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 ecotoxics (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 Яманская 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 (Zc), загрязнения почв и геоаккумуляции (Igeo). 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 уровень загрязнения соответствует допустимому. Применение индекса Igeo показало, что почвы «практически не загрязнены» металлами. Значения индекса загрязнения почв менее 1, что свидетельствует об отсутствии загрязнения. Почвы залежного поля Ямальской опытной станции 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 как 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. 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.

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...
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;
– 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.

\[
SPI = \sum_{m} \left( \frac{C_i}{C_{MPC}} \right)^{n} \quad (3)
\]

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]

$$I_{geo} = \log_2 \frac{C_n}{1.5B_n}$$  \hspace{1cm} (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 | Fe₂O₃ | TiO₂ |
|------------------|----|----|----|----|----|----|------|----|---|-------|------|
| 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 |
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 Zc index (Fig. 4) showed that vertically the soil quality could be classified as “acceptable” (Zc < 16). The polymetallic pollution was of the regressive-accumulative type, with maximum pollution found in the Ap agrohumus horizon (Zc = 9.5, n = 9) and minimum pollution registered in horizon C parent material (Zc = 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 Igeo 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” (Igeo < 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...
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 ($1 < I_{geo} < 2$). 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

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

| Parameter | Sr | Pb | As | Zn | Ni | Co | MnO | Cr | V | FeO$_3$ | TiO$_2$ |
|-----------|----|----|----|----|----|----|------|----|----|--------|--------|
| 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 $K_c$ and index $Z_c$ for elements, including heavy metals, in topsoil (0–10 cm)**

| Parameter | Sr | Pb | As | Zn | Ni | Co | MnO | Cr | V | $Z_c$ |
|-----------|----|----|----|----|----|----|------|----|----|-------|
| 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 |

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**Table 5. Concentration coefficient $K_c$ and index $Z_c$ for elements, including heavy metals, in topsoil (0–10 cm)**
Table 8. $I_{geo}$ index values for elements, including heavy metals, in topsoil (0–10 cm)

| Parameter | Sr   | Pb   | As   | Zn   | Ni   | Co  | MnO  | V    | n = 40 |
|-----------|------|------|------|------|------|-----|------|------|--------|
| Minimum   | -0.1 | -0.6 | 0.1  | 0.1  | 0.1  | 0.1 | 0.1  | 0.1  | 0.1    |
| Maximum   | 0.1  | 1.4  | 3.6  | 0.9  | 0.4  | 0.4 | 0.7  | 0.7  | 0.9    |
| Average   | 0.2  | 2.3  | 0.4  | 0.5  | 0.7  | 0.9 | 1.0  | 1.0  | 0.9    |
| SD        | 0.1  | 0.6  | 0.1  | 0.1  | 0.1  | 0.1 | 0.1  | 0.1  | 0.1    |

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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