Original Research

Investigation and Assessment of ^{137}Cs and ^{40}K Accumulation in Vegetable Segments

Renata Mikalauskienė*, Donatas Butkus

Department of Environmental Protection, Vilnius Gediminas Technical University
Saulėtekio 11, LT-10223 Vilnius, Lithuania

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Abstract

Our article deals with the accumulation of artificial (^{137}Cs) and natural (^{40}K) radionuclides in the segments of carrots *(Daucus carota L.)*, potatoes *(Solanum tuberosum L.)*, beet *(Beta vulgaris L.),* and head cabbage *(Brassica oleracea L.)*. The main physical properties of soils and their possible impact on the specific activity of ^{137}Cs and ^{40}K in vegetables have been determined. The specific activities of ^{137}Cs and ^{40}K in the soil and vegetable segments were measured; transfer (*TF*) and ^{137}Cs discrimination (*DF*) factors were identified.

It was determined that artificial radionuclide ^{137}Cs transfer factors from the soil to vegetable segments were subject to fluctuate from 0.02 to 0.39. The accumulation of natural radionuclide ^{40}K in vegetable segments is almost three times more intensive than that of artificial ^{137}Cs – the values of the ^{40}K transfer factor varied from 0.06 to 1.32. The ^{137}Cs discrimination factor (*DF*) in vegetable segments ranged from 0.01 to 1.07.

Keywords: ^{137}Cs, ^{40}K, specific activity, transfer factor, discrimination factor, soil, sandy loam, silty loam

Introduction

The environment is inseparably linked with radioactive materials: ionizing radiation, emitted by radioactive elements, constantly affects life and its development. Therefore, a necessity has arisen to permanently monitor and control radionuclide contamination in the environment, to assess consequences that may be caused by the increased exposure of ionizing radiation, and to plan measures for avoiding pollution effects [1, 2]. Radionuclides contained in the soil may migrate and accumulate in the biota in the same way as the nutrients. The distribution of radionuclides in the soil and transfer to the biosphere components depend on the chemical form of the elements and soil properties, like the amount, natural humidity, and density of the organic matter [3].

The main source of radionuclide penetration into the human organism is foodstuffs, predetermining the internal human exposure and constituting approximately 90% of the total exposure dose [4]. The contamination of the agricultural lands with radionuclides increases their concentration and pollution of the grown agricultural products; therefore, exposure of people consuming those products is increasing [5]. Large amounts of ^{137}Cs and ^{40}K get into organisms of people and animals with the food, therefore determination of radioactivity of elements in food products and animal folder is essential [6].

Ionizing radiation conditioned by radionuclides affects the environment and its components; plants like filters uptake radioactive materials from the atmosphere and the soil [7]. Since plants almost always are the primary nutrition chain, and radionuclides, both natural and artificial, enter through leaves and roots, people are subject to the permanent internal exposure dose with food [8, 9].

Plants are essential for human nutrition. The accumulating plants – potatoes, beets, cabbage, carrots,

*e-mail: renata.mikalauskiene@gmail.com

etc. – are called the suppliers of carbohydrates and supplement considerably the human diet [10]. Therefore, the necessity comes forth to conduct comprehensive research aimed at assessing not only the separate sources of ionizing radiation exposure in the soil-to-vegetable system [11], but also their migration and accumulation regularities in separate parts – segments – of vegetables.

Research shows that the highest values of specific activities of technical radionuclides in the aboveground and underground parts of the plants depend on the type of plant and level of contamination in their habitats [12]. Vegetables accumulate certain ions from the soil through the root system [13]. One of the most important microelements is ^{40}K, the chemical analogue of which is artificial radionuclide ^{137}Cs [14].

The main property describing the capacity of different media of the environment to accumulate ^{137}Cs and ^{40}K radionuclides is called the transfer factor (TF). The growth of plants is determined by properties of climate and soil [15]. The availability of chemical elements to plants as well as the their uptake from soil are influenced by environmental factors, both of natural and anthropogenic nature: organic matter, temperature, soil structure and moisture, and pH, among others [16]. Transfer factor values for agricultural plants are normally within the range of 0.001-1 for mineral soils with textures of loam or clay. For organic or sandy soils, TF values could be more than 1 or even as high as 28.5 for some agricultural crops [17, 18]. The values of the transfer factor in the different combinations of the soil and plant systems are generalized and applied by assessing and modeling the radioactive transfer and the impact of radioactive materials on the environment and its components [19].

With cesium lacking, plants accumulate monovalent potassium more intensively. It was found that ^{137}Cs soil transfer factor (TFCs) was interrelated with potassium content in soil [20]. This phenomenon is called ^{137}Cs discrimination for soil-to-plant transfer [21]. ^{40}K therefore appears to be one of the major factors influencing plant uptake of radiocaesium [19]. To predict the peculiarities of ^{137}Cs and ^{40}K accumulation in the nutrition chains, it is important to determine their dispersion regularities in the soil and vegetables.

The objective of the work is to identify the specific activities of natural and artificial radionuclides ^{137}Cs and ^{40}K in the soil and to assess the values of their transfer and ^{137}Cs discrimination factors in the segments of carrots *(Daucus carota L.)*, beets *(Beta vulgaris L.)* potatoes *(Solanum tuberosum L.)*, and head cabbage *(Brassica oleracea L.)*.

Experimental Research Methods

In 2011 three habitats were selected: in the territories of Šiauliai district, Ukmergė district, and Alytus district, accounting for the soil contamination with ^{137}Cs (Fig. 1).

According to the spectrometric measurements, performed in 1987, ^{137}Cs-specific activity in the soil of the Alytus district after the Chernobyl NPP accident made around 70 Bq/kg, Kėdainiai district approx. 30 Bq/kg, and Šiauliai district fluctuated from 7 Bq/kg to 8 Bq/kg [22].

During experimental research, vegetables were grown in the selected habitats with the aim of identifying the transfer and discrimination factor values from the soil to vegetable segments.

In the soil samples of different habitats, the natural moisture content in the soil (W), amount of the organic matter (OM), and density (ρ) were determined; the soil granulometric composition (structure) under field

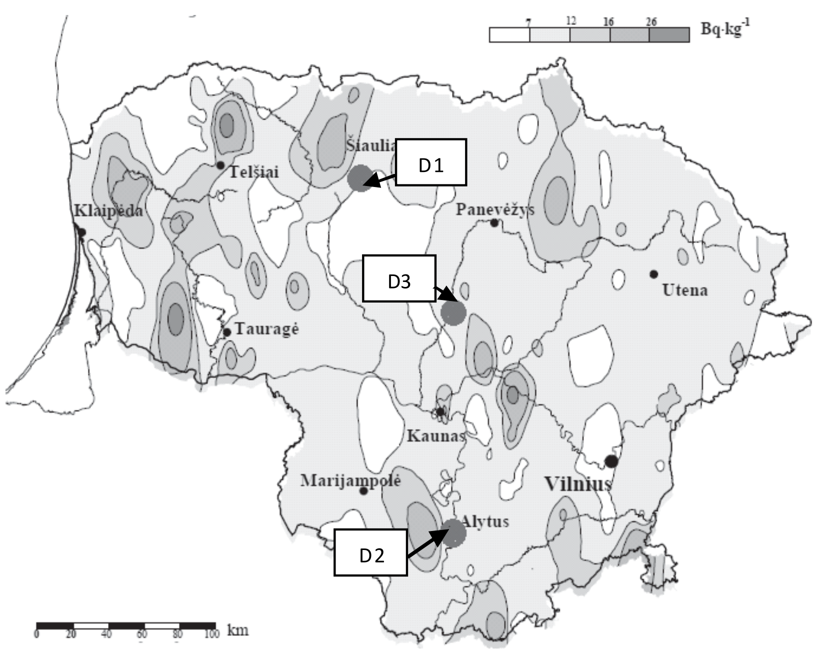

Fig. 1. Experimental habitats: D1-Šiauliai district, D2-Alytus district, D3-Kėdainiai district [33].

conditions was analyzed. Sampling is carried out in agriculture locations (arable soil). All samples were extracted from 20 cm depth and were not divided into strata. The specific activity of ^{137}Cs and ^{40}K is measured in the dry soil and vegetable segments.

The granulometric composition structure of the soil samples is identified under field conditions. The granulometric composition of the soil is characterized according to the hardness of dry clods, stickiness of moist mass, plasticity, kneading, hoarseness, or softness by rubbing the soil between the fingers [23].

Natural soil moisture content (*W*) is the ratio of the mass of water contained in the soil pores m_w with the mass of solid particles m_s, expressed as a in percentage. The mass of solid particles by its numerical value is equal to the dry mass. The mass of water (evaporated by drying) is calculated by deducting the mass of solid particles from the mass of moist soil [24].

Organic matter (*OM*) content is determined by ashing of the soil at high temperature. The burnt soil mass Δm and the burnt mass content corresponds to the soil OM content and were calculated by formulas [25]. Soil density (ρ) was calculated by a formula [26].

Preparation of Vegetable Samples for Gamma Spectrometric Analysis

Prior to spectrometric analysis, vegetables of a separate kind are washed (soil is removed from the surface) and if possible divided into separate segments:

1. Aboveground part (leaves and heads):
   - leaves of root and tuberous vegetables are not separated
   - heads of head vegetables are divided into separate parts: outer (top leaves), middle (inner leaves), and core
2. Underground part (roots):
   - roots of the head vegetable are not separated
   - roots of tuberous vegetables are divided into two parts: outer (peel) and inner
   - roots of root vegetables are divided into three parts: outer (peel), middle, and core

For determination of the specific activity ($A_{i,j}$), samples of vegetable segments, chopped by an electric chopper and dried in a laboratory drying cabinet at 105ºC to constant weight, were used.

Dry samples are poured into a measuring vessel (Burk cell) by shaking it constantly for a sample to get laid naturally. The filled-up Burk cell is weighed by electronic scales with a precision of 0.001 g.

Determination of ^{137}Cs- and ^{40}K-Specific Activities in Vegetable Segments and Soil

Aiming to receive the qualitative and quantitative information on the concentration of the radionuclide activity of the prepared sample, a spectrometric analysis is applied.

The specific activities of radionuclides in the soil and soil segments are determined by means of a gamma spectrometer HPGe (high purity germanium) detector.

Using an HPGe detector, it is possible to separate gamma quanta, the energies of which differ not less than 1.5 keV.

The special gamma spectra processing software GammaVision®-32 identifies the radionuclides in the sample and calculates their specific activities. Prior to measuring the radionuclide activity in the sample, the gamma spectrometer is calibrated by using the main sources.

^{137}Cs and ^{40}K are identified according to the radiation energy characteristic of each radionuclide: ^{137}Cs – 662 keV, ^{40}K – 1460 keV. The sample measurement duration is 1-1.5 days.

According to the measured radionuclide activity and sample weight in the measuring cell, the specific activity of the radionuclide in the sample is calculated (Bq/kg). The specific activity of the radionuclides is calculated by formula [27, 28]:

$$A_a = \frac{\frac{S}{t} - \frac{S_f}{t_f}}{\eta \cdot \varepsilon \cdot m} \quad (1)$$

...where A_a is the specific activity of the tested radionuclide in the sample, Bq/kg; *S* is the radionuclide peak area, received by measuring the radionuclide activity in the sample, imp; *t* is sample measurement time, s; S_f is the peak area, received by measuring the background radiation, imp; t_f is the background radiation measurement time, s; η is number of gamma rays emitted by a nuclide during one act of radioactive decay; ε is spectrometric system efficiency; and *m* is the sample weight, kg.

Determination of Radionuclide Transfer and Discrimination Factors

To determine the accumulation of radionuclides in agricultural crops it is necessary to identify the values of their transfer factor (*TF*) from the soil to vegetable segments. Transfer factor in this case is determined from the soil to vegetables – ordinary carrots *(Daucus carota L.)*, edible potatoes *(Solanum tuberosum L.)*, reed beets *(Beta vulgaris L.)*, head cabbage *(Brassica oleracea L.),* and to their ordinary segments.

The main specific feature that describes the ability of different environmental media to accumulate radionuclides is the transfer factor and it is determined by comparing the vegetable segment mass unit activity with soil activity, and their ratio is taken [11, 29]:

$$(TF)_i = \frac{A_{i,j}}{A_{i,d}} \quad (2)$$

...where $(TF)_i$ is *i*-th radionuclide transfer factor; $A_{i,j}$ is *i*-th radionuclide-specific activity in *j*-th vegetable segment, Bq/kg; $A_{i,d}$ is *i*-th radionuclide specific activity in the soil, Bq/kg.

Table 1. Physical characteristics of the soil.

Habitat	Structure	Moisture, W, %	Organic matter, OM, %	Dry soil density, ρ, 10^3 kg/m^3
D1	Silty loam	14.1	7.9	1.55
D2	Sandy loam	22.0	12.8	1.15
D3	Silty loam	11.8	6.1	1.43

D1-Šiauliai district, D2-Alytus district, D3-Kėdainiai district

The ratio of ^{137}Cs and ^{40}K activities is the factor most frequently used in evaluating the radionuclide transfer in the soil-to-plant system, in this case in the system soil – vegetable segments. It was established that ^{40}K blocked ^{137}Cs uptake in plant roots and thus weakened ^{137}Cs migration [30] and vice versa – the increased ^{137}Cs activity concentration in the plant may be related with the lack of ^{40}K [31].

To determine the impact of ^{40}K on ^{137}Cs uptake in vegetable segments, ^{137}Cs discrimination factor is established [21]:

$$(DF)_{137_{Cs}} = \frac{\left(\frac{A_{137_{Cs}}}{A_{40_K}}\right)_{i,j}}{\left(\frac{A_{137_{Cs}}}{A_{40_K}}\right)_{i,d}} = \frac{(TF)_{137_{Cs}}}{(TF)_{40_K}} \quad (3)$$

...where $(DF)_{137_{Cs}}$ is ^{137}Cs discrimination factor; $A_{137_{Cs}}$ is ^{137}Cs-specific activity in the soil ($A_{i,d}$) and vegetable segments ($A_{i,j}$), Bq/kg; A_{40_K} is ^{40}K-specific activity in the soil ($A_{i,d}$) and vegetable segments ($A_{i,j}$), Bq/kg; $(TF)_{137_{Cs}}$ is ^{137}Cs transfer factor; $(TF)_{40_K}$ is ^{40}K transfer factor.

Results and Discussion

The results of analysis of soil natural moisture content (*W*), organic matter (*OM*) content, dry soil density (*ρ*), and soil granulometric composition (structure) identified under field conditions in the soils of different habitats are provided in Table 1.

Light sandy loam soil allows moisture to permeate well, but a little bit higher index of organic matter content in the Alytus district habitat (D2) 12.8% retains precipitation on the soil surface (22%). Whereas, the soils possessing the silty loam structure (D1 and D3) allow moisture to permeate for a little (14.1%-11.8%).

Fluctuation of organic matter in the soils of habitats under study differs greatly: in the soil, possessing sandy loam structure, (D2) the organic matter content, as compared to silty loam soils (D1 and D3), is rather high at 12.8%. Soils, having more clay in their composition,

Table 2. ^{137}Cs-specific activities in soil and carrot (*Daucus carrota L.*) segments.

Segment	Mass of sample, m, 10^{-3} kg	Time of measurement, t, s	Specific activity, A_a, Bq/kg	Standard error of activity determination, ΔA, Bq/kg
Šiauliai district (D1)				
D	80.4	343320	2.1	±0.2
M1	29.9	77653	0.8	±0.7
M2	31.6	86590	0.5	±0.4
M3	25.8	86361	0.2	±0.1
M4	16.1	90452	0.5	±0.4
Alytus district (D2)				
D	59.7	355360	6.9	±0.4
M1	23.8	84495	0.9	±0.8
M2	24.5	84615	0.4	±0.3
M3	26.4	88420	0.7	±0.6
M4	19.8	87797	0.7	±0.6
Kėdainiai district (D3)				
D	74.2	330540	3.4	±0.4
M1	34.8	90096	0.7	±0.6
M2	33.5	76824	0.9	±0.8
M3	34.4	82969	0.4	±0.3
M4	15.2	85329	0.7	±0.5

D-soil, M1-peel, M2-middle part, M3-core, M4-aboveground part

are noted for the lower content of the organic matter from 6.1% to 7.9% (D3 and D1).

The soil horizons possessing less organic matter and of heavier granulometric composition (D1 and D3) are denser ($1.55 \cdot 10^3$ – $1.43 \cdot 10^3$ kg/m^3).

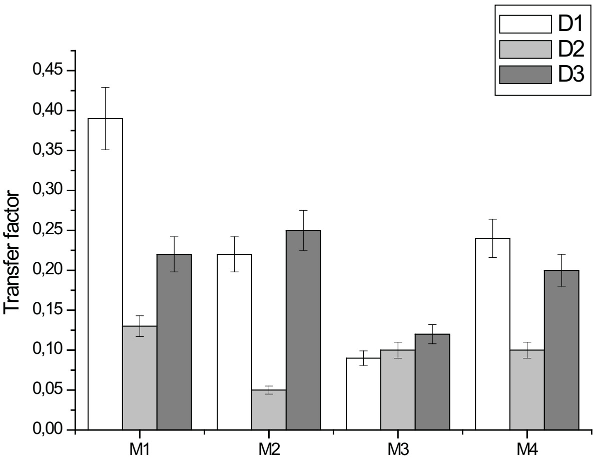

Fig. 2. ^{137}Cs transfer factor from the soil to carrot *(Daucus carota L.)* segments: D1-Šiauliai district, D2-Alytus district, D3-Kėdainiai district, M1-peel, M2-middle part, M3-core, M4-aboveground part.

Table 3. ^{137}Cs-specific activities in soil and beet (*Beta vulgaris L.*) segments.

Segment	Mass of sample, m, 10^{-3} kg	Time of measurement, t, s	Specific activity, A_a, Bq/kg	Standard error of activity determination, ΔA, Bq/kg
Šiauliai district (D1)				
D	80.4	343320	2.1	± 0.2
B1	35.5	83045	0.3	±0.2
B2	36.9	83918	0.2	±0.1
B3	53.7	90786	0.6	±0.3
B4	19.6	81009	0.8	±0.7
Alytus district (D2)				
D	59.7	355360	6.9	±0.4
B1	24.6	85144	0.5	±0.3
B2	18.3	81617	0.6	±0.3
B3	19.4	74062	0.9	±0.5
B4	18.7	82498	0.7	±0.4
Kėdainiai district (D3)				
D	74.2	330540	3.4	±0.4
B1	39.3	84178	0.3	±0.2
B2	27.2	85836	0.4	±0.2
B3	24.4	99787	0.8	±0.4
B4	20.1	83413	0.6	±0.3

D-soil, B1-peel, B2-middle part, B3-core, B4-aboveground part

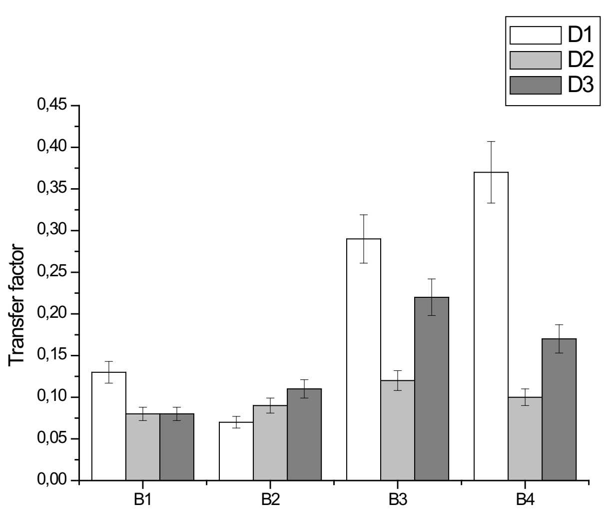

Fig. 3. ^{137}Cs transfer factor from the soil to beet *(Beta vulgaris L.)* segments: D1-Šiauliai district, D2-Alytus district, D3-Kėdainiai district, B1-peel, B2-middle part, B3-core, B4-aboveground part.

Research Results of ^{137}Cs and ^{40}K Accumulation in the Soil-to-Vegetable Segments System

The radionuclide accumulation in vegetable segments is assessed, taking into account the main source of radionuclide penetration into vegetables – the soil, its radioactive contamination, and physical properties. Based on the results of ^{137}Cs and ^{40}K-specific activities in vegetable segments, transfer factors were calculated by Formula 2 provided in the section of methodics.

Investigation results of the specific activities of artificial and natural radionuclides ^{137}Cs- and ^{40}K in the samples of carrot, beet, potato, and cabbage dry weight segments, in D1, D2, and D3 habitats are presented in Tables 2-9.

As seen from research data, ^{137}Cs-specific activities in the dry soil fluctuate from 2.1±0.2 to 6.9±0.4 Bq/kg. Maximum value of the artificial radionuclide ^{137}Cs-specific activity, measured in the D2 habitat soil sample, is 6.9±0.4 Bq/kg. Radioactive contamination in this locality is still impacted by the 1986 Chernobyl accident.

^{137}Cs accumulation in carrot segments (Table 2) is highest in the carrot peel (M1), from 0.7±0.6 to 0.9±0.8 Bq/kg, and the lowest specific activity is measured in the middle part of the carrot (M2) and core (M3) 0.4±0.3 Bq/kg and 0.2±0.1 Bq/kg.

The highest values of ^{137}Cs soil-to-vegetable segments transfer factor (Fig. 2) are established for the carrot peel (M1) and aboveground parts (M4), respectively, from 0.13 to 0.39 and from 0.10 to 0.24. In all habitats (D1, D2, and D3) the values of ^{137}Cs transfer factor are lowest to carrot cores (M3): from 0.09 to 0.12.

The most active accumulation of ^{137}Cs occurs in the beet core (B3) and aboveground part (B4) – from 0.6±0.4 Bq/kg to 0.9±0.5 Bq/kg. The lowest accumulation is measured in the middle part (B2), in the habitat D1 – 0.2±0.1 Bq/kg (Table 3).

The lowest value of ^{137}Cs transfer factor (Fig. 3) from the soil to the beet peel (B1) and middle part (B2) is from 0.07 to 0.13, and the highest transfer factor values are determined to the beet core (B3) and aboveground part (B4), accordingly from 0.12 to 0.29 and from 0.10 to 0.37. In the Šiauliai district habitat (D1), the value of the transfer factor to the beet aboveground part is highest at 0.37, even though the specific activity in the soil of that territory as compared to the remaining two habitats is lowest 2.1±0.2 Bq/kg.

When comparing the specific activity results of both root vegetables (carror and beet), it is seen that ^{137}Cs accumulation is affected not only by soil properties (Table 1): the soil structure in the Alytus district habitat is sandy loam; therefore, the vertical migration of radionuclide ^{137}Cs in this territory is more rapid to the deeper layers of the soil, and the horizontal migration to the vegetable segments is not so active as in the soils having silty loam structure (Šiauliai and Kėdainiai districts), where radionuclides are retained in the surface layer of the soil. Also, the physiological peculiarities of vegetables and their growth rate may be one of the reasons for accumulation; for example, bees growS faster (early variety) than late-

Table 4. ^{137}Cs-specific activities in soil and potato (*Solanum tuberosum L.*) segments.

Segment	Mass of sample, m, 10^{-3} kg	Time of measu-rement, t, s	Specific activity, A_a, Bq/kg	Standard error of activity deter-mination, ΔA, Bq/kg
Šiauliai district (D1)				
D	80.4	343320	2.1	±0.2
BL1	33.8	83155	0.6	±0.1
BL2	51.5	84442	0.5	±0.4
BL3	15.9	76048	0.3	±0.2
Alytus district (D2)				
D	59.7	355360	6.9	±0.4
BL1	33.3	89290	0.8	±0.6
BL2	44.7	88082	0.4	±0.3
BL3	9.5	82757	0.4	± 0.2
Kėdainiai district (D3)				
D	74.2	330540	3.4	±0.4
BL1	33.7	88615	0.7	±0.5
BL2	46.9	81095	0.3	±0.2
BL3	13.7	83992	0.6	±0.4

D-soil, BL1-peel, BL2-inner part, BL3-aboveground part

season carrots, therefore growth and radionuclide transfer to beet segments with nutrient materials was more rapid.

It is seen from Table 4 that ^{137}Cs accumulation in all habitats is highest in the potato peel (BL1) from 0.6±0.1 Bq/kg to 0.8±0.6 Bq/kg, in the middle (BL2) and aboveground (BL3) parts is conditionally equal: 0.3±0.2 – 0.6±0.4 Bq/kg.

Table 5. ^{137}Cs-specific activities in soil and cabbage (*Brassica oleracea L.*) segments.

Segment	Mass of sample, m, 10^{-3} kg	Time of measure-ment, t, s	Specific activity, A_a, Bq/kg	Standard error of activity determination, ΔA, Bq/kg
Alytus district (D2)				
D	59.7	355360	6.9	±0.4
K1	21.2	93512	1.0	±0.5
K2	20.4	81155	0.2	±0.1
K3	11.4	83955	0.4	±0.2
K4	17.6	87822	0.7	±0.6
Kėdainiai district (D3)				
D	74.2	330540	3.4	±0.4
K1	21.2	82403	0.5	±0.3
K2	22.0	89677	0.4	±0.2
K3	10.8	96347	0.4	±0.3
K4	20.2	85745	0.6	±0.3

D-soil, K1-underground part, K2-core, K3-inner leaves, K4-outer leaves

Making an analysis of ^{137}Cs transfer factors to the segments of a tuberous vegetable (Fig. 4), it is seen that the most intensive transfer of this radionuclide is to the potato peel (BL1): 0.12-0.29; less intensive to the inner part of potato (BL2): 0.06-0.24; and lowest to the aboveground part (BL3): 0.05-0.18.

Most active ^{137}Cs accumulation is in the underground part of cabbage (K1) and in the outer leaves (K4): changes respectively from 0.5±0.3 Bq/kg and 1.0±0.5 Bq/kg in the underground part; in outer leaves from 0.6 ±0.3 Bq/kg to

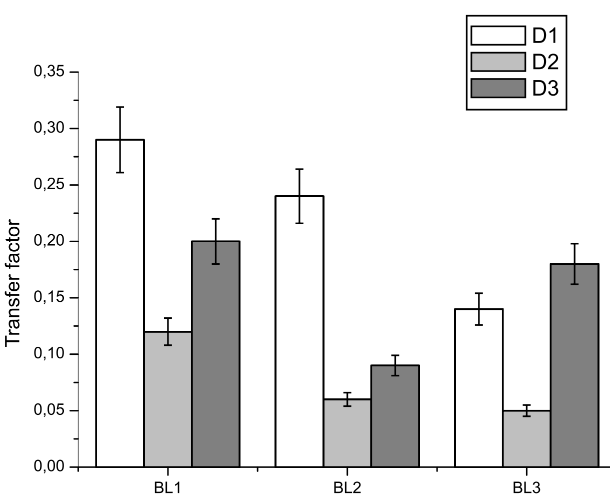

Fig. 4. ^{137}Cs transfer factor from the soil to potato *(Solanum tuberosum L.)* segments: D1-Šiauliai district, D2-Alytus district, D3-Kėdainiai district, BL1-peel, BL2-inner part, BL3- aboveground part.

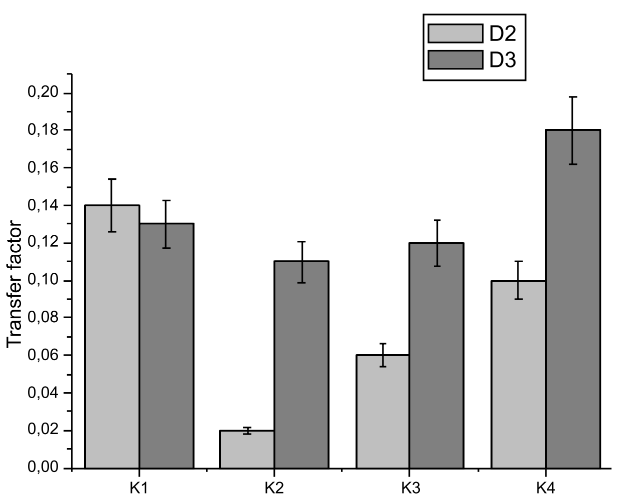

Fig. 5. ^{137}Cs transfer factor from the soil to cabbage *(Brassica oleracea L.)* segments: D2-Alytus district, D3-Kėdainiai district, K1-underground part, K2-core, K3-inner leaves, K4-outer leaves.

Table 6. ^{40}K-specific activities in soil and carrot (*Daucus carrota L.*) segments.

Segment	Mass of sample, m, 10^{-3} kg	Time of measure-ment, t, s	Specific activity, A_a, Bq/kg	Standard error of activity determination, ΔA, Bq/kg
Šiauliai district (D1)				
D	80.4	343320	718	±11
M1	29.9	77653	409	±18
M2	31.6	86590	198	±13
M3	25.8	86361	369	±9
M4	16.1	90452	266	±10
Alytus district (D2)				
D	59.7	355360	418	±8
M1	23.8	84495	464	±20
M2	24.5	84615	262	±13
M3	26.4	88420	229	±16
M4	19.8	87797	296	±19
Kėdainiai district (D3)				
D	74.2	330540	740	±15
M1	34.8	90096	730	±22
M2	33.5	76824	390	±18
M3	34.4	82969	557	±13
M4	15.2	85329	496	±19

D-soil, M1-peel, M2-middle part, M3-core, M4-aboveground part

Table 7. ^{40}K-specific activities in soil and beet (*Beta vulgaris L.*) segments.

Segment	Mass of sample, m, 10^{-3} kg	Time of measure-ment, t, s	Specific activity, A_a, Bq/kg	Standard error of activity determination, ΔA, Bq/kg
Šiauliai district (D1)				
D	80.4	343320	718	±11
B1	35.5	83045	572	±12
B2	36.9	83918	382	±10
B3	53.7	90786	387	±15
B4	19.6	81009	412	±16
Alytus district (D2)				
D	59.7	355360	418	±8
B1	24.6	85144	473	±11
B2	18.3	81617	431	±21
B3	19.4	74062	551	±24
B4	18.7	82498	392	±20
Kėdainiai district (D3)				
D	74.2	330540	740	±15
B1	39.3	84178	640	±22
B2	27.2	85836	490	±11
B3	24.4	99787	567	±19
B4	20.1	83413	710	±17

D-soil, B1-peel, B2-middle part, B3-core, B4-aboveground part

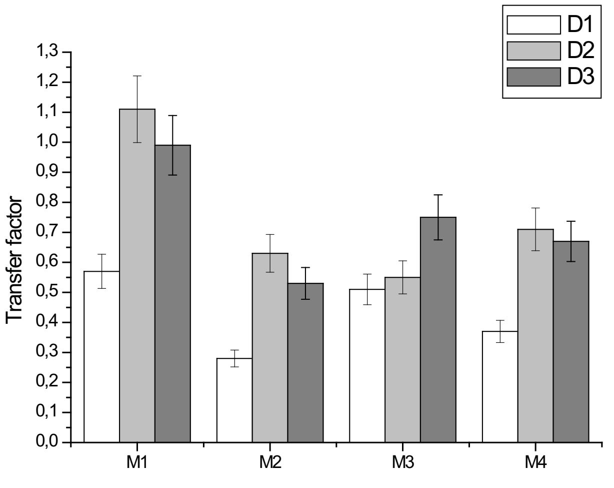

Fig. 6. ^{40}K transfer factor from the soil to carrot *(Daucus carota L.)* segments: D1-Šiauliai district, D2-Alytus district, D3-Kėdainiai district, M1-peel, M2-middle part, M3-core, M4-aboveground part.

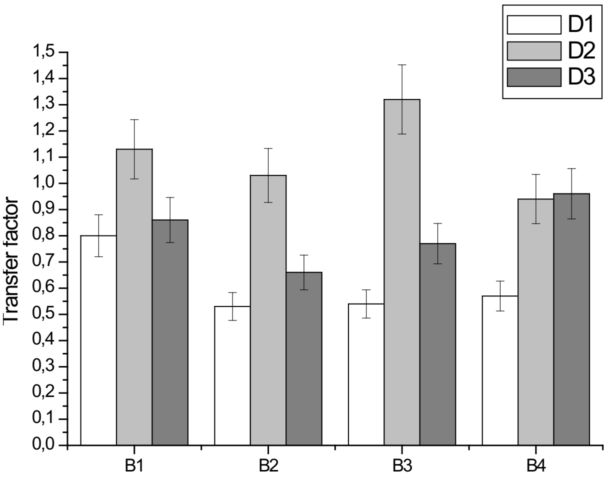

Fig. 7. ^{40}K-transfer factor from the soil to beet *(Beta vulgaris L.)* segments: D1-Šiauliai district, D2-Alytus district, D3-Kėdainiai district, B1-peel, B2-middle part, B3-core, B4-aboveground part.

Table 8. ^{40}K-specific activities in soil and potato (*Solanum tuberosum L.*) segments.

Segment	Mass of sample, m, 10^{-3} kg	Time of measurement, t, s	Specific activity, A_a, Bq/kg	Standard error of activity determination, ΔA, Bq/kg
Šiauliai district (D1)				
D	80.4	343320	718	±11
BL1	33.8	83155	396	±10
BL2	51.5	84442	396	±16
BL3	15.9	76048	98	±10
Alytus district (D2)				
D	59.7	355360	418	±8
BL1	33.3	89290	392	±18
BL2	44.7	88082	392	±19
BL3	9.5	82757	27	±5
Kėdainiai district (D3)				
D	74.2	330540	740	±15
BL1	33.7	88615	404	±18
BL2	46.9	81095	388	±18
BL3	13.7	83992	229	±14

D-soil, BL1-peel, BL2-inner part, BL3-aboveground part

0.7±0.6 Bq/kg. The lowest accumulation is established in the cabbage core (K2), in the Alytus district habitat (D2) 0.2±0.1 Bq/kg.

The highest values of ^{137}Cs transfer factor from the soil to head vegetable (cabbage) segments are determined to

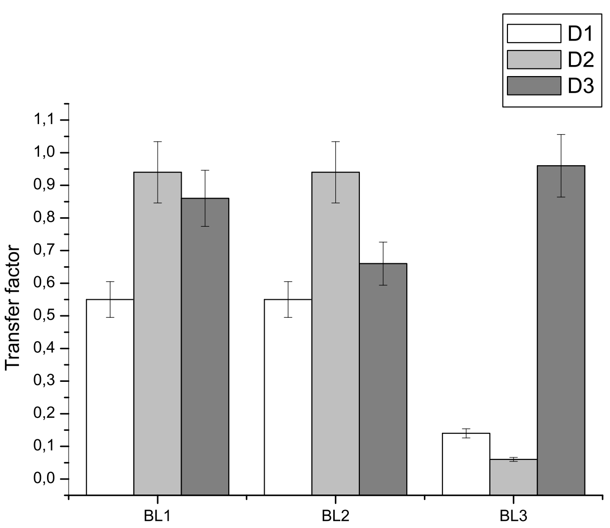

Fig. 8. ^{40}K transfer factor from the soil to potato *(Solanum tuberosum L.)* segments: D1-Šiauliai district, D2-Alytus district, D3-Kėdainiai district, BL1-peel, BL2-inner part, BL3- aboveground part.

the underground part (K1) and outer leaves (K4): from 0.13 to 0.14 and from 0.10 to 0.18. The lowest transfer factor to the cabbage core (K2) is 0.2-0.11.

Evaluating the values of ^{137}Cs transfer factor in Figs. 1-4, it is possible to assert that artificial radionuclide accumulation in all vegetable segments is very low, since the transfer factor values do not exceed the unity. When transfer factor is equal to 0.1÷1, it is maintained that the radionuclide has a tendency to low accumulation or no accumulation at all [22]. It was noted that vegetable segments accumulated the radioactive ^{137}Cs element to a certain limit, independent of the soil contamination level. The emergence of the accumulation limit may be predetermined by the vegetable vegetation time and maturity period, within which the most active assimilation of nutrients also including radioactive materials from the soil occurs, and individual physiology of vegetables.

^{40}K-specific activities in the soil (Tables 6-9) vary from 418±8 to 740±15 Bq/kg. In the soil samples (D1 and D3) with a silty loam structure (Table 1) the concentration of ^{40}K activities is higher than in the sandy soil (D2).

In all habitats the accumulation of radioactive ^{40}K in carrot segments (M1, M2 and M3) takes place analogically (Table 6): the highest specific activity is determined in the peel (M1) (409±18 – 730±22 Bq/kg), medium in the core (M3) (229±16 – 557v13 Bq/kg), and lowest in the middle part of carrot (M2) – (198v13 – 390v18 Bq/kg).

Natural radionuclide ^{40}K is transferred best to the carrot peel (M1), transfer factor in this segment fluctuates from 0.57 to 1.11. The lowest transfer of ^{40}K occurs in the middle part of carrot (M2) – from 0.28 to 0.63.

In the Šiauliai district habitat (D1) ^{40}K-specific activity value is highest in the beet peel (B1) – 572±12 Bq/kg, in other segments (B2, B3 and B4) the radionuclide activity concentration is distributed rather evenly.

From the data provided in Table 7 it is seen that beet segments grown in the Alytus district habitat (D2), when soil contamination reaches 418±8 Bq/kg, assimilate maximum ^{40}K activity concentration from 392±20 Bq/kg to 551±24 Bq/kg. In the Kėdainiai district habitat (D3) ^{40}K highest specific activity values are measured in B1, B3, and B4 segments: from 567±19 Bg/kg to 710±17 Bq/kg, and lowest ^{40}K specific activity value is in the beet middle part (B2) – 490±11 Bq/kg.

^{40}K to beet segments is transferred more evenly than to carrot segments. A somewhat higher transfer factor was determined only to the beet peel (B1) in all habitats from 0.80 to 1.13. The Alytus district habitat (D2) is distinguished by very intensive ^{40}K transfer to all beet segments: transfer factor in this habitat varied from 0.94 to 1.32.

After investigation of ^{40}K-specific activity in potato segments (Table 8), it was identified that irrespective of different habitat soil contamination, radioactive ^{40}K gets accumulated conditionally equally in the peel (BL1) and inner potato part (BL2) – fluctuates from 388±18 Bq/kg to 404±18 Bq/kg. In the aboveground parts (BL3) the radionuclide specific activity in the Šiauliai district (D1) and Alytus district (D2) habitats is lowest at 27±7 – 98±10 Bq/kg, and accumulation intensity depends on the

Table 9. ^{40}K-specific activities in soil and cabbage (*Brassica oleracea L.*) segments.

Segment	Mass of sample, m, 10^{-3} kg	Time of measurement, t, s	Specific activity, A_a, Bq/kg	Standard error of activity determination, ΔA, Bq/kg
Alytus district (D2)				
D	59.7	355360	418	±8
K1	21.2	93512	160	±19
K2	20.4	81155	487	±12
K3	11.4	83955	215	±19
K4	17.6	87822	276	±19
Kėdainiai district (D3)				
D	74.2	330540	740	±15
K1	21.2	82403	373	±13
K2	22.0	89677	446	±11
K3	10.8	96347	175	±13
K4	20.2	85745	400	±13

D-soil, K1-underground part, K2-core, K3-inner leaves, K4-outer leaves

contamination of habitat soils – specific activities in the aboveground part (BL3) are proportionate to the measured soil (D) specific activities in the habitats (D1 and D2).

The highest ^{40}K transfer is determined on the potato peel (BL1) and inner part (BL2) – transfer factor values vary from 0.52 to 0.94 (Fig. 8). The lowest amount of ^{40}K is transferred from the soil to the aboveground potato part (BL3) in the Šiauliai district (D1) and Alytus district (D2) habitats: transfer factor values to this segment are, respectively, 0.14 and 0.06. Maximum transfer factor 0.96 is established in the aboveground part of potatoes (BL3), grown in the Kėdainiai district habitat (D3). This tendency may be related to atmospheric transfers, i.e. radioactive ^{40}K to the potato aboveground part enters with precipitation or with soil dust transferred by the wind.

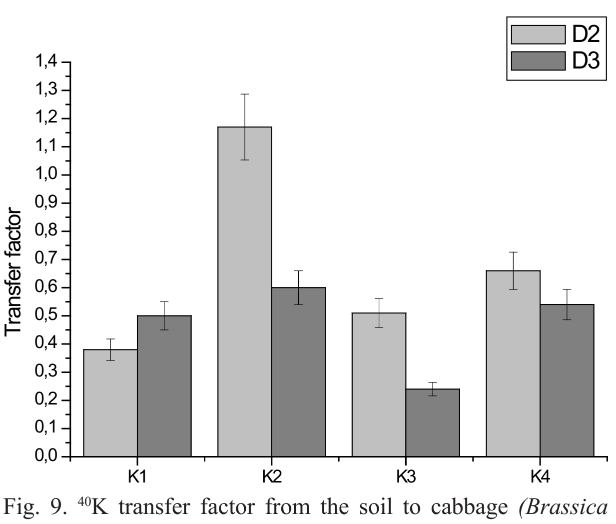

Fig. 9. ^{40}K transfer factor from the soil to cabbage *(Brassica oleracea L.)* segments: D2-Alytus district, D3-Kėdainiai district, K1-underground part, K2-core, K3-inner leaves, K4-outer leaves.

^{40}K-specific activities (Table 9) are highest in the cabbage core (K2): 487±12 – 446±11 Bq/kg, lowest in the inner leaves (K3): 215±19 – 175±13 Bq/kg.

Radionuclide accumulation unevenness is observed in the Kėdainiai district (D3) habitat: when Alytus district (D2) habitat soil contamination is 418±8 Bq/kg, ^{40}K maximum amount 487±12 Bq/kg gets accumulated in the cabbage core (K2). In the Kėdainiai district (D3) habitat, the specific activity 446±11 Bq/kg is in the cabbage core, where soil contamination is 740±15 Bq/kg. One of the possible reasons may be the different soil structure (Table 1) – ^{40}K migrates more rapidly to the cabbage segments in the Alytus district habitat (D2), since sand fraction prevails in the soil of this habitat. Whereas, due to the soil in the Kėdainiai district habitat (D3) having silty loam structure, ^{40}K transfer to the cabbage segments is lower.

Natural radionuclide ^{40}K is transferred mostly to the core (K2), where transfer factor to this segment is 0.60-1.17 and outer leaves (M4) 0.54 and 0.66. The lowest ^{40}K transfer factor values are established to the underground part of cabbage (K1) and to inner leaves (K3) – the average value of the transfer factor to those segments is 0.41.

In evaluating ^{137}Cs and ^{40}K transfer factors in Figs. 2-9, it is possible to state that natural radionuclide ^{40}K accumulation in some vegetable segments under study is almost three times more intensive than that of artificial radionuclide ^{137}Cs. The literature mentions the same results were found in peat and saw sedge – potassium is absorbed at about a three-times-higher rate than cesium by the plant [32].

Results of the Discrimination Factor Values in the Soil-Vegetable Segments System

Results of identification of ^{137}Cs discrimination factor values for radioactive transfer from the soil to carrot, beet, potato and cabbage segments in D1, D2, and D3 habitats are provided in Tables 10-13.

^{137}Cs discrimination factor values were determined by means of Formula 3, presented in the section of methodics.

After calculations, it was established that discrimination factor in the peel (M1) and the middle part (M2) of carrots grown in the Šiauliai district (D1) habitat has the highest values, 0.69 and 0.86. In this habitat, ^{40}K impact on artificial radionuclide ^{137}Cs transfer is lowest. In the Alytus district habitat (D2), ^{137}Cs discrimination factor in carrot segments, as compared to the Šiauliai district (D1) habitat discrimination factor values, is low, respectively, 0.12 (M1) and 0.09 (M2).

Results provided in Table 11 show that the highest ^{137}Cs discrimination factor is established in the aboveground part of beet (B4): 0.66 (D1 habitat) and the lowest in the Alytus district habitat: in the peel (B1) and middle part (B2) – 0.01.

Table 10. ^{137}Cs discrimination factor for transfer from the soil to carrot *(Daucus carota L.)* segments.

Habitat/ Segment	M1	M2	M3	M4
D1	0.69±0.10	0.86±0.12	0.17±0.02	0.66±0.09
D2	0.12±0.02	0.09±0.01	0.19±0.03	0.15±0.02
D3	0.65±0.09	0.50±0.07	0.15±0.02	0.30 ±0.04

D1-Šiauliai district, D2-Alytus district, D3-Kėdainiai district, M1-peel, M2-middle part, M3-core, M4-aboveground part

Table 11. ^{137}Cs discrimination factor for transfer from the soil to beet *(Beta vulgaris L.)* segments.

Habitat/ Segment	B1	B2	B3	B4
D1	0.17±0.02	0.17±0.02	0.07±0.02	0.66±0.09
D2	0.01±0.00	0.01±0.00	0.01±0.00	0.12±0.02
D3	0.02±0.00	0.17±0.02	0.02±0.00	0.17±0.02

D1-Šiauliai district, D2-Alytus district, D3-Kėdainiai district, B1-peel, B2-middle part, B3-core, B4-aboveground part

Table 12. ^{137}Cs discrimination factor for transfer from the soil to potato *(Solanum tuberosum L.)* segments.

Habitat/ Segment	**BL1**	**BL2**	**BL3**
D1	0.52±0.07	0.45±0.06	1.07±0.15
D2	0.12±0.02	0.06 ±0.01	0.90±0.13
D3	0.37±0.02	0.17±0.02	0.57±0.08

D1-Šiauliai district, D2-Alytus district, D3-Kėdainiai district, BL1-peel, BL2-inner part, BL3-aboveground part

Table 13. ^{137}Cs discrimination factor for transfer from the soil to cabbage *(Brassica oleracea L.)* segments.

Habitat/ Segment	K1	K2	K3	K4
D2	0.38±0.05	0.02±0.00	0.12±0.02	0.15±0.02
D3	0.28±0.04	0.20±0.03	0.50 ±0.07	0.33±0.05

D2-Alytus district, D3-Kėdainiai district, K1-underground part, K2-core, K3-inner leaves, K4-outer leaves

In the Kėdainiai district habitat (D3) the average discrimination factor value 0.1739 is established in the middle (B2) and aboveground parts (B4) of beet (Table 11).

In the aboveground part of potato (BL3), in the Šiauliai district (D1) habitat, the highest discrimination factor value is 1.07, lowest from 0.06 to 0.45 in the inner part of potato (BL2) in all habitats.

The discrimination factor values given in Table 13 show that ^{40}K impact on ^{137}Cs transfer is lowest in the Alytus district habitat (D2), to the underground cabbage part (K1): ^{137}Cs discrimination factor 0.38, and in the Kėdainiai district habitat (D3), to outer leaves (K4): ^{137}Cs discrimination factor 0.33. The lowest discrimination factor value is identified in the cabbage core (K2) and inner (K3) leaves, in the Alytus district habitat (D2), respectively 0.02 and 0.12.

Conclusions

The soil with sandy loam structure (D2) and $1.15 \cdot 10^3$ kg/m^3 density allows moisture to permeate well, but due to the amount of organic matter (12.8% humus), precipitation is retained in the surface layer of the soil (22.0%). The denser ($1.43 \cdot 10^3$-$1.55 \cdot 10^3$ kg/m^3) silty loam soils (D1 and D3) are distinguished by low moisture (11.8%-14.1%) and a small amount of organic matter 7.9% and 6.1%.

The measured ^{137}Cs- and ^{40}K-specific activities in the soil samples of the habitats under study fluctuate: ^{137}Cs from 2.1±0.2 to 6.9±0.4 (Bq/kg); ^{40}K from 418±8 to 740±15 (Bq/kg).

^{137}Cs accumulation is highest in the carrot peel (M1): transfer factor to this segment varies from 0.13 to 0.39 and ^{40}K from 0.57 to 1.11. In the middle part (M2) the lowest ^{40}K transfer factor from 0.28 to 0.53 was determined. In the core (M3) ^{137}Cs accumulation is lowest: transfer factor values fluctuate from 0.09 to 0.12.

In the beet peel (B1) ^{40}K accumulation is highest (TF = 0.80±1.13), and ^{137}Cs is lowest (average value of transfer factor 0.09). In the middle part (B2) the lowest accumulation of ^{40}K (TF = 0.28±0.53) is identified, and in the core (B3) and the aboveground part (B4) ^{137}C accumulation is highest (TF = 0.12±0.29 and (TF = 0.10±0.37).

In the potato peel (BL1) ^{137}Cs (TF = 0.12±0.29) and ^{40}K (TF = 0.55±0.94) accumulation is highest. In the middle part (BL2) ^{40}K (TF = 0.52v0.94) accumulation is highest, ^{137}Cs is lowest (TF = 0.06±0.24). In the aboveground part (BL3) ^{137}Cs accumulation is lowest (transfer factor value in this segment is 0.05±0.18) and ^{40}K (TF = 0.06±0.14) in two districts – D1 and D2.

In the cabbage core (K2) ^{40}K accumulation is highest (TF = 0.60±1.17), and ^{137}Cs is lowest (minimum TF value 0.02). In the inner leaves (K3) ^{40}K accumulation is lowest (TF = 0.24±0.51). In the outer leaves (K4) ^{137}Cs accumulation is highest (TF = 0.10±0.18).

The maximum value of discrimination factor 1.07 is established in the aboveground part of potato (BL3). In this segment the ^{40}K impact on the transfer of artificial radionuclide ^{137}Cs is lowest. The minimum value of discrimination factor is determined in the beet peel (B1) and in the middle part (B2) – 0.01. The ^{40}K impact on the transfer of artificial radionuclide ^{137}Cs to these segments is highest.

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