



Activity concentrations of natural and anthropogenic nuclides in Yamal-Nenets Soils: a radiological hazard assessment

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Abstract

Investigating radionuclide distributions in Arctic soils is essential for evaluating environmental and health risks in the region. Low-background gamma spectrometry was used to determine the activity concentrations of ^{40}K , ^{226}Ra , ^{232}Th , and ^{137}Cs in nine soil samples collected in the Yamal-Nenets Autonomous Okrug, Russia. The mean activity concentrations of radionuclides were: $350 \pm 151 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{40}K , $2.2 \pm 1.1 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{137}Cs , $18.2 \pm 9.4 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{232}Th , and $16.6 \pm 8.0 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{226}Ra . Correlation analysis revealed a strong positive relationship between the natural radionuclides ($r=0.85\text{--}1.00$), confirming a common geogenic sources. The calculated radiological hazard indices—including R_{aeq} , H_{ex} , outdoor absorbed gamma dose rate, annual effective dose, and lifetime cancer risk—were all below internationally recommended reference levels, indicating that the investigated soils pose no significant radiological risk to the public.

Keywords Radiological risk · Natural radionuclides · Radiocesium · Arctic zone

Introduction

Yamal is one of the largest regions in Russia, spanning up to seven natural subzones. Although the soil cover of the Yamal region has been studied for a considerable time [1–3], the accumulation of natural and anthropogenic radionuclides in its soils has not been adequately addressed. This gap is primarily due to the small number of samples studied, a consequence of the difficulties associated with organizing expeditions and conducting detailed surveys across such a

vast territory. Establishing baseline radionuclide concentrations in soil of Arctic zones is important for monitoring anthropogenic contamination and understanding climate-driven changes.

In the Russian Arctic zone, the most detailed radiological studies have been focused on the floodplain-channel part of the Ob River, the Eurasia's largest waterway, which plays a key role in the region's ecological functioning and major biogeochemical processes. These studies have established that ^{137}Cs accumulates predominantly in the floodplain soils of the Lower Ob, while ^{90}Sr transits through this section and is transferred to the Gulf of Ob with minimal retention [4]. Although zonal patterns in radionuclide distribution can be identified in soils [5], such patterns may be less pronounced in northern Western Siberia due to the regulating influence of the Ob River on regional runoff. In Western Siberia, soil contamination with radionuclides can be also attributed to historical nuclear weapons tests [6]. For instance, between 1949 and 1951, $76\cdot 10^6 \text{ m}^3$ of liquid radioactive waste with a total activity of 10^{17} Bq was discharged into the Techa River, part of the Ob-Irtysh river system [7], leading to accumulation of radionuclides in soils and bottom sediments. Consequently, radiological research in the region has primarily focused on floodplain soils and riverbeds.

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At the same time, soils in the watersheds of various natural zones within Yamal remain practically unstudied.

Therefore, the aim of this study is to investigate the activity concentrations of ^{40}K , ^{226}Ra , ^{232}Th , and ^{137}Cs in different types of soil (Phaeozems, Cryosols, Podzols, and Arenosols) collected from both the mountainous and lowland parts of the Yamal-Nenets Autonomous Okrug, formed from parent materials of varying origins.

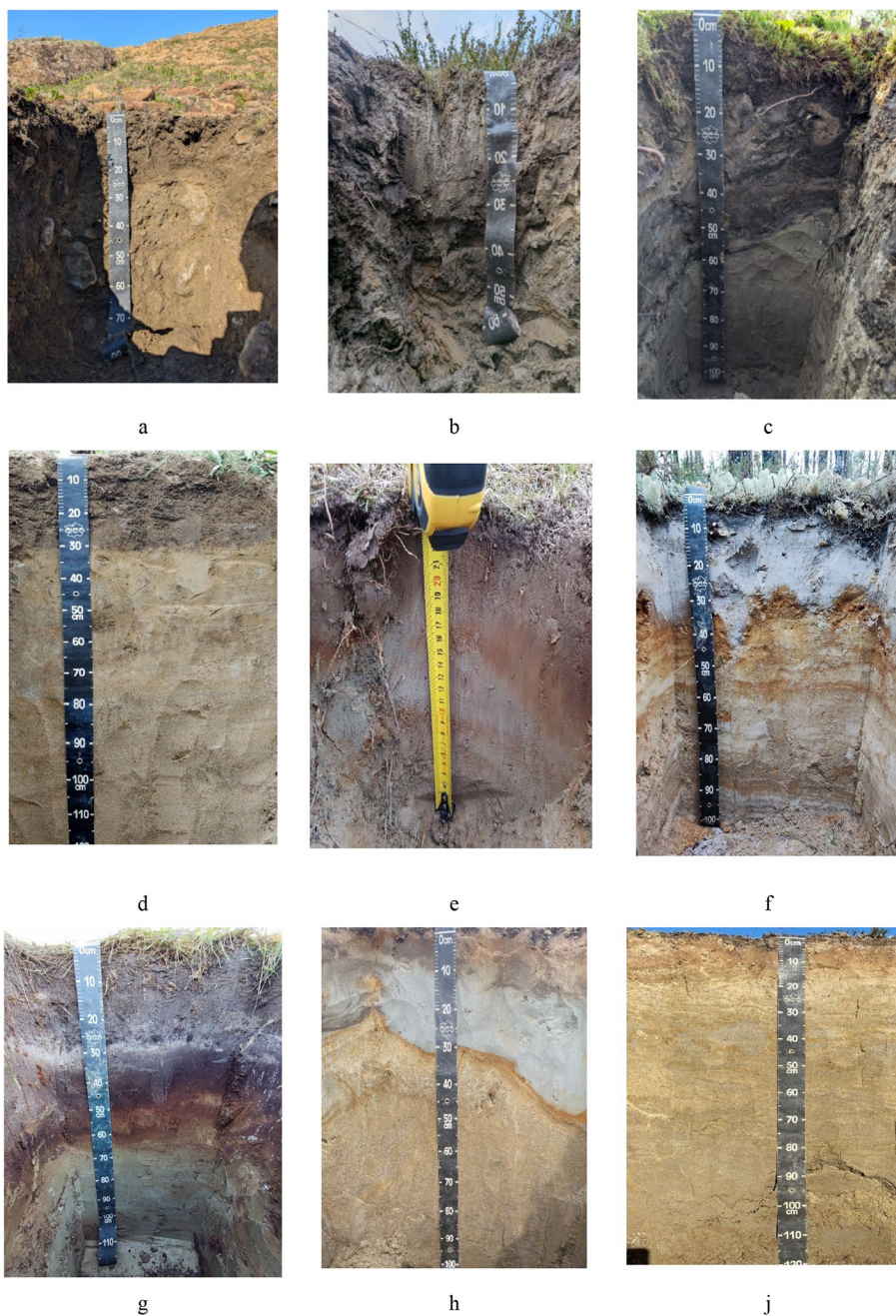
Materials and methods

Study area and soil sampling

The study focused on representative soil types of the Yamal region, selected according to their pedogenesis and degree of anthropogenic influence (Fig. 1).

Soil profile C2 (Fig. 1a) is situated in the Polar Urals, within the Rai-Iz mountain range. This Skeletic Phaeozem (WRB, 2022) has developed on the eluvium of ultramafic rocks, with vegetation characteristic of dryad tundra. The

Fig. 1 **a** section C2, Skeletic Phaeozem, Polar Urals, **b** section C8, Follic Cryosol, carbon supersite “Seven Larches”, **c** section C9, Histic Turbic Cryosol (Arenic), vicinity of Salekhard, **d** Plaggic Podzol (Siltic) of the Yamal experimental station, **e** Gleyic Turbic Cryosol in the vicinity of the village of Seyakha, **f** Nadym, Albic Ortsteinic Podzol (Arenic), **g** Nadym, Hortic Albic Gleyic Podzol (Siltic), **h** Albic Turbic Podzol (Arenic), and **j** Gleyic Lamellic Arenosol from the Yaroto Lakes region



profile coordinates are 66.872347 N, 65.398757 E, at an elevation of 407 m above sea level. It occupies a transitional-eluvial position on a mountain slope. The proximity of a chromium-nickel mine suggests a potential impact on the chemical state of the regional soil cover.

Soil profile C8 (Fig. 1b) is located at carbon measurements test area “Seven Larches” of the Yamalo-Nenets Autonomous Okrug. It represents a background, natural soil classified as a Follic Cryosol (WRB, 2022), formed on medium-loamy boulder-pebble Quaternary deposits. Profile coordinates are 66.695745 N, 66.289898 E, at an elevation of 15 m above sea level.

An additional background soil profile, C9 (Fig. 1c), is located near Salekhard. Developed on well-sorted sandy alluvial deposits from the Ob River, this cryoturbated soil is classified as a Histic Turbic Cryosol (Arenic) (WRB, 2022) on ancient alluvium. The profile coordinates are 66.505843 N, 66.698987 E, at an altitude of 16 m above sea level.

Another sampling site is represented by a Plaggic Podzol (Siltic) (WRB, 2022), located within the experimental field of the Yamal Experimental Station (Fig. 1d). This soil has been under continuous cultivation for nearly a century. The profile coordinates are 66.526622 N, 66.655385 E, at an elevation of 15 m above sea level near Salekhard. This soil is of particular interest as it represents one of the northernmost long-term agricultural soils reported worldwide. In contrast, the soil from the village of Seyakha (Fig. 1e)—the northernmost sampling site included in this study—is a background tundra soil classified as a Gleyic Turbic Cryosol (WRB, 2022). The section coordinates are 70.149815 N, 72.495074 E, at an altitude of 7 m above sea level.

The soils surrounding Nadym are formed on sandy parent materials of the Nadym-Purovsky geochemical province [8]. The first soil is Albic Ortsteinic Podzol (Arenic) (WRB, 2022) (Fig. 1f). The parent material is lacustrine-alluvial sandy deposits with loam “ribbon-like” interlayers. The section coordinates are 65.338028 N, 72.964679 E, at an elevation of 6 m above sea level.

The second section (Fig. 1g) in the vicinity of Nadym is anthropogenically disturbed soil—Hortic Albic Gleyic Podzol (Siltic) (WRB, 2022). This former agricultural soil has remained fallow for more than 30 years. Currently, the soils are abandoned, undergoing secondary podzolization. The parent material is lacustrine alluvial sandy deposits with loam interlayers. The coordinates of the section are: 65.508734 N, 72.634370 E, elevation—7 m above sea level.

Two additional background soils are located in the central Yamalo-Nenets Autonomous Okrug, in the southern part of the Yamal Peninsula (Fig. 1h). Profile P1 is a background soil classified as an Albic Turbic Podzol (Arenic) (WRB, 2022). The profile coordinates are 67.860000 N, 70.501111 E. Profile P2 is a background soil, a Gleyic Lamellic Arenosol (WRB, 2022). The site is developed on layered, gleyed

sandy deposits. The profile coordinates are 67.859722 N, 71.091111 E.

At each site, three sub-samples were collected from an area of about 5 × 5 m according to the IAEA Guidelines on Soil and Vegetation Sampling for Radiological Monitoring [9]. The locations of the sampling sites are shown in Fig. 2.

Radionuclides' activity measurement

Each soil sub-sample was analyzed separately and the results are presented as mean ± standard deviation (SD). Prior to analysis, soils were cleaned, homogenized, dried at 105 °C, and hermetically sealed in 500 mL Marinelli vessels for 30 days to attain equilibrium between ²²⁶Ra and its progeny. Gamma-ray spectrometry was performed with a HPGe detector (Canberra Industries, Inc., USA) with a 40% relative efficiency and a resolution of 1.80 keV (FWHM) at the 1332 keV γ-ray of ⁶⁰Co. Spectra were acquired over counting intervals ranging from 25,000 to 57,000 s (depending on the samples activity) and processed with Canberra Genie 2000 software.

The detector efficiency was calibrated using mixed gamma sources in the same geometric configuration as the samples. The efficiency calibration covered the energy range from 72.80 to 1770.22 keV, using certified reference sources including ¹³³Ba (lowest calibration energy at 72.80 keV) and ²⁰⁷Pb (highest calibration energy at 1770.22 keV). Certified activity values provided by D. I. Mendelev All-Russian Research Institute for Metrology (VNIIM), St. Petersburg, Russia. More information about s certified reference sources is provided in the supplementary material.

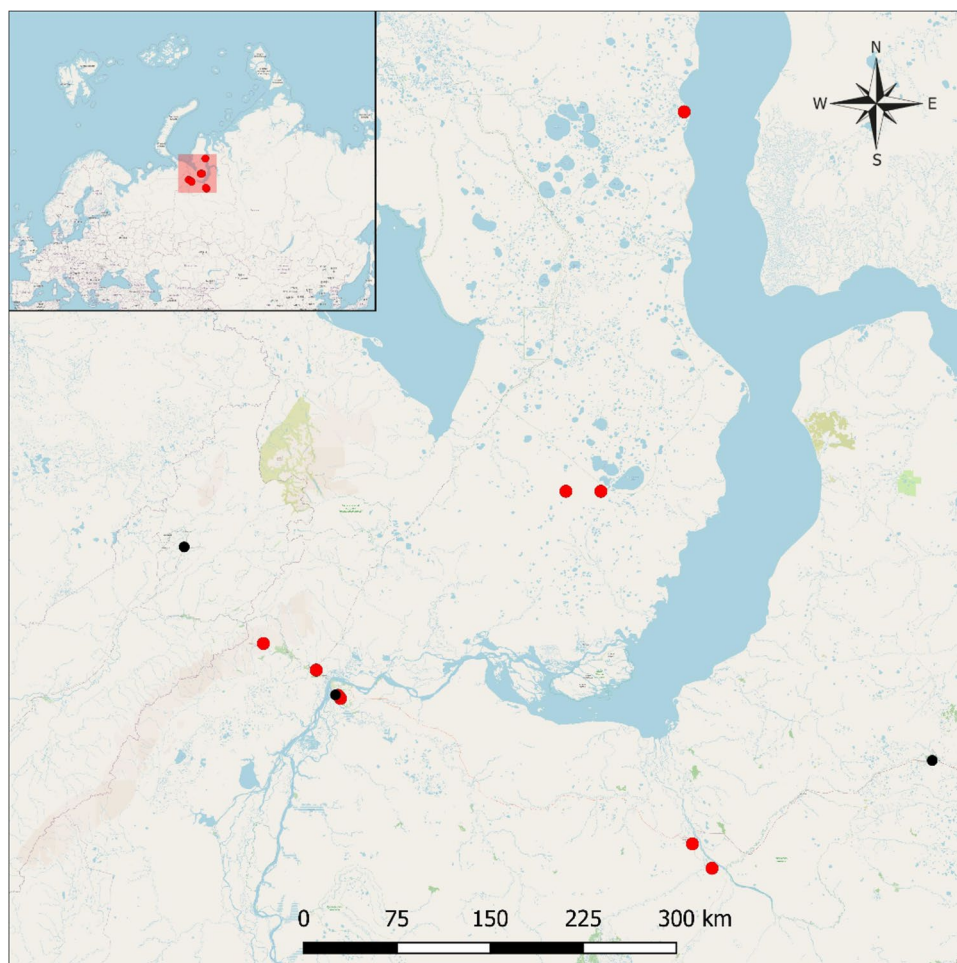
To account for variations in sample density and differences in self-attenuation between calibration standards and samples, all samples, standards and the blank sample were initially measured with a collimated ²⁴¹Am point source. This enabled experimental determination of the mass attenuation coefficient for each matrix using the Eq. (1):

$$\left(\frac{\mu}{\rho}\right)_{exp,E} = \frac{1}{\rho x} \ln \left(\frac{R_{blank}(E)}{R_{sample}(E)} \right) \quad (1)$$

where $R_{blank}(E)$ is the count rate at energy E without the sample, while $R_{sample}(E)$ is the count rate at energy E with the sample of thickness x (in cm). ρ is the physical density of the sample (in g·cm⁻³). The linear attenuation coefficient $\mu(E)$ describes the probability of photon interaction per unit path length at a specific photon energy E . Due to its dependence on the material's bulk density ρ , the linear coefficient is normalized by the density. This yields the mass attenuation coefficient μ/ρ , usually expressed in units of cm²·g⁻¹.

Experimental mass attenuation coefficients were compared with theoretical “Total Attenuation without Coherent Scattering” values from the XCOM database. The chemical

Fig. 2 Soils sampling map in Yamal-Nenets Autonomous Okrug, Russia



composition input to XCOM was iteratively adjusted until it matched the experimental data, producing a list of compounds and their relative weight abundances suitable for modeling in software such as EFFTRAN. Self-attenuation corrections and true coincidence summing effects were subsequently calculated using EFFTRAN software [10].

Background was subtracted using an empty-container spectrum acquired for 172,800 s. This spectrum was

subtracted channel-by-channel from each sample spectrum. The minimum detectable activity concentrations are given in Table 1.

The activity concentration of ^{137}Cs was determined from its 661.66 keV γ -ray emission, whereas that of ^{40}K was determined using its 1460.8 keV photopeak. Assuming secular equilibrium between ^{226}Ra and its progeny, and between ^{232}Th and its decay products, the ^{226}Ra activity was assessed

Table 1 Activity concentrations of ^{40}K , ^{137}Cs , ^{232}Th , and ^{226}Ra in soils collected from the Yamal-Nenets Autonomous Okrug (in $\text{Bq}\cdot\text{kg}^{-1}$)

Sample ID	Soil	^{40}K	^{137}Cs	^{232}Th	^{226}Ra
1	Skeletal phaeozem	144 ± 5	2.6 ± 0.08	12 ± 0.3	10 ± 0.4
2	Folic cryosol	480 ± 10	1.6 ± 0.06	35 ± 0.4	31 ± 0.9
3	Histic turbic cryosol (Arenic)	358 ± 7	0.9 ± 0.04	18 ± 0.3	17 ± 0.5
4	Plaggic podzol (Siltic)	422 ± 8	2.6 ± 0.08	24 ± 0.5	22 ± 0.7
5	Gleyic turbic Cryosol	503 ± 10	1.5 ± 0.06	27 ± 0.5	24 ± 0.7
6	Albic ortsteinic podzol (Arenic)	210 ± 6	<MDA	7.4 ± 0.1	7.7 ± 0.3
7	Hortic albic gleyic podzol (Siltic)	136 ± 4	4.0 ± 0.08	6.3 ± 0.2	7.4 ± 0.3
8	Albic turbic podzol (Arenic)	517 ± 10	<MDA	20 ± 0.4	18 ± 0.5
9	Gleyic lamellic arenosol	376 ± 8	<MDA	14 ± 0.3	12 ± 0.4
MDA		7.7	0.25	1.1	0.7

via the gamma emissions of its progeny ^{214}Pb (295 keV) and ^{214}Bi (609, 1120, and 1764 keV), while ^{232}Th was quantified using the 338 and 911 keV lines from ^{228}Ac .

Radiological risks assessment

To assess the radiological risks posed by both natural and anthropogenic radionuclides present in soils, several indices, including radium equivalent activity (R_{aeq} , $\text{Bq}\cdot\text{kg}^{-1}$), absorbed gamma dose rate in air (D , $\text{nGy}\cdot\text{h}^{-1}$), annual effective dose (AEDE, $\text{mSv}\cdot\text{y}^{-1}$, excess lifetime cancer risk (ELCR), and external index (H_{ex}) [11, 12] were calculated. The R_{aeq} and H_{ex} serve as screening tools for external gamma radiation, with recommended safety thresholds of $\leq 370 \text{ Bq}\cdot\text{kg}^{-1}$ and ≤ 1 , respectively. The D quantifies the gamma field strength at 1 m above ground, while the AEDE converts this into the annual radiation dose received by a person. The ELCR estimates the lifetime probability of cancer induction from chronic low-dose exposure using the nominal risk coefficient recommended by the ICRP. Together, these indices characterize external exposure and its potential health consequences. These indices were calculated using Eqs. 2–6:

$$R_{\text{aeq}} = C_{\text{Ra}} + 1.43C_{\text{Th}} + 0.077C_{\text{K}} \quad (2)$$

$$D = 0.427C_{\text{Ra}} + 0.662C_{\text{Th}} + 0.0432C_{\text{K}} \quad (3)$$

$$\text{AEDE} = D \cdot \text{DCF} \cdot \text{IOF} \cdot T \quad (4)$$

$$\text{ELCR} = \text{AEDE} \cdot \text{LD} \cdot \text{RF} \cdot 10^{-3} \quad (5)$$

$$H_{\text{ex}} = \frac{C_{\text{Ra}}}{370} + \frac{C_{\text{Th}}}{259} + \frac{C_{\text{K}}}{4810} \quad (6)$$

where C_{Ra} , C_{Th} , and C_{K} are the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K , respectively, $\text{Bq}\cdot\text{kg}^{-1}$, DCF is the dose conversion coefficient (0.7 Sv Gy^{-1}), OF is the outdoor occupancy factor (0.2), representing the fraction of time an individual is assumed to spend outdoors, T is the annual exposure time (8760 h y^{-1}), LD is the average life duration (70 years) and RF is the risk factor (0.05 Sv^{-1}) [13, 14]. For stochastic effects, the ICRP 106 used a value of $\text{RF} = 0.05 \text{ Sv}^{-1}$ for the public [15].

Statistical analysis Statistical parameters, such as the mean, median, min, max, standard deviation (SD), coefficient of variation (CV), kurtosis, and skewness were achieved by using Excel software (Redmond, WA, USA). Skewness and kurtosis were used to detect asymmetry and extreme values indicative of localized hot spots, while the CV allowed comparison of relative variability among different radionuclides. The correlation analysis was used as an indicator of the rela-

tionships between natural and anthropogenic radionuclides. Correlation analysis was performed using Spearman's rank correlation coefficient, which are more appropriate for small sample size ($n=9$) and the non-normal distribution of the data. Furthermore, p -values ($p < 0.05$) were adjusted using the Holm method to account for multiple comparisons.

Results and discussion

The activity concentrations of natural radionuclides and ^{137}Cs are presented in Table 1, along with their associated uncertainties, while basic statistics is presented in Table 2. Because only nine soil samples were analyzed, the statistical power of regional comparisons and correlation analyses is limited.

The activity concentration of ^{137}Cs was below the minimum detectable activity (MDA) in background soil samples collected from the Nadym environs (sample 6). Samples were collected in the forest-tundra subzone, in a larch-birch forest with a slight admixture of spruce. The activity concentrations of ^{137}Cs were also below MDA in samples from the central part of the Yamalo-Nenets Autonomous Okrug (samples 8 and 9). Sample 8 was collected on a flat polygonal dwarf shrub-lichen tundra near Lakes Ngevadyodato and Yakhadymalto, while sample 9, also background soil, was collected in the southern hyparctic tundra subzone, on a flat polygonal dwarf shrub-lichen tundra. ^{137}Cs activity in tundra soil is often reported near or below MDA in studies focusing on specific remote areas, such as Arctic zone or deeper soil horizons [16, 17]. Low activity concentrations of ^{137}Cs in Arctic soils can be explained by low vegetation coverage, soil properties and lower historic Chernobyl atmospheric fallout [18, 19]. Soils on the mentioned sites were mainly sandy. It is known that ^{137}Cs levels are often lower in sandy soils compared to organic or clay-rich soils,

Table 2 The basic statistics for soil samples collected in different zones of Yamal-Nenets Autonomous Okrug, Russia

	^{40}K	^{137}Cs	^{232}Th	^{226}Ra
Min	136	0.88	6.3	7.39
Max	517	4.0	35.4	30.6
Mean	350	2.2	18.2	16.6
SD	151	1.1	9.4	8.0
CV, %	43	50	52	48
Median	376	2.1	18.4	17.5
Skewness	− 0.48	0.66	0.49	0.45
Kurtosis	− 1.51	0.22	− 0.30	− 0.79
World average values [14]	400		30	35

primarily because sandy soils lack the fine minerals required to bind and trap the radioactive isotope [20].

In the remaining samples, ^{137}Cs activity concentrations ranged from 0.9 to 4.0 $\text{Bq}\cdot\text{kg}^{-1}$, with an average value of 2.2 $\text{Bq}\cdot\text{kg}^{-1}$. The highest ^{137}Cs activity was found in anthropogenically modified soil collected in the vicinity of Nadym (sample 7). The higher activity concentrations of ^{137}Cs in arable soils, can be associated with its reduced bioavailability and higher fixation [21]. It should be noted that only a limited number of anthropogenically modified soils were analyzed, and to make conclusions in future studies, more samples need to be analyzed. In contrast, forest soils usually contain higher ^{137}Cs exchangeable and organic matter-bound fractions [21]. The measured activity concentrations of ^{137}Cs were lower than values reported by Nifontova [22] for moss-lichen cover in Yamal Peninsula, by Kuzmenkova et al. [16] for tundra landscapes in the north-west of Kola Peninsula, and by Puchkov and Yakovlev [23] for the soil from the Kanin tundra.

The activity concentrations of ^{40}K ranged from 136 to 517 $\text{Bq}\cdot\text{kg}^{-1}$, with an average of 350 $\text{Bq}\cdot\text{kg}^{-1}$. In samples 2, 4, 5, and 8, the activity concentration of ^{40}K exceeded the worldwide average activity concentration of 400 $\text{Bq}\cdot\text{kg}^{-1}$ reported by UNSCEAR [14]. ^{40}K is naturally occurring radioactive isotope of potassium, abundant in most soils. In tundra zones dense moss and lichen cover can concentrate ^{40}K , linking its soil content to plant biomass [24]. High ^{40}K activity can also be related to the geological composition of soil-forming rocks [25]. In tundra soils ^{40}K typically shows a positive correlation with other natural radionuclides such as ^{232}Th and ^{226}Ra [26].

The activity concentrations of ^{232}Th in soil samples ranged from 6.3 to 35 $\text{Bq}\cdot\text{kg}^{-1}$ with an average of 18.2 $\text{Bq}\cdot\text{kg}^{-1}$. These values are below world average activity concentration of 30 $\text{Bq}\cdot\text{kg}^{-1}$ reported by UNSCEAR [14], except for the soil collected at the “Seven Larches” carbon measurement test area (sample 2). This site is also characterized by the highest ^{226}Ra activity concentration. However, the activity concentration of ^{226}Ra (7.4–31 $\text{Bq}\cdot\text{kg}^{-1}$) across all sites remained below the average global reference value of 35 $\text{Bq}\cdot\text{kg}^{-1}$ [14].

The basic statistics for analyzed soil samples is presented in Table 2.

The coefficient of variation (CV) reflects the spatial characteristics of radionuclides distribution. Larger CV values indicate a more uneven distribution of elements and a greater degree of influence from external disturbances or anthropogenic factors [27]. The CVs for radionuclides activities range from 43 to 52% (Table 3), demonstrating high spatial heterogeneity [28]. A negative skewness for ^{40}K indicates slightly left-skewed asymmetry, which is consistent with a median value higher than the mean. Kurtosis values for natural radionuclides were negative, showing that their distribution is

Table 3 The radiological hazard indices for soil samples collected in different zones of Yamal-Nenets Autonomous Okrug, Russia

Site	$R_{\text{eq}}, \text{Bq kg}^{-1}$	H_{ex}	$D, \text{nGy h}^{-1}$	AEDE mSv y^{-1}	ELCR ($\times 10^{-3}$)
1	38.3	0.10	18.4	0.023	0.08
2	118.1	0.32	57.1	0.070	0.25
3	71.5	0.19	35.1	0.043	0.15
4	89.0	0.24	43.5	0.053	0.19
5	100.9	0.27	49.6	0.061	0.21
6	34.4	0.09	17.2	0.021	0.07
7	26.9	0.07	13.2	0.016	0.06
8	85.9	0.23	42.9	0.053	0.18
9	61.0	0.16	30.6	0.037	0.13
min	26.9	0.07	13.2	0.02	0.06
max	118.1	0.32	57.1	0.07	0.25
mean	69.6	0.19	34.2	0.04	0.15

platykurtic [29]. In contrast, positive skewness and kurtosis values for ^{137}Cs suggest a pronounced right-skewed distribution [27].

The elevated ^{232}Th (35 $\text{Bq}\cdot\text{kg}^{-1}$) and ^{226}Ra (31 $\text{Bq}\cdot\text{kg}^{-1}$) activity concentrations were determined in sample 2 (“Seven Larches” carbon measurement supersite), which represent the maximum values in the entire dataset. Boulder-pebble glacial till typically consists of unsorted, polymictic material transported over considerable distances by glacial ice, potentially incorporating lithoclasts from diverse source rocks including those enriched in U- and Th-bearing accessory minerals (e.g., monazite, zircon, apatite, and titanite). Monazite in particular is a primary carrier of thorium in granitic and metamorphic source rocks [30], and its presence in glacially reworked till is well documented [31]. This mineralogical heterogeneity of the glacial parent material may explain the elevated activities of natural radionuclides compared to soils formed on more uniform, lithologically simpler deposits such as the sorted sandy alluvial sediments of other sampling sites.

Several additional pedogenic factors may further contribute to the enrichment of ^{232}Th and ^{226}Ra in this soil. First, the Folc Cryosol at “Seven Larches” is characterised by a well-developed organic horizon, and both thorium and radium are known to accumulate in the organic fraction of soils due to their strong affinity for humic substances [32]. Thorium, in particular, forms stable complexes with organic acids, which substantially reduces its mobility and promotes its retention in organic-rich surface horizons [33]. Second, the medium loam texture of the parent material provides a relatively high content of clay-sized and silt-sized particles compared to the sandy substrates predominant elsewhere in the study area, and fine mineral fractions are established concentrators of natural radionuclides [34]. Collectively,

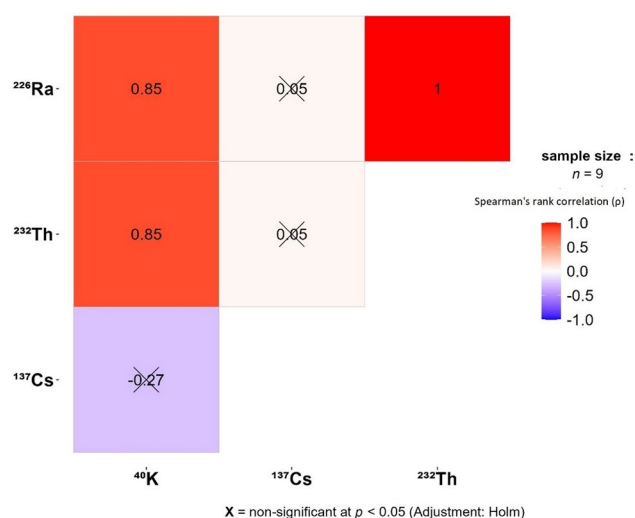


Fig. 3 Correlation analysis results for soil samples collected in different zones of Yamal-Nenets Autonomous Okrug, Russia

the combination of a polymictic glaciogenic parent material enriched in radionuclide-bearing accessory minerals, an organic-rich Follic horizon with strong geochemical retention capacity for Th and Ra, and fine loamy texture likely accounts for the distinctly elevated natural radioactivity at this site. This interpretation is consistent with the observation that all radiological hazard indices for that soil were the highest among the studied profiles.

The results of the correlation analysis (Fig. 3) show high positive correlations ($p < 0.05$) among the natural radionuclides ^{40}K , ^{232}Th and ^{226}Ra . The weak correlation of natural radionuclides with ^{137}Cs suggests its different source of origin, most probably an anthropogenic one. High correlation between ^{232}Th and ^{226}Ra in studied soils reflects a common lithogenic (geogenic) control over their spatial distribution [35]. In undisturbed natural soils where secular radioactive equilibrium has been attained, the activities of daughter radionuclides mirror those of their respective long-lived parents, and the ratio of ^{232}Th to ^{226}Ra remains relatively constant across samples from mineralogically similar parent materials [36]. The fact that this ratio is maintained throughout the geochemically diverse soils of the Yamal-Nenets region—ranging from Skeletic Phaeozems developed on ultramafic eluvium to Cryosols on Quaternary loamy-boulder deposits—indicates that the heterogeneity of radionuclide content is principally driven by variability in the geochemical composition of the parent material, rather than by post-depositional redistribution or differential element mobility. It should be noted, that since correlation analysis was based on a small number of samples it can be considered as exploratory rather than conclusive.

Assessing radiological hazards in soil involves measuring radionuclide concentrations to calculate hazard indices,

ensuring they remain below safe limits. The equivalent radium activity values, ranging from 27 to 118 $\text{Bq}\cdot\text{kg}^{-1}$ (Table 3), were well below the maximum recommended limit of 370 $\text{Bq}\cdot\text{kg}^{-1}$ [13]. The mean H_{ex} values were almost five times lower than unity, indicating a low radiological hazard. Even when considering the maximum value, it remains significantly below the safe level of unity and does not pose a significant risk from exposure.

The outdoor absorbed gamma dose rates, ranging from 13.2 to 57 $\text{nGy}\cdot\text{h}^{-1}$, did not exceed the world average of 59 $\text{nGy}\cdot\text{h}^{-1}$ established by UNSCEAR [14]. In terms of annual effective dose the average value was found to be 0.04 $\text{mSv}\cdot\text{y}^{-1}$, which is lower than the global average of 0.07 $\text{mSv}\cdot\text{y}^{-1}$ [14]. However, in soil samples collected at the “Seven Larches” carbon supersite, the value corresponded to world average reference value. It is important to note that the values of other indices for this soil sample were also higher compared to the other samples. The ELCR values ranging from 0.06×10^{-3} to 0.25×10^{-3} were below the total average of 1.45×10^{-3} [37].

All radiological index values were below those reported for soils collected on Novaya Zemlya [38].

Conclusions

This study assessed the activity concentrations of ^{40}K , ^{226}Ra , ^{232}Th , and ^{137}Cs in representative soils of the Yamal-Nenets Autonomous Okrug, Russia. The activity concentrations of ^{40}K and ^{232}Th in several samples exceeded the global average values. ^{137}Cs was not detected in background soils, and its activity concentrations were higher in arable soils. A strong positive correlation was found between natural radionuclides. No significant correlations were observed between ^{137}Cs and the natural radionuclides, consistent with its predominantly anthropogenic origin. All calculated radiological hazard indices remained below internationally accepted safety thresholds, indicating no significant public health risk. The notably high activity concentrations of natural radionuclides in soil samples from the “Seven Larches” carbon supersite warrant specific attention. Overall, this study provides essential baseline data on environmental radioactivity in the Yamal region, establishing a valuable reference for future monitoring and public health evaluations.

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Data availability All will be provided on the request.

Declarations

Conflicts of interest The authors declare no conflicts of interest.

Ethical approval Not applicable.

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