 2020;1(1). https://doi.org/10.1038/s41598-020-68295-6

2. Logan TJ, Traina SJ. Trace metals in agricultural soils. In: Allen HE, Perdue EM, Brown DS, editors. Metals in groundwater. Boca Raton: CRC Press; 2020. p. 309–347.

3. Bezuglova OS, Gorbov SN, Tischenko SA, Aleksikova AS, Tagiverdiev SS, Sherstnev AK, *et al.* Accumulation and migration of heavy metals in soils of the Rostov region, south of Russia. Journal of Soils and Sediments. 2016;16(4):1203–1213. https://doi.org/10.1007/s11368-015-1165-8

4. Suleymanov A, Abakumov E, Zakharenko I, Suleymanov R. Assessment and mapping of landfills on soils in the Serpukhov district (Moscow region). Geodesy and Cartography. 2021;47(4):181–185. https://doi.org/10.3846/gac.2021.12922

5. Polyakov V, Kozlov A, Suleymanov A, Abakumov E. Soil pollution status of urban soils in St. Petersburg city, North-west of Russia. Soil and Water Research. 2021;16(3):164–173. https://doi.org/10.17221/95/2020-SWR

6. Gebeyehu HR, Bayissa LD. Levels of heavy metals in soil and vegetables and associated health risks in Mojo area, Ethiopia. PLoS ONE. 2020;15(1). https://doi.org/10.1371/journal.pone.0227883

7. Gao L, Wang Z, Li S, Chen J. Bioavailability and toxicity of trace metals (Cd, Cr, Cu, Ni, and Zn) in sediment cores from the Shima River, South China. Chemosphere. 2018;192:31–42. https://doi.org/10.1016/j.chemosphere.2017.10.110

8. Khan A, Khan S, Khan MA, Aamir M, Ullah H, Nawab J, *et al.* Heavy metals effects on plant growth and dietary intake of trace metals in vegetables cultivated in contaminated soil. International Journal of Environmental Science and Technology. 2019;16(5):2295–2304. https://doi.org/10.1007/s13762-018-1849-x

9. Chernykh N. The development of forest-tundra soils for agricultural crops. Agricultural and industrial economy of the Yamalo-Nenets Autonomous Okrug. Salekhard; 1977. 14–19 p. (In Russ.).

Черных Н. Опыт освоения лесотундровых почв под сельскохозяйственные культуры // Сельское и промысловое хозяйство Ямало-Ненецкого национального округа. Салехард, 1977. С. 14–19.

10. Morgun EN, Abakumov EV. Agricultural research and crop yields in the Yamal-Nenets Autonomous District: Retrospective analysis (1932–2019). Scientific Bulletin of the Yamal-Nenets Autonomous District. 2019;104(3):4–9. (In Russ.). https://doi.org/10.26110/ARCTIC.2019.104.3.001

11. Tikhanovsky AN. Potatoes in Yamal. Novosibirsk: Akademizdat; 2021. 160 p. (In Russ.).

Тихановский А. Н. Картофель на Ямале. Новосибирск: Академиздат, 2021. 160 с.

12. Abakumov EV, Morgun EN. State and prospects for the use of fallow lands in the Yamalo-Nenets Autonomous Okrug. Biosphere Economy: Theory and Practice. 2021;40(11):5–17. (In Russ.).

Абакумов Е. В., Моргун Е. Н. Состояние и перспективы использования залежных земель в Ямало-Ненецком автономном округе // Биосферное хозяйство: теория и практика. 2021. Т. 11. № 40. С. 5–17.

13. Chernykh NA, Cbeltygmasheva IS, Baeva JI. Soil polution and quality of plants production. RUDN Journal of Ecology and Life Safety. 2003;(9):179–187. (In Russ.)

Черных Н. А., Челтыгмашева И. С., Баева Ю. И. Загрязнение почв тяжелыми металлами и качество растениеводческой продукции // Вестник Российского университета дружбы народов. Серия: Экология и безопасность жизнедеятельности. 2003. № 9. С. 179–187.

14. Zhong Y, Igalavithana AD, Zhang M, Li X, Rinklebe J, Hou D, *et al.* Effects of aging and weathering on immobilization of trace metals/metalloids in soils amended with biochar. Environmental Science: Processes and Impacts. 2020;22(9):1790–1808. https://doi.org/10.1039/d0em00057d

15. Neverova OA, Egorova IN. Evaluation of hips (*Rosa majalis Herrm*.) gathered on the coal opencast dump in the Kemerovo region. Food Processing: Techniques and Technology. 2015;38(3):139–145. (In Russ.).

Неверова О. А., Егорова И. Н. Оценка качества плодов шиповника (*Rosa majalis Herrm*.), произрастающего на породном отвале угольного разреза в условиях Кемеровской области // Техника и технология пищевых производств. 2015. Т. 38. № 3. С. 139–145.

16. Komarov VI, Selivanov OG, Martsev AA, Podoletc AA, Lukyanov SN. Heavy metals contamination in arable horizon of soils of agricultural appointment of the Vladimir Region. Agrohimia. 2019;(12):75–82. (In Russ.). https://doi.org/10.1134/S0002188119100089

17. Paromov VV, Zemtsov VA, Kopysov SG. Climate of West Siberia during the slowing phase of warming (1986–2015) and prediction of hydro-climatic resources for 2021–2030. Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering. 2017;328(1):62–74. (In Russ.).

Паромов В. В., Земцов В. А., Копысов С. Г. Климат Западной Сибири в фазу замедления потепления (1986–2015 гг.) и прогнозирование гидроклиматических ресурсов на 2021–2030 гг // Известия Томского политехнического университета. Инжиниринг георесурсов. 2017. Т. 328. № 1. С. 62–74.

18. Arinushkina E. Chemical analysis of soils. Moscow: Izdatel′stvo Moskovskogo universiteta; 1952. 240 p. (In Russ.).

Аринушкина Е. Химический анализ почв и грунтов М.: Издательство Московского университета, 1952. 240 с.

19. Saltan N, Slukovskaya M, Mikhaylova I, Zarov E, Skripnikov P, Gorbov S, *et al.* Assessment of soil heavy metal pollution by land use zones in small towns of the industrialized Arctic Region, Russia. In: Vasenev V, Dovletyarova E, Valentini R, Cheng Z, Calfapietra C, Inostroza L, Leuchner M, editors. Springer Geography. Cham: Springer; 2020. pp. 100–110. https://doi.org/10.1007/978-3-030-75285-9_10

20. Baghaie AH, Aghili F. Investigation of heavy metals concentration in soil around a PbZn mine and ecological risk assessment. Environmental Health Engineering and Management Journal. 2019;6(3):151–156. https://doi.org/10.15171/EHEM.2019.17

21. Kowalska JB, Mazurek R, Gąsiorek M, Zaleski T. Pollution indices as useful tools for the comprehensive evaluation of the degree of soil contamination – A review. Environmental Geochemistry and Health. 2018;40(6):2395–2420.

22. Rehman I, Ishaq M, Ali L, Khan S, Ahmad I, Din I, *et al.* Enrichment, spatial distribution of potential ecological and human health risk assessment via toxic metals in soil and surface water ingestion in the vicinity of Sewakht mines, district Chitral, Northern Pakistan. Ecotoxicology and Environmental Safety. 2018;154:127–136. https://doi.org/10.1016/j.ecoenv.2018.02.033

23. Łyszczarz S, Błońska E, Lasota J. The application of the geo-accumulation index and geostatistical methods to the assessment of forest soil contamination with heavy metals in the Babia Góra National Park (Poland). Archives of Environmental Protection. 2020;46(3):69–79. https://doi.org/10.24425/aep.2020.134537

24. Sabet Aghlidi P, Cheraghi M, Lorestani B, Sobhanardakani S, Merrikhpour H. Analysis, spatial distribution and ecological risk assessment of arsenic and some heavy metals of agricultural soils, case study: South of Iran. Journal of Environmental Health Science and Engineering. 2020;18(2):665–676. https://doi.org/10.1007/s40201-020-00492-x

25. Nizamutdinov T, Abakumov E, Morgun E. Morphological features, productivity and pollution state of abandoned agricultural soils in the Russian Arctic (Yamal Region). One Ecosystem. 2021;6. https://doi.org/10.3897/oneeco.6.e68408

26. Nizamutdinov T, Abakumov E, Morgun E, Loktev R, Kolesnikov R. Agrochemical and pollution status of urbanized agricultural soils in the central part of Yamal region. Energies. 2021;14(14). https://doi.org/10.3390/en14144080

27. Nizamutdinov T, Morgun E, Pechkin A, Kostecki J, Greinert A, Abakumov E. Differentiation of trace metal contamination level between different urban functional zones in permafrost affected soils (The example of several cities in the Yamal Region, Russian arctic). Minerals. 2021;11(7). https://doi.org/10.3390/min11070668

28. Tomashunas VM, Abakumov EV. The content of heavy metals in soils of the Yamal peninsula and the Bely Island. Hygiene and Sanitation. 2014;93(6):26–31. (In Russ.).

Томашунас В. М., Абакумов Е. В. Содержание тяжелых металлов в почвах полуострова Ямал и острова Белый // Гигиена и санитария. 2014. Т. 93. № 6. С. 26–31.

29. Alekseev II, Dinkelaker NV, Oripova AA, Semyina GA, Morozov AA, Abakumov EV. Assessment of ecotoxicological state of soils of the Polar Ural and Southern Yamal. Hygiene and Sanitation. 2017;96(10):941–945. (In Russ.). https://doi.org/10.18821/0016-9900-2017-96-10-941-945

30. Ji X, Abakumov E, Antcibor I, Tomashunas V, Knoblauch C, Zubzycki S, *et al.* Influence of anthropogenic activities on metals in arctic permafrost: a characterization of benchmark soils on the Yamal and Gydan peninsulas in Russia. Archives of Environmental Contamination and Toxicology. 2019;76(4):540–553. https://doi.org/10.1007/s00244-019-00607-y

31. Moskovchenko DV, Kurchatova AN, Fefilov NN, Yurtaev AA. Concentrations of trace elements and iron in the Arctic soils of Belyi Island (the Kara Sea, Russia): patterns of variation across landscapes. Environmental Monitoring and Assessment. 2017;189(5). https://doi.org/10.1007/s10661-017-5928-0

32. Romanenko EA, Moskovchenko DV, Kudryavtsev AA, Shigabaeva GN. Mobile forms of metals in soils in the Nadym-Pur interfluve (Western Siberia). Bulletin of Nizhnevartovsk State University. 2020;(2):136–145. (In Russ.). https://doi.org/10.36906/2311-4444/20-2/18

33. Moskovchenko DV, Romanenko EA. Elemental composition of soils of the Pur-Taz interfluve. Dokuchaev Soil Bulletin. 2020;(103):51–84. (In Russ.). https://doi.org/10.19047/0136-1694-2020-103-51-84

34. Opekunova MG, Opekunov AYu, Kukushkin SYu, Ganul AG. Background contents of heavy metals in soils and bottom sediments in the north of Western Siberia. Eurasian Soil Science. 2019;(4):422–439. (In Russ.). https://doi.org/10.1134/S0032180X19020114

35. Pechkin AS, Agbalian EV, SHinkaruk EV, Khnycheva NA, Melnikova VV, Iulbarisova KV, *et al.* Background physical and chemical characteristics of the soil cover of the northern part of the state reserve “Verkhne-Tazovsky”. Nature management and protection: natural monuments, biological and landscape diversity of the Tomsk Ob region and other regions of Russia: Proceeding of the 9th All-Russian scientific conference with international participation; 2020; Tomsk. Tomsk: Tomsk State University; 2020. p. 211–215. (In Russ.). https://doi.org 10.17223/978-5-94621-954-9-2020-50

36. Kovalsky VV. Geochemical ecology. Moscow: Nauka; 1974. 299 p. (In Russ.).

Ковальский В. В. Геохимическая экология. М.: Наука, 1974. 299 с.