

Distribution of ^{137}Cs and ^{40}K in spring wheat (*Triticum aestivum* L. var. *lutescens*) grown on radioactively contaminated areas of the Bryansk region

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Among cultivated crops, wheat along with rye accumulates ^{137}Cs in grain and green biomass to the lowest extent; therefore, its cultivation in radioactively contaminated areas is a radiologically justified measure for reducing the population's collective dose. Spring crops are of particular interest because of their shorter life cycle and less pronounced root development compared with winter crops. The aim of this study was to investigate the distribution parameters of ^{137}Cs and ^{40}K in soft spring golden wheat (*Triticum aestivum* L. var. *lutescens*) grown on a radioactively contaminated sod-podzolic loam that had not been subjected to intensive ameliorative practices. The hypothesis was tested that the transfer of ^{137}Cs and ^{40}K to wheat organs is related to soil profile depth. Samples were collected from an arable field where the contamination density of ^{137}Cs in the 0–30 cm soil layer was 342 ± 44 kBq/m². Agrochemical analysis indicated slightly acidic pH and moderately high contents of organic matter, available potassium, and phosphorus. Cesium and potassium were found to be distributed among plant organs in similar proportions. Concentration ratios and aggregated transfer factors for the radionuclides were determined from soil to roots, stems, inflorescences, and grain. The concentration ratios were compared with IAEA data for cereal crops in temperate environments and, for cesium, were in close agreement with the published values. The IAEA concentration ratios for potassium in wheat stems and shoots (1.1; n=2) appeared to be substantially underestimated compared with the values obtained in the present study (4.41 ± 1.37 ; n=5), whereas good agreement was observed for potassium transfer to grain. It was shown that, with increasing soil profile depth, the aggregated transfer factors for ^{137}Cs and ^{40}K remain stable, reflecting uniform uptake of these radionuclides throughout the root zone. No effect of the texture of the subsoil horizon or the plough pan on the transfer of ^{137}Cs and ^{40}K was observed. Spearman's rank correlation analysis based on small sample sizes revealed a negative correlation ($r_s = -0.9$) between sample values of the activity concentrations of ^{137}Cs and ^{40}K along the following translocation pathways: ^{40}K in soil – ^{137}Cs in inflorescences; ^{40}K in soil – ^{137}Cs in grain; ^{40}K in inflorescences – ^{137}Cs in grain; and ^{40}K in grain – ^{137}Cs in grain.

Key words: radiation ecology, environmental health, radiation monitoring, radioactively contaminated territories, Bryansk region, food security, cesium-137, potassium-40, spring wheat, transfer of cesium and potassium from soil to wheat, radiobiology.

Introduction

Remediation measures for territories affected by radioactive contamination following the accident at the Chernobyl Nuclear Power Plant (ChNPP) include directing agricultural activities towards sectors that reduce the collective effective dose received by the population through the consumption of agricultural products. Meat livestock production and grain cultivation are radiologically justified agricultural activities characterized by low export of anthropogenic radionuclides with agricultural products [1].

Among cultivated plants, wheat and rye exhibit some of the lowest levels of ^{137}Cs accumulation in grain and green biomass, making the study of their cultivation parameters of considerable practical importance. Grain is primarily used for human consumption, whereas straw (green biomass) is used as feed for livestock. Grain is also used as feed for poultry and other farm animals in both household farming and agricultural production, with humans ultimately being the final consumers of the resulting products.

In the Bryansk Region, ^{137}Cs is the predominant radioactive soil contaminant. Its transfer parameters into crop products may change at different stages following radioactive contamination under the influence of radioactive decay, radiocesium migration, its geochemical fixation in soil, and biogeochemical processes [2]. Accordingly, comparing data obtained during the early stages of radioactive contamination with current data is of practical importance.

Spring wheat varieties may be more suitable for cultivation in radioactively contaminated areas than winter varieties due to their shorter life cycle and shallower root systems. On the other hand, shallower rooting may instead promote more intensive transfer of radiocesium into the aboveground parts of plants, since radiocesium is predominantly concentrated in the upper soil horizons.

The aim of the present study was to investigate the distribution parameters of ^{137}Cs and ^{40}K in soft spring golden wheat (*Triticum aestivum* L. var. *lutescens*) cultivated in radioactively contaminated areas on loamy sod-podzolic soil that had not been subjected to intensive agricultural amelioration measures. The hypothesis that soil depth is associated with the intensity of ^{137}Cs and ^{40}K transfer into the organs of spring wheat was tested. The results obtained may be used to predict the transfer of cesium and potassium into the organs of soft spring golden wheat and provide a basis for further research.

Materials and methods

The study was conducted in 2024 in the village of Vereshchaki, Bryansk Region, located 185 km from the damaged Unit 4 of the ChNPP. The settlement is classified as a zone of residence with the right to resettlement, where the current ^{137}Cs soil contamination density ranges from 5 to 15 Ci/km² (185–555 kBq/m²). Samples of soft spring golden wheat (*Triticum aestivum* L. var. *lutescens*) were collected from a private household farm.

Samples were collected using a five-point envelope sampling pattern within a 1 ha arable field in mid-August, prior to harvesting, at the wax ripeness stage, when grain moisture content was approximately 20%. Whole wheat plants, including their root systems, were collected. At each wheat sampling point, soil samples were collected from the 0–10, 10–20, and 20–30 cm horizons using a concentric soil sampler. The soil samples were oven-dried at 105 °C to constant dry mass and subsequently sieved to ensure homogenization and remove stones.

The wheat samples were mechanically cleaned of soil, washed with warm water, and then oven-dried. Each whole wheat sample was subsequently separated into roots, stems, and inflorescences (spikes). Wheat stems and roots were ground into a homogeneous mass using an electric grinder. The intact inflorescences were initially analyzed, after which the grain was separated by manual threshing, followed by sieving and removal of impurities using air currents, for subsequent gamma-spectrometric analysis.

The activity concentrations of ^{137}Cs and ^{40}K in soil and wheat samples from each sampling point were determined by gamma spectrometry using an SKS-99 Sputnik NaI(Tl) gamma spectrometer equipped with the Progress software package. Measurements were performed using a 500 cm³ Marinelli beaker completely filled with the prepared samples. According to the technical specifications of the gamma spectrometer, the minimum detectable activity (MDA) per counting sample (density of 1 g/cm³) was 3 Bq. Dimensionless concentration ratios describing the transfer of radionuclides from the 0–10 cm soil horizon into wheat organs were calculated using Eq. (1):

$$CR = \frac{A_{plant}}{A_{soil}}, \quad (1)$$

where

A_{plant} – activity concentration of ^{137}Cs or ^{40}K in a wheat organ (Bq/kg),

A_{soil} – activity concentration of ^{137}Cs or ^{40}K in the 0–10 cm soil horizon (Bq/kg).

Aggregated transfer factors of radionuclides (m²/kg) from integrated soil layers into wheat organs were calculated using Eq. (2):

$$TF = \frac{A_{plant}}{P}, \quad (2)$$

where

A_{plant} – activity concentration of ^{137}Cs or ^{40}K in a wheat organ (Bq/kg),

P – activity inventory of ^{137}Cs or ^{40}K in the soil layer (Bq/m²), calculated using Eq. (3):

$$P = \sum_{i=1}^n A_i \times h_i \times \rho_i, \quad (3)$$

where

A_i – activity concentration of the sample (Bq/kg),

h_i – depth of the soil horizon (m),

ρ_i – soil bulk density of the horizon (kg/m³), determined using Eq. (4):

$$\rho = \frac{m}{S \times h_i} \times 10^3, \quad (4)$$

where

m – dry mass of the sample (g),

S – cross-sectional area of the sampler (cm²),

h_i – depth of the soil horizon (cm),

10^3 – conversion factor from g/cm³ to kg/m³.

Soil samples intended for agrochemical analysis were air-dried at room temperature without preliminary treatment. Table 1 presents the determined parameters and the corresponding regulatory documents specifying the measurement methods.

Table 1

List of parameters and regulatory documents for agrochemical soil analysis

Determined parameter, unit of measurement	Regulatory document specifying the measurement method
Plant-available potassium compounds (K_2O) according to Kirsanov, mg/kg	GOST R 54650
Exchangeable magnesium, mmol/100 g	GOST 26487, Section 2
Exchangeable calcium, mmol/100 g	GOST 26487, Section 2
Sulfur mass concentration, mg/kg	PND F 16.1:2.2:3.37-2002
Particle-size distribution/grain-size composition, fraction less than 0.1 mm, %	GOST 12536, Section 4.2
Hydrolytic acidity, mmol/100 g	GOST 26212
Total arsenic concentration, mg/kg	M-MVI 80-2008, Section 4 (FR.1.31.2013.14150)
Total zinc concentration, mg/kg	M-MVI 80-2008, Section 4 (FR.1.31.2013.14150)
Total copper concentration, mg/kg	M-MVI 80-2008, Section 4 (FR.1.31.2013.14150)
Organic matter mass fraction, %	GOST 26213
Total nickel concentration, mg/kg	M-MVI 80-2008, Section 4 (FR.1.31.2013.14150)
Plant-available phosphorus compounds (P_2O_5) according to Kirsanov, mg/kg	GOST R 54650
Total cadmium concentration, mg/kg	M-MVI 80-2008, Section 4 (FR.1.31.2013.14150)
Mercury concentration, mg/kg	M-MVI 80-2008, Section 5 (FR.1.31.2013.14150)
Sum of exchangeable bases, mmol/100 g	GOST 27821
Chloride ions, mg/kg	PND F 16.1.8-98
Nitrate ions, mg/kg	PND F 16.1.8-98
pH of salt extract, pH units	GOST 26483
Ammonium nitrogen, mg/kg	FR.1.31.2011.09210
Total lead concentration, mg/kg	M-MVI 80-2008, Section 4 (FR.1.31.2013.14150)
Nitrate nitrogen concentration, mg/kg	PND F 16.1:2.2:3.67-10

Agrochemical soil analysis was performed by the accredited laboratory of Ekologicheskaya Ekspertiza LLC (EcoStandard Group) under an official contract (No. MF112024-14). The following equipment was used: UNICO 2100, PE-5400 UV, and Kvant.Z spectrophotometers; a Stayer liquid chromatograph equipped with a conductivity detector; a MARK-901 portable pH meter/millivoltmeter; and an S 20/50 laboratory sieve (mesh).

Statistical analysis included descriptive and nonparametric methods implemented in statistical software packages. The results are presented as arithmetic means and standard deviations. The threshold for statistical significance was set at $p = 0.05$.

Results and discussion

The results of the agrochemical soil analysis are presented in Table 2. The morphological characteristics and particle-size distribution of the soil correspond to a loamy sod-podzolic soil with slightly acidic conditions [3].

Table 2

Results of agrochemical soil analysis

Parameter	Result	Unit
Particle-size distribution/grain-size composition, fraction less than 0.1 mm	46.4 ± 0.1	%
pH of salt extract	5.5 ± 0.1	pH units
Organic matter mass fraction	6.9 ± 0.7	%
Chloride ions	32 ± 6	mg/kg
Nitrate ions	114 ± 23	mg/kg
Sum of exchangeable bases	11.5 ± 1.7	mmol/100 g
Hydrolytic acidity	11.2 ± 1.3	mmol/100 g
Nitrate nitrogen	12 ± 3	mg/kg
Ammonium nitrogen	4.4 ± 2.0	mg/kg
Plant-available potassium (K_2O)	178 ± 27	mg/kg
Plant-available phosphorus (P_2O_5)	332 ± 66	mg/kg
Exchangeable magnesium	0.77 ± 0.08	mmol/100 g
Exchangeable calcium	3.06 ± 0.28	mmol/100 g
Total sulfur	< 80	mg/kg
Cadmium	< 0.05	mg/kg
Lead	3.5 ± 1.0	mg/kg
Nickel	2.9 ± 0.9	mg/kg
Zinc	12 ± 4.0	mg/kg
Copper	3.5 ± 1.1	mg/kg
Mercury	< 0.005	mg/kg
Arsenic	0.55 ± 0.17	mg/kg

The soil was characterized by high contents of organic matter and plant-available potassium compounds and a very high content of plant-available phosphorus. The contents of nitrate nitrogen, exchangeable calcium, and exchangeable magnesium were low, while that of ammonium nitrogen was very low [4, 5]. The concentrations of heavy and minor metals, as well as arsenic and sulfur, were at the limits of determination and did not exceed the sanitary standards [6].

Table 3 presents the measured activity concentrations of ^{137}Cs and ^{40}K in the soil horizons. Analysis of the sample values using the Kruskal–Wallis test revealed no statistically significant differences in the activity concentrations of ^{137}Cs and ^{40}K throughout the soil profile, indicating a uniform vertical distribution of these radionuclides within the investigated soil horizons.

Table 3

Activity concentrations of ^{137}Cs and ^{40}K in soil horizons, Bq/kg

Soil horizon	n	^{137}Cs	^{40}K
0–10 cm	5	727 ± 91	307 ± 72
10–20 cm	5	721 ± 97	273 ± 44
20–30 cm	5	680 ± 88	269 ± 52

Table 4 presents the measured activity concentrations of ^{137}Cs and ^{40}K in the organs of spring wheat. The standard deviation values indicate moderate variability in the activity concentrations of ^{137}Cs and ^{40}K among wheat samples collected from different locations within the arable field.

Table 4

Activity concentrations of ^{137}Cs and ^{40}K in spring wheat (dry mass), Bq/kg

Wheat organ	n	^{137}Cs	^{40}K
Roots (pooled samples)	2	168	1320
Stems (straw)	5	72 ± 24	1295 ± 233
Inflorescences (spikes)	5	51 ± 18	583 ± 163
Grain	5	21 ± 8	259 ± 78

It is known that the cultivation of agricultural crops on soils with high contents of plant-available potassium inhibits the transfer of ^{137}Cs from soil to plants [7]. The uptake of ^{137}Cs can also be suppressed through soil liming and other agricultural amelioration measures [8], none of which had been implemented on the investigated household farm.

Spearman's rank correlation analysis (two-tailed test) revealed negative correlations between the activity concentrations of ^{40}K and ^{137}Cs in the soil–inflorescence, soil–grain, inflorescence–grain, and grain–grain relationships (Table 5). Despite the limited statistical power of nonparametric correlation analysis with small sample sizes, the consistency of the correlation estimates supports the antagonistic relationship between ^{137}Cs and ^{40}K along their translocation pathways.

Table 5

Results of Spearman's rank correlation analysis, n = 5 (sampling points)

Compared parameters (activity concentration, Bq/kg)	r_s	p
^{40}K in the 0–10 cm soil horizon vs. ^{137}Cs in inflorescences	–0.9	0.037
^{40}K in the 0–20 cm soil layer vs. ^{137}Cs in grain	–0.9	0.037
^{40}K in the 0–30 cm soil layer vs. ^{137}Cs in inflorescences	–0.9	0.037
^{40}K in inflorescences vs. ^{137}Cs in grain	–0.9	0.037
^{40}K in grain vs. ^{137}Cs in grain	–0.9	0.037

The natural isotopic abundance of ^{40}K is practically constant at approximately 0.0117%. Accordingly, the activity concentration of ^{40}K in plants correlates with their potassium content, while its activity concentration in soil correlates with the total potassium content. This relationship is supported by established models for predicting radiocesium transfer into plants, which incorporate the activity concentration of ^{40}K as an indicator of total potassium content [7].

Total soil potassium comprises plant-available potassium, which is the main form accessible for plant nutrition; reserve (slowly exchangeable) potassium fixed in 2:1-type clay minerals; and nonexchangeable (bound) potassium incorporated into primary minerals. Plant-available, reserve, and nonexchangeable potassium account for approximately 1–2%, 1–10%, and 90–98% of total soil potassium, respectively [9]. A dynamic equilibrium exists among the different forms of soil potassium: depletion of plant-available potassium is compensated by its release from reserve forms, whereas excess potassium becomes fixed in minerals through ion-exchange reactions [10].

The release of potassium from bound into plant-available forms is influenced by biogeochemical processes in the rhizosphere. Plant roots, microorganisms, and mycorrhizal fungi

release organic acids and other exometabolites that promote the partial weathering of potassium-bearing minerals, allowing the released potassium to occupy exchange sites [11, 12]. Cesium and potassium, both belonging to Group IA of the alkali metals, are fixed in minerals through similar mechanisms [13]. Table 6 presents the concentration ratios (CRs) for the transfer of radionuclides from the 0–10 cm soil horizon into wheat organs, calculated using Eq. (1).

Table 6

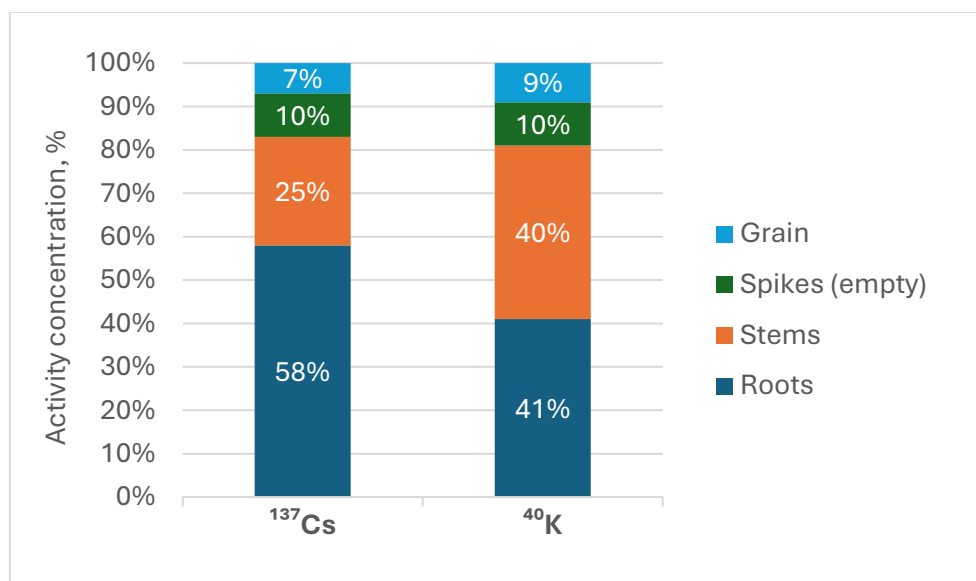
Dimensionless CRs for ^{137}Cs , ^{40}K transfer from the 0–10 cm soil horizon into wheat organs

Wheat organ	n	^{137}Cs	^{40}K
Roots (pooled samples)	2	0.24	4.47
Stems (straw)	5	0.10 ± 0.04	4.41 ± 1.37
Inflorescences (spikes)	5	0.08 ± 0.03	1.90 ± 0.28
Grain	5	0.03 ± 0.02	0.85 ± 0.20

The obtained CR of ^{137}Cs for grain grown on podzolic soils was slightly higher than the mean CR (F_v) reported by the IAEA [14] for cereal crops grown on podzolic soils (0.02; $n = 158$), but was almost identical to the mean value reported for all soil types (0.029; $n = 470$). The obtained CRs of ^{137}Cs for stems and inflorescences were comparable to the IAEA mean value for stems and shoots of cereal crops grown on podzolic soils (0.11; $n = 36$), but were slightly lower than the mean value for all soil types (0.15; $n = 130$).

The obtained CR of ^{40}K for grain was in close agreement with the IAEA data for all soil types (0.74; $n = 2$), whereas the obtained CRs of ^{40}K for stems and inflorescences were substantially higher than the IAEA mean value for stems and shoots (1.1; $n = 2$). No comparative data were available for the CRs of cesium and potassium in the root systems or inflorescences (spikes) of cereal crops.

A clear decreasing gradient in the accumulation of ^{137}Cs and ^{40}K was observed among spring wheat organs along their translocation pathway from roots to grain (Fig. 1). Cesium and potassium accumulated in wheat in similar proportions.

Fig. 1. Distribution of ^{137}Cs and ^{40}K among spring wheat organs, %.

The bulk densities of the 0–10, 10–20, and 20–30 cm soil horizons, determined using Eq. (4), were 1.53, 1.56, and 1.74 g/cm³, respectively. Soil compaction was observed in the 20–30 cm horizon, probably associated with textural differentiation of the soil profile and, in cultivated fields, with the formation of a plow pan resulting from conventional moldboard plowing at a constant depth. The activity inventories of ¹³⁷Cs and ⁴⁰K in integrated soil layers, calculated using Eq. (3), are presented in Table 7. Table 8 presents the aggregated transfer factors (TF) of ¹³⁷Cs and ⁴⁰K from integrated soil layers into wheat organs, calculated using Eq. (2).

Table 7

Mean soil contamination density (inventory) of ¹³⁷Cs and ⁴⁰K in integrated soil layers, kBq/m²

Soil layer	n	¹³⁷ Cs	⁴⁰ K
0–10 cm	5	112 ± 14	47 ± 11
0–20 cm	5	224 ± 29	90 ± 11
0–30 cm	5	342 ± 44	137 ± 19

Table 8

Aggregated TFs of ¹³⁷Cs and ⁴⁰K from soil into wheat organs (dry mass), m²/kg × 10⁻³

Wheat organ	n	Soil layer	¹³⁷ Cs	⁴⁰ K
Roots (pooled samples)	2	0–10 cm	1.51	28.1
	2	0–20 cm	0.75	14.7
	2	0–30 cm	0.49	9.7
Stems (straw)	5	0–10 cm	0.64 ± 0.21	28.8 ± 8.9
	5	0–20 cm	0.32 ± 0.10	14.5 ± 2.6
	5	0–30 cm	0.21 ± 0.07	9.5 ± 1.5
Inflorescences (spikes)	5	0–10 cm	0.46 ± 0.18	12.4 ± 1.8
	5	0–20 cm	0.23 ± 0.09	6.5 ± 1.4
	5	0–30 cm	0.15 ± 0.06	4.3 ± 1.0
Grain	5	0–10 cm	0.18 ± 0.07	5.5 ± 1.3
	5	0–20 cm	0.09 ± 0.03	2.9 ± 0.7
	5	0–30 cm	0.06 ± 0.02	1.9 ± 0.5

By normalizing the aggregated TFs to a common soil layer thickness (10 cm), it is possible to identify the horizons in which radionuclide uptake is more intensive and determine whether the mobility of ¹³⁷Cs and ⁴⁰K decreases in deeper soil layers due to their fixation by soil minerals (Fig. 2). Another relevant question is whether the plow pan, which restricts root penetration and water movement into the subsoil horizon, limits the removal of radionuclides from deeper soil horizons.

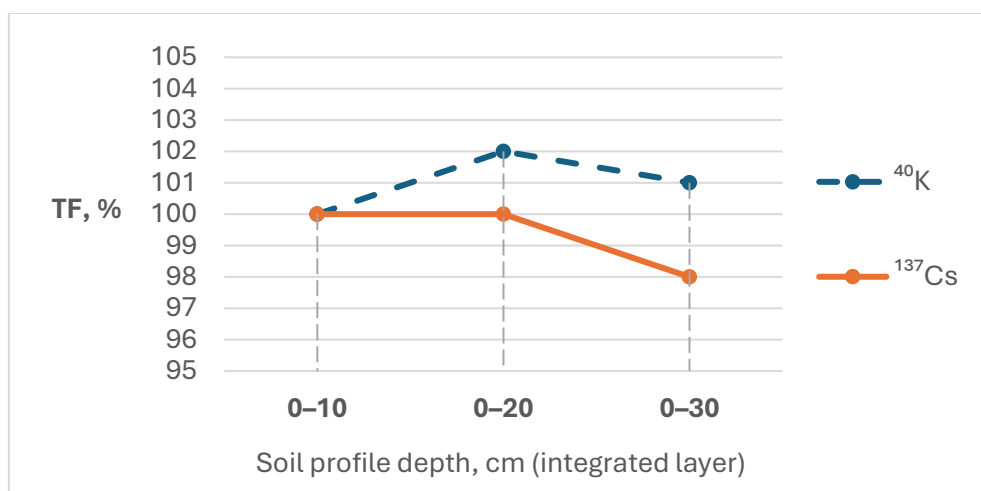


Fig. 2. Relative changes in aggregated TFs with soil depth into the aboveground parts of wheat (stems + inflorescences), %.

The results obtained indicate that root uptake of ^{137}Cs and ^{40}K is practically uniform throughout the investigated soil profile (0–30 cm). For both radionuclides, the variation in aggregated TFs with increasing soil depth does not exceed 2%.

Conclusion

The distribution of ^{137}Cs and ^{40}K in soft spring golden wheat (*Triticum aestivum* L. var. *lutescens*) was investigated under field conditions during the long-term phase of radioactive contamination following the ChNPP accident. The main agrochemical properties of the soil were determined, along with the surface contamination density of radionuclides in the plow and subplow horizons.

CRs and aggregated TFs of ^{137}Cs and ^{40}K from soil horizons into spring wheat organs were determined for slightly acidic loamy sod-podzolic soil with moderately high contents of organic matter, plant-available potassium, and phosphorus. The obtained values were compared with IAEA data for temperate climates. While the mean values for cesium were comparable, the IAEA data substantially underestimated potassium transfer into wheat stems and shoots, whereas the values for potassium transfer into grain were in good agreement. Moderate horizontal variability in the TFs of ^{137}Cs and ^{40}K , not exceeding 30%, was observed across arable field sites characterized by homogeneous distributions of these radionuclides.

It was established that, as the depth of the integrated soil layer increased to 30 cm, the TFs of ^{137}Cs and ^{40}K normalized to a common soil depth remained stable (variation not exceeding 2%), reflecting uniform root uptake of these radionuclides (bioavailability gradient) at different depths within the root zone. No effect of subplow horizon texture or the plow pan on the transfer of ^{137}Cs and ^{40}K was detected.

Spearman's rank correlation analysis of small samples revealed negative correlations ($r_s = -0.9$) between the measured activity concentrations of ^{137}Cs and ^{40}K along the following radionuclide translocation pathways: ^{40}K in soil – ^{137}Cs in inflorescences; ^{40}K in soil – ^{137}Cs in grain; ^{40}K in inflorescences – ^{137}Cs in grain; and ^{40}K in grain – ^{137}Cs in grain. These findings reflect not only the antagonistic relationship between plant-available potassium and cesium during their transfer from

soil into wheat, but may also indicate antagonism between these radionuclides during their translocation from vegetative to reproductive organs of wheat.

The main limitation of the present study is the low resolution of the gamma spectrometer used (MDA for ^{137}Cs = 3 Bq) and the associated measurement uncertainty when activity concentrations are expressed per unit dry mass of the prepared samples. However, the high activity concentrations of ^{137}Cs in the soil and wheat organs compensate for this limitation. Another important limitation is the uncertainty regarding the wheat cultivar, although this is partially compensated for by taxonomic identification to the level of botanical variety (varietas). The small sample size for individual soil layers and wheat organs ($n = 5$) represents a substantial limitation associated with the labor-intensive nature of sample preparation. The mass of the root system collected at each sampling point was insufficient for individual measurements. Although the pooled root samples from all sampling sites ($n = 2$) provide information on the activity concentrations of ^{137}Cs and ^{40}K in the wheat root system, the sample size is insufficient for a reliable characterization of this component of the radionuclide transfer pathway. These limitations should be taken into account in future studies, particularly to enable correlation analyses with adequate statistical power.

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