^{90}Sr and ^{137}Cs Accumulation in Plants in the Area of Radiation Accidents

N. N. Kazachonok and I. Y. Popova

Abstract An investigation of radioactive contamination of soil, crops, vegetables, feed, grass of hayfields and pastures, wild berries, and mushrooms as a result of radioactive contamination due to operation of radiochemical plant, Production Association (PA) "Mayak," was carried out on the territory of northeastern part of Chelyabinsk region in 2006–2012. ^{90}Sr and ^{137}Cs content in the agricultural products and wild mushrooms in the whole territory of 30–35 km from PA "Mayak" did not exceed maximum permissible level and was not dangerous for the population. ^{90}Sr accumulation in wild berries and grass of hayfield and pastures on the territory of East-Ural radioactive trace did not exceed the radiological sanitary limits which could be dangerous for the population and farm animals. On the rest of the territory, both berries and grass were non-contaminated. The accumulation coefficients of ^{90}Sr and ^{137}Cs in agricultural products and wild plants and mushrooms vary significantly. The highest values of the accumulation coefficients, sometimes >1, were found for grass of hayfields and pastures. Among agricultural plants, the highest values of the accumulation coefficients were found for carrot, Sudan grass, and corn, whereas the lowest values were found for cabbage, beetroot, and potato. The accumulation coefficients of the radionuclides found for vegetables from private farmers were lower than the ones from large agricultural plant. A content of ^{90}Sr and ^{137}Cs in soil in an easy accessible form for the plants depends on the soil humidity and may vary significantly. ^{90}Sr deposited in soil is transferred into soil solution as ionic species. ^{137}Cs in soil solution is present as colloidal species.

Keywords Radioactive contamination · East-Ural radioactive trace · Strontium-90 · Cesium-137 · Soil · Grass · Vegetables · Agricultural goods · Accumulation coefficient

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N. N. Kazachonok (✉) · I. Y. Popova
Urals Research Center for Radiation Medicine, 68 A, Vorovskoho Street,
454076 Chelyabinsk, Russia
e-mail: kazachenok.nina@mail.ru

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Contents

1 Introduction

The forecasting of entry of radioactive isotopes into the products of agriculture and forestry in the areas affected by radioactive contamination is an important and urgent problem. Despite increased security measures at nuclear power plants and radiochemical enterprises, radiation accidents accompanied by the release of radioactive substances into the environment are regularly happening on the planet. The study of radionuclides entry into the plants in 50–60 years after the fallout of radioactive substances on the soil surface is necessary for a long-term forecasting of radiation risks for people and the environment.

2 Materials and Methods

The researches have been conducted in 2006–2012 in the territory of northeastern part of Chelyabinsk region that suffered from radioactive contamination caused by the activity of radiochemical industrial complex of the Production Association "Mayak." The specific activity of ^{137}Cs in the soil samples was measured by means of scintillation gamma-ray spectrometer with the software "Progress." From 2011, the spectrometer facility MKC-01A "MULTIRAD" was used for this purpose. In the low-activity soil samples and in the plant ash, ^{137}Cs level was measured using the radiochemical iodine–antimony method after concentrating it on the nickel ferrocyanide. The specific activity of ^{90}Sr in the samples was measured by means of the extractive method based on daughter ^{90}Y using monoisooctylmethylphosphonate. The ß-activity of the selected radionuclides was measured using low-background radiometric facilities UMF-1500 and UMF-2000 with flame-photometric control of strontium carrier yield. All applied methods and measuring means have state calibration certificates.

3 Results and Discussion

Accumulation of ^{90}Sr and ^{137}Cs in the cereal crops and vegetable harvests under the conditions of a large agricultural enterprise. The ability of plants to accumulate radioactive substances is shown by the proportionality coefficients (C_p) between the soil contamination level and the level of contamination of agricultures. Also used are the transport coefficient (C_t)—the ratio of the radionuclide-specific activity in the marketable part of the harvest to the soil contamination density—and the accumulation coefficient (C_a)—the ratio of the radionuclide-specific activity in the marketable part of the harvest to the specific activity of the radionuclide in soil. These coefficients and their dependence on various factors are studied by many researchers.

We conducted research in 2007 in the territory of the agricultural enterprise «Sovkhoz Beregovoy» LLC. The territory of this enterprise was situated in the middle part of the East-Ural radioactive trace (EURT) that resulted from the explosion of a waste tank of the Production Association "Mayak" in 1957. The nearest settlements are Beregovoy, Karabolka, and Bulzi. The soil on which the "Sovkhoz Beregovoy" LLC is situated was formed as a gray forest medium to heavy loamy soil. The soil was treated for many years, its agrochemical properties have changed, and the humus horizon was exhausted in some places. Nevertheless, at that stage of the study when calculating the contamination density, we viewed it as a gray forest heavy loamy soil.

In all sampling points, the density of contamination with ^{137}Cs and ^{90}Sr exceeds the level determined by global fallouts. The average density of contamination with ^{137}Cs of a 0- to 40-cm soil layer from eastern irrigated field with vegetable rotation is 6.3 ± 1.1 kBq^{-1} m^2 and with ^{90}Sr is 8.1 ± 1.5 kBq^{-1} m^2. The contamination with ^{90}Sr of a 0–40 cm soil layer from the southern part of the farm is 7.4 ± 1.8 k Bq^{-1} m^2, and the contamination of a 0–20 cm soil layer with ^{137}Cs is 4.4 ± 1.8 kBq^{-1} m^2. The contamination of a 0–40 cm soil layer from the northern part with ^{137}Cs is 10.4 ± 1.8 kBq^{-1} m^2 and with ^{90}Sr is 45.9 ± 14.1 kBq^{-1} m^2. The highest contamination with ^{90}Sr (111.5 ± 28.9 kBq^{-1} m^2) is observed between 6 and 10 km from the Beregovoy village, where goes the axis of EURT.

The specific activity of samples of agricultural products fluctuated widely. The least contaminated were cabbage, beets, and potatoes. And the specific activity of ^{90}Sr and ^{137}Cs did not exceed 1 Bq kg^{-1}. The maximum permissible level of ^{137}Cs in vegetables is 120 Bq kg^{-1} and ^{90}Sr is 40 Bq kg^{-1} (SanPiN2.2.2.1078-01). This is due to a small contamination of soil in the eastern part and low values of C_a. The accumulation coefficients are shown in the Table 1. C_a of cereal crops is a little higher; in addition, some samples were taken in areas with a high contamination density. Therefore, the specific activity of ^{37}Cs in grain ranged from 0.05 to 3.42 Bq kg^{-1} and that of ^{90}Sr ranged from 0.45 to 28.1 Bq kg^{-1}. The maximum permissible level of ^{137}Cs in the food grain is 70 Bq kg^{-1}, and the maximum permissible level of ^{90}Sr in the food grain is 40 Bq kg^{-1} (SanPiN2.2.2.1078-01). The greatest values of C_a were observed in carrots, Sudan grass, and corn.

Table 1 Average values of C_a ^{137}Cs and ^{90}Sr in commodity part of crops for a layer of 0–20 cm of the gray forest soil

Culture	Production	Grade	C_a	
			^{137}Cs	^{90}Sr
Peas	Grain	Agrointel	0.062 ± 0.035	0.084 ± 0.029
Wheat	Grain	Duet	0.078 ± 0.052	0.036 ± 0.011
Oats	Grain	Orion	0.032 ± 0.016	0.054 ± 0.025
Barley	Grain	Omsk-90	0.039 ± 0.032	0.070 ± 0.050
Onions	–	–	0.016 ± 0.008	0.026 ± 0.009
Cabbage	Head of cabbage	Surprise	0.019 ± 0.008	0.029 ± 0.005
Carrots	Root crop	Samson	0.146 ± 0.187	0.237 ± 0.251
Beet	Root crop	Boro	0.016 ± 0.008	0.026 ± 0.007
Potatoes	Tubers	Nevsky	0.008 ± 0.003	0.020 ± 0.012
Corn	Grass	Ekaterina	0.049 ± 0.040	0.242 ± 0.186
Sudan grass	Grass	Kamyshlovskaya	0.083 ± 0.035	0.175 ± 0.054

However, these cultures were not grown on the most contaminated territories in the year when the study was conducted, so their specific activity did not exceed the maximum permissible level and ranged in carrots from 0.18 to 4.86 Bq kg^{-1} for ^{137}Cs and from 0.4 to 5.77 Bq kg^{-1} for ^{90}Sr, and in silage cultures from 0.54 to 3.2 Bq kg^{-1} for ^{137}Cs and from 1.2 to 21.8 Bq kg^{-1} for ^{90}Sr. Although in the year when the study was conducted, the permissible levels of radionuclides were not exceeded, we cannot say with certainty that contamination could not be greater in other weather conditions. Therefore, it required an annual radiological control of products grown in the territory of the northern part and in the area of the middle part of the road Bulzi–Beregovoy.

It is considered that as far as radionuclides change into bound forms that are less available to plants, their C_p decrease on the average. Thus, during the first year after the formation of EURT, C_t for potatoes (in Bq kg^{-1}/37 kBq^{-1} m^2) was 6.7 (according to our calculations, this corresponds approximately to C_a—0.044). In 1961–1962, C_t for grain was 9.3 (corresponds to C_a—0.060), for potatoes—6.7 (corresponds to C_a—0.044), for cabbage—11 (corresponds to C_a—0.071), for carrots—7.4 (corresponds to C_a—0.048), and for onions—8.4 (corresponds to C_a—0.054). During 1965–1967, according to different authors, C_t for grain was 6.7 (corresponds to C_a—0.044), for potatoes—0.6 (corresponds to C_a—0.004) and 1.0 (corresponds to C_a—0.006), for cabbage—8.9 (corresponds to C_a—0.058), for onions—15 (corresponds to C_a—0.097), and for carrots—17.4 (corresponds to C_a—0.113). In 1997, C_t for potatoes were 1.5 (corresponds to C_a—0.010) EMCRA (2001).

In 1999, in the Guidelines for agro-industry and forestry in the sanitary protection zone of the East-Ural radioactive trace were given summaries of the planned accumulation of ^{90}Sr in products that correspond according to our calculations in gray forest soils to the following C_a: wheat—0.038, barley—0.029, oats—0.036, corn (herbage)—0.408, potatoes—0.04, beets—0.062, and cabbage—0.060 (The guide to conducting agro-industrial production and forestry in the territory of a sanitary protection zone East Ural radioactive trace/Chelyabinsk: Administrator. Chernobyl Region 1999).

As can be seen from Table 1, the values of C_a for oats and barley that we obtained in 2007 were higher than values according to the summary data of 1999; for other cultures, they were lower. However, it must be considered that the assortment of agricultures is constantly changing and that even for the same cultivar in the same field at different sampling points, C_a and C_t can vary greatly.

Species and cultivars of agricultural plants vary in their ability to absorb ions selectively. Studies show that varietal differences in the accumulation of ^{137}Cs between the cultivars of cereal crops and pulses reach three times (Malikov et al. 1981). In the study of the ability to accumulate ^{90}Sr of 54 wheat cultivars, the intervarietal differences in two years amounted to 2.9 and 3.9 times (Korneeva et al. 1976). Four years after the Chernobyl accident were published the data that, when the cultivars of cereals were properly selected, the amount of ^{137}Cs in the harvest from the contaminated soils decreased by two to six times and in potatoes, by 13 times (Aleksakhin et al. 1990), whereas C_t are not the same on different soil types, so in 1965–1967, they ranged for grain (in Bq kg^{-1}/37 kBq^{-1} m^{-2}) from 7.4 (on leached black earth) to 13 on the gray forest soil and 18.5 on the soddy-podzolic soil (EMCRA 2001).

The availability of radionuclides to plants is influenced by their distribution in the soil profile and the agrochemical soil properties. In 1986–1990, in the territory of Russia after the Chernobyl accident were taken protective measures in order to reduce the content of ^{137}Cs in plant products (liming of acid soils, use of higher doses of phosphorus–potassium fertilizers). As a result, the contamination of grain and potatoes decreased by 1990 by 20–30 times. [The atlas of modern and expected aspects of consequences of the Chernobyl accident in affected territories of Russia and Belarus (ASPA Russia-Belarus, Moscow-Minsk 2009)].

This diversity is especially expressed in the samples in which specific activity is comparable with the level of sensitivity of the method of radiochemical analysis. Therefore, we cannot say with certainty that in the territory of EURT, C_p continue to decrease in the remote period after the accident.

3.1 *Accumulation of ^{90}Sr and ^{137}Cs in the Harvest of Vegetables from Private Farms*

In the private farms, the conditions of entry of radionuclides into plants vary significantly. The farmers usually do not follow the rules of agricultural machinery, use manual labor, and bring into the soil a small amount of mineral fertilizers. As an organic fertilizer, the farmers use manure from animals fed with contaminated feed. In addition in the farms are not usually grown purebred and revitalized plants. Therefore, the content of radionuclides in vegetables from private farms may be different than the content of radionuclides in vegetables from large agricultural enterprises.

For example, in the Bryansk region, after the Chernobyl accident, as a rule, the levels of contamination of products produced on private farms is 1.5–2.0 times higher than in the collective farms. [The atlas of modern and expected aspects of consequences of the Chernobyl accident in affected territories of Russia and Belarus (ASPA Russia-Belarus, Moscow-Minsk 2009).]

For assessing the contamination of settlements in the zone of influence of PA "Mayak" in 2009–2011 were taken samples of garden soil, potatoes, and other vegetables.

During the study period, 83 samples of garden soil were taken. Table 2 presents the average values of specific activity of radionuclides in the soil from different settlements. There is a significant inverse correlation of the average specific activity of ^{137}Cs in the soil of 36 settlements with distance from the source of contamination—$r = -0.43$ ($p < 0.01$). For the activity of ^{90}Sr, the correlation with the distance is not statistically significant and positive $r = 0.29$. This is due to the fact that the most contaminated with ^{90}Sr is the soil in the settlements that are close to the territory of EURT—Karabolka and Allaki and located at a distance of 38–39 km from the source of contamination. The highest coefficient of inverse correlation was obtained between the activity of ^{137}Cs in the soil and the angle of deviation from the southeast direction (azimuth 136°), $r = -0.49$ ($p < 0.01$). For ^{90}Sr, the direction for which the strongest connection was detected corresponds to the direction of axis of EURT (azimuth 30°), $r = -0.34$ ($p < 0.05$).

It should be noted that the levels of soil contamination with radionuclides within one settlement can vary greatly. Apparently, this is connected with a multiyear application of manure produced by cows fed with contaminated hay. So, in the settlement Karabolka on the household plot under the address Shkolnaya Street, 20, the activity of ^{90}Sr in the hay was 56.1 Bq kg^{-1} and in the soil, it was 279 Bq kg^{-1}. On a plot under the address Shkolnaya Street, 11-1, the activity of ^{90}Sr in a sample of hay taken in April 2011 was 2,524 Bq kg^{-1} and in the sample taken in June 2011, it was 1,709 Bq kg^{-1}. In five soil samples taken from this plot using the envelope method, the activity of ^{90}Sr varied from 239 to 820 Bq kg^{-1}. On the neighboring plot under the address Shkolnaya Street, 26, located across the road, are no cows at the moment. The activity of ^{90}Sr in the soil is here 134 Bq kg^{-1}.

We can conclude from the results of tests conducted by Urals Research Center for Radiation Medicine earlier that usually about 10 % of the samples of garden soil, potatoes, vegetables, and other products produced in the personal household plots in the studied area are very different in content of radionuclides. The reason for this is that some owners violate the regime of EURT protection zone.

Therefore, for a rough estimation of the radiation situation in the whole territory, we calculated the average values for 90 % of the samples with the lowest values of radionuclide activity.

The average activity of ^{137}Cs in 90 % of the soil samples was 58 Bq kg^{-1}, and the maximum activity was 193 Bq kg^{-1} (in the settlement Kyzylbulyak). The

Table 2 Specific activity and C_a ^{137}Cs and ^{90}Sr in the soil and potatoes on the average on settlements in 2009–2011

Settlement	Soil Bq kg^{-1}		Potatoes Bq kg^{-1}		C_a	
	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
Allaki	38.1	198.9	0.36	0.78	0.0094	0.0039
Argayash	47	24.2	0.39	0.2	0.0083	0.0083
Ayazgulova	103.7	40.6	0.52	0.33	0.0050	0.0081
Bizhelyak	111	66	0.97	0.96	0.0087	0.0145
Bolshoe Taskino	98.2	46.8	0.64	0.28	0.0065	0.0060
Bolshoi Kuyash	124	43.3	0.53	0.58	0.0043	0.0134
Gornii	83	24.6	0.41	0.35	0.0049	0.0142
Ibragimova	61	35.7	0.59	0.38	0.0097	0.0106
Karabolka	34.6	423.4	0.64	1.11	0.0185	0.0026
Karagaykul	46.3	43.7	1.33	0.3	0.0287	0.0069
Kasli	32.8	99.8	0.46	0.38	0.0140	0.0038
Komsomolskii	38.5	36.5	0.28	0.12	0.0073	0.0033
Krasnii Partisan	42	76.2	0.37	0.51	0.0088	0.0067
Kuvalzhikha	42.7	23.3	0.25	0.29	0.0059	0.0124
Kuvalzhikha	29	4.9	0.31	–	0.0107	–
Kuznechikha	31.4	26.8	0.68	0.09	0.0217	0.0034
Kurmanova	27.5	20.4	0.19	0.12	0.0069	0.0059
Kyzylbulyak	193	136.9	0.44	0.91	0.0023	0.0066
Kyshtym	36	28.8	0.87	0.22	0.0242	0.0076
Malii Kunashak	75	77.5	0.90	0.44	0.0120	0.0057
Mauk	26	29.2	0.36	0.24	0.0138	0.0082
Novogornii	90	48.6	0.69	0.63	0.0077	0.0130
Novaya Soboleva	33.8	19	0.26	0.15	0.0077	0.0079
Sarykulmyak	109.3	70.7	0.29	0.52	0.0027	0.0074
Severnii	25.4	36.6	0.84	0.28	0.0331	0.0077
Selezni	158.5	86.4	0.55	0.21	0.0035	0.0024
Slyudorudnik	29.6	36.5	0.47	0.22	0.0159	0.0060
Suleymanova	159.7	74.5	0.59	0.39	0.0037	0.0052
Syrgaydi	39	24	0.41	0.14	0.0105	0.0058
Tayginka	57.9	57.4	1.11	0.67	0.0192	0.0117
Tatysh	131	71.2	0.79	0.82	0.0060	0.0115
Tyubuk	18.2	63.2	0.26	0.39	0.0143	0.0062
Uvildi	33.2	29.4	1.00	0.35	0.0301	0.0119
Hudayberdinsky	147.2	92.1	0.58	0.38	0.0039	0.0041

average activity of ^{90}Sr was 44.4 Bq kg^{-1}; the maximum activity of ^{90}Sr was 820 Bq kg^{-1} (in the settlement Karabolka).

During the study period were selected 95 samples of potatoes. The average activity of ^{137}Cs in 90 % of the samples was 0.44 Bq kg^{-1}, and the maximum activity was 2.43 Bq kg^{-1}. The average activity of ^{90}Sr in 90 % of samples was 0.34 Bq kg^{-1}, and the maximum activity was 4.12 Bq kg^{-1}. In all samples of potatoes, the content of ^{137}Cs and ^{90}Sr is significantly lower than the maximum

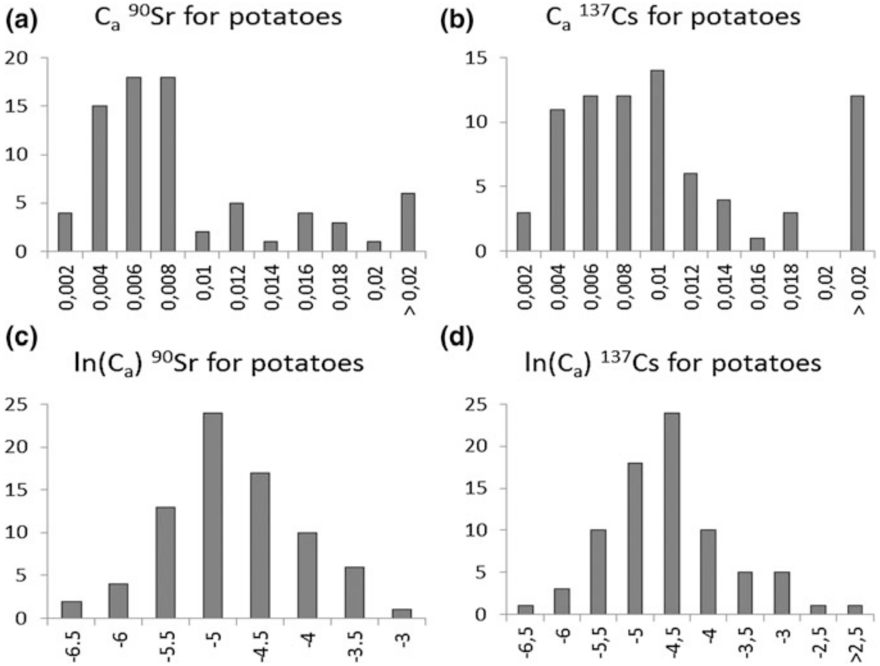

Fig. 1 **a** The histogram of distribution of C_a ^{90}Sr for potatoes. **b** The histogram of distribution of C_a ^{137}Cs for potatoes. **c** The histogram of distribution of ln(C_a) ^{90}Sr for potatoes. **d** The histogram of distribution of ln(C_a) ^{137}Cs for potatoes

permissible levels (in potatoes and vegetables, MPL of ^{137}Cs is 80 Bq kg^{-1} and MPL of ^{90}Sr is 40 Bq kg^{-1}, SanPiN 2.3.2.1078-01). Specific activities of ^{137}Cs and ^{90}Sr in potatoes are not connected—$r = -0.04$.

For all pairs of samples "soil—potatoes" were calculated accumulation for coefficients. The ability of potatoes to accumulate ^{137}Cs from soil (C_a) does not correlate with the ability to accumulate ^{90}Sr—$r = -0.009$.

The ranges of fluctuations of C_a ^{90}Sr and C_a ^{137}Cs are very large. Figure 1a, b shows histograms of distribution of radionuclides C_a in potatoes.

The histograms illustrate that the values of C_a of ^{90}Sr and ^{137}Cs in potatoes from different household plots in the zone of influence of PA "Mayak" can vary considerably. Furthermore, the distribution of C_a is not normal. As can be seen from the Fig. 1c and d, the lognormal distribution suits better for statistical processing of data about C_a. However, as mentioned above, the violation of the protection zone regime by some owners complicates the statistical analysis. In our opinion, the most promising in this case is the application of the principles of fuzzy logic (Kazachonok 2013), but a correct development of the analysis method requires a large amount of experimental data.

Table 2 presents the average values of specific activity of radionuclides in potatoes from different settlements and the values of their C_a.

As can be seen from Table 2, C_a ^{137}Cs in potatoes in private farms were similar to C_a ^{137}Cs in «Sovkhoz Beregovoy» LLC. C_a ^{90}Sr in private farms appeared to be several times lower. As exactly ^{90}Sr poses the greatest danger in the territory of EURT, this difference requires further study.

We also analyzed 14 samples of carrots and 12 samples of beets. The average specific activity of ^{137}Cs in 90 % of the carrots samples was 0.59 Bq kg^{-1}, and the maximum activity of ^{137}Cs in carrots was 3.9 Bq kg^{-1}. The average specific activity of ^{137}Cs in 90 % of the beets samples was 0.35 Bq kg^{-1}, and the maximum activity of ^{137}Cs in the beets was 1.57 Bq kg^{-1}. For ^{90}Sr, the average activity was, respectively, 1.41 Bq kg^{-1} in carrots and 1.31 Bq kg^{-1} in beets, the maximum values of ^{90}Sr activity were 3.98 Bq kg^{-1} in carrots and 19.6 Bq kg^{-1} in beets. We have analyzed one sample of cabbage, one sample of radish and one sample of apples. The activity of ^{90}Sr and ^{137}Cs did not exceed their 1.0 Bq kg^{-1}.

Radionuclides C_a vary greatly. This complicates very much the prediction of radioactive contamination of agricultural products. In addition, radionuclides C_a in vegetables in farms were lower than in «Sovkhoz Beregovoy» LLC.

3.2 *Accumulation of ^{90}Sr and ^{137}Cs in Grass Biomass in Natural Ecosystems*

The study of regularities of radionuclides accumulation in the grass biomass is necessary for predicting the radioactive contamination of feed for farm animals.

In 2009–2011, we took 50 samples of hay from private farms. The average specific activity of ^{137}Cs in the hay in 90 % of the samples was 8.9 Bq kg^{-1}, and the maximum specific activity was 70.4 Bq kg^{-1} (in the village of Bolshoe Taskino). The average specific activity of ^{90}Sr in 90 % of samples was 23 Bq kg^{-1}, and the maximum values that exceed the reference level had the hay samples from the village of Allaki (112, 656 and 1,132 Bq kg^{-1}) and from the village of Karabolka (1,709 Bq kg^{-1} and 2,524 Bq kg^{-1}). The owners of household plots knew that they make hay on the axis of EURT and were aware that it is forbidden to make hay in these plots. The activities of ^{137}Cs and ^{90}Sr in hay do not correlate, $r = -0.07$. Therefore, a study of radionuclide accumulation in herbaceous plants is important.

In 2008–2011, we measured the content of ^{90}Sr and ^{137}Cs in the aboveground biomass of herbaceous plants from the grasslands on the territory within a radius of 30–35 km from the PA "Mayak."

The farmers in the Chelyabinsk region make hay and graze cows on natural grasslands. Therefore, we did not classify the samples by the species of plant, but collected and analyzed the entire biomass of grass at a distance of not more than 1 m from the soil sampling point. All values of radionuclides content in the grass and C_a are calculated for the dry weight of grass. The reference levels (RL) of radionuclides in the feed according to the "instructions on the radiological control

Table 3 RL of radionuclides in a stern Bq kg^{-1}

Type of a forage	^{90}Sr	^{137}Cs
Hay	100	600
Fresh grass	50	370

Table 4 The contents ^{90}Sr and ^{137}Cs in a grass on a haying site on the first transect

Place of selection of test	Specific activity Bq kg^{-1}		C_a		C_t	
	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs
1	366	17.9	0.25	0.048	1.10	0.193
2	677	6.1	0.48	0.024	2.03	0.104
3	584	12.4	0.71	0.057	3.31	0.248
4	483	6.8	0.37	0.024	1.38	0.093
5	361	11.4	0.46	0.076	2.12	0.333
6	1,454	31.8	2.10	0.142	9.67	0.629
7	985	17.7	1.08	0.083	4.78	0.373
8	876	14.5	1.15	0.080	4.68	0.356
9	535	16.0	0.59	0.061	2.65	0.276
10	549	50	0.88	0.221	3.40	0.844
11	210	28.3	0.51	0.118	2.21	0.520
Average value			0.78 ± 0.31	0.08 ± 0.03	3.4 ± 1.4	0.36 ± 0.13

of feed quality" (The instruction about radiological quality control of forages. RL of the content of radionuclides of caesium-134, -137 and strontium-90 in sterns and feed additives)/(it is approved by the Ministry of Agriculture of the Russian Federation 01.12.1994 N 13-7-2/216)) are presented in Table 3.

In 2008, we measured the content of ^{90}Sr and ^{137}Cs in grass in two transects that cross EURT perpendicular (Tables 4 and 5). The first transect was located 20 km away from the PA "Mayak" in the grassland at the top of a slight slope to the shore of Lake Alabuga (Table 4). The first soil and grass sampling point was located at a distance of 20 m from the skirt of the birch forest, and the subsequent points were separated by a distance of 20 m from the previous points. Point 11 was at a distance of 40 m from the shore of Lake Alabuga.

During the study period, the density of soil contamination with ^{90}Sr in this area ranged from 161 to 350 kBq^{-1} m^2 and the specific activity of ^{90}Sr in grass samples in all sampling points was many times higher than RL. The values of C_a ^{90}Sr in grass are high, in some cases they exceed 1.0. Despite the fact that all sampling points were located within an ecosystem that has homogeneous species composition, the range of C_a values is quite large.

The grass contamination with ^{137}Cs in this area did not exceed RL, and C_a ^{137}Cs is significantly lower than C_a ^{90}Sr. The connection between C_a ^{90}Sr and C_a ^{137}Cs was not found, the correlation coefficient—0.50. The correlation between the

Table 5 The contents ^{90}Sr and ^{137}Cs in a grass on the second transect

Ecosystem	Place of selection of test (distance from Chelyabinsk in km)	Specific activity Bq kg^{-1}		C_a		C_t	
		^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs
Meadow	94	48.9	7.30	2.27	0.181	17.21	1.499
Wood	95	120[a]	6.60	1.94	0.068	11.15	0.539
Field	96	700[a]	47.10	3.79	2.639	30.86	21.619
Field	97	169[a]	10.60	0.64	0.101	5.30	0.845
Field	98	1400[a]	10.10	3.06	0.124	25.03	1.032
Field	98.5	640[a]	11.70	2.50	0.111	13.40	0.843
Field	99	88.6	7.80	0.74	0.152	6.19	1.265
Wood	100	58.8	6.50	0.71	0.025	5.27	0.204
Meadow	101	23.9	62.60	1.38	0.824	10.79	6.815
Wood	102	50.6	30.60	0.66	0.132	5.41	1.085
Field	103	181[a]	6.50	7.07	0.176	55.52	1.462
Wood	104	28.7	14.10	0.90	0.034	4.72	0.278
Average value				2.1 ± 1.0	0.38 ± 0.42	15.9 ± 8.5	3.1 ± 3.4

Note [a] above a reference level

specific activity of ^{90}Sr and ^{137}Cs in grass is even lower—0.15. The dependence of C_a and C_t on the average activity of ^{90}Sr and ^{137}Cs in soil and on soil contamination density with ^{90}Sr and ^{137}Cs was not detected.

The second transect was located 30 km away from the PA "Mayak." The soil and grass sampling points were marked according to the distance from Chelyabinsk city. Table 5 presents data on the content of ^{90}Sr and ^{137}Cs in the grass on this transect. In this area, the sampling points were located in different ecosystems: birch forest, pine forest, grassland, hayfield, and neglected field. In six grass samples of 12, the activity of ^{90}Sr exceeded 100 Bq kg^{-1}, and at one point, it amounted to 1,400 Bq kg^{-1}. The values of C_a are very high too, especially in meadows and fields. The spread of C_a values is also very large; especially large is the spread of C_a ^{137}Cs. We assume that this can be explained by the fact that sampling was performed at the end of the growing season, when the accumulation of mineral elements in plant biomass is maximal. In winter, overwintering plants and perennials, the potassium content in the cytoplasm increases while preparation for the winter. Parallel can be accumulated its biochemical analogue—^{137}Cs.

In 2009–2012 was studied the contamination of grass in the territory within a radius of 30–35 km from PA "Mayak." Grass on the entire territory of study contained a relatively small amount of ^{137}Cs. Even in the EURT, the maximum activity of ^{137}Cs was 62.6 Bq kg^{-1}, and out of EURT, it was from 2.5 to 14.1 Bq kg^{-1}. C_a ^{137}Cs during the study period was 0.06–0.08, so we can assume that the excess of RL of ^{137}Cs accumulation in grass in the areas of settlements is hardly probable. The accumulation of ^{90}Sr in the grass outside the EURT area is also small—from 6.9 to 31.5 Bq kg^{-1}. However, C_a ^{90}Sr is significantly higher than C_a ^{137}Cs, and on the

Table 6 C_t technogenic and natural radionuclides concerning a layer of earth of 0–40 cm (Bq kg^{-1}) (kBq^{-1} sq. m^{-1})

Distance from water in M	^{137}Cs	^{90}Sr	^{40}K	^{226}Ra	^{232}Th
10	0.8	3.5	7.1	In the soil it is not found	In the soil it is not found
10	1.0	4.4	6.6	6.3	In a grass it is not found
20	0.7	7.3	5.0	11.3	In a grass it is not found
50	0.2	0.6	3.7	1.8	0.9
50	0.1	2.3	3.2	3.7	In a grass it is not found

average, in different years of study, it was 0.55–0.78, and in some samples, it exceeded 1.0. The accumulation of ^{90}Sr increases apparently at the end of vegetation to a greater extent than the accumulation of ^{137}Cs. Grass selected on July 15, 2011 near the village of Bolshoy Kuyash contained 3.1 Bq kg^{-1} of ^{137}Cs and 13.5 Bq kg^{-1} of ^{90}Sr. Grass selected in the same point on September 27, 2011 contained 4.7 Bq kg^{-1} of ^{137}Cs and 30.9 Bq kg^{-1} of ^{90}Sr. In September 2008, the coefficient of accumulation of ^{90}Sr in the grass averaged 2.14.

In the areas of settlements located near the axis of EURT (Karabolka, Allaki, Bolshoy Kuyash), the specific activity of ^{90}Sr in the grass can exceed RL. Next to the Lake Alabuga located near the axis of EURT in all grass samples, the content of ^{90}Sr exceeded by several times the reference level and reached 2,630 Bq kg^{-1} in 2011.

The study of radionuclides accumulation in the grass from Techa River floodplain was complicated by the fact that the distribution of ^{90}Sr and ^{137}Cs in the profile of the floodplain soil is very heterogeneous. In the meadow floodplain soils, the major part of radionuclides remains in the upper soil layer and therefore, C_a ^{90}Sr and ^{137}Cs can be calculated based on the average content of these radionuclides in the upper soil layer. The calculation of C_t for these soils is also easy. Table 6 shows the values of C_t of anthropogenic and natural radionuclides in grass samples taken from the pasture on the bank of Techa River near the village of Zatechenskoe. When comparing the data in Tables 4, 5, and 6, it can be seen that C_t ^{90}Sr and ^{137}Cs in floodplain meadow soil and meadow soil near the Lake Alabuga differ only a little.

While calculating C_a in bog soils, the following factors must be considered:

1. Plant roots are short on air and have too much water, so they are situated in the upper soil layer.
2. The greatest content of radionuclides may be in the deep layers of the soil.
3. The highest concentration of water-soluble forms of radionuclides may be in the upper soil layer due to capillary rise and evaporation of soil water.
4. Floodplain soil is composed of a very large number of heterogeneous layers, so it is very difficult to measure the floodplain soil bulk density and to calculate the contamination density.

Table 7 shows the results of the analysis of floodplain grass and soil samples taken on the right bank of the River Techa near the bog Asanovoe at 5 m from the

Table 7 The contents ^{90}Sr and ^{137}Cs in the inundated soil and a grass in 2012 on the Asanovy bog, Bq kg^{-1}

Selection depth in m^2	Test	^{90}Sr	^{137}Cs
	Grass	1,380	4,673
	Peat	4,180	309,000
0–10	Soil	5,989	565,000
10–20	Soil	6,584	649,00
20–30	Soil	6,227	249,000
30–40	Soil	9,097	28,600
40–50	Soil	8,273	20,400
50–60	Soil	7,759	5,388
60–70	Soil	6,405	2,050
70–80	Soil	1,763	844
80–90	Soil	827	619
90–100	Soil	466	433

water. It is impossible to choose correctly the soil layer for calculation of C_a. It is necessary for calculation of C_a to measure accurately the bulk density of the soil and the activity of radionuclide in each thin layer. Bog soil is always waterlogged, so it is very difficult to divide it into layers.

3.3 Accumulation of ^{90}Sr and ^{137}Cs in Forest Products

In 2008–2011, we measured the content of ^{90}Sr and ^{137}Cs in wood, berries, and mushrooms.

Table 8 shows the values of the specific activity of ^{90}Sr and ^{137}Cs in young birch before the leaves start to yellow and fall off. The samples were taken on the axis of EURT 30 km away from the PA “Mayak” and 99 km away from Chelyabinsk. ^{90}Sr is mostly accumulated in the leaves, and ^{137}Cs is mostly accumulated in the branches. In general, C_a of radionuclides in birch and grass sampled at the same place (Table 5) differ only a little.

On October 31, 2008, we collected the fallen leaves in the birch forest near the Lake Alabuga. The specific activity of ^{90}Sr in fallen leaves was 5,904 Bq kg^{-1}, and that of ^{137}Cs was 54 Bq kg^{-1}. The annual contribution of yearly litter to the pollution of forest floor with ^{90}Sr is there estimated at 2.37 kBq^{-1} m^2 or 2.1 % of the floor contamination that existed in the spring 2008. The contribution of litter to the contamination of floor with ^{137}Cs was 0.02 kBq^{-1} m^2.

In 2008–2011, we have taken samples of mushrooms and berries in the territory within a radius of 30–35 km from the PA “Mayak.” In all the samples of mushrooms, the specific activity of ^{137}Cs and ^{90}Sr was significantly below the maximum permissible levels (SanPiN2.2.2.1078-01). The activity of ^{137}Cs in 2008–2011 was from 0.55 to 39.0 Bq kg^{-1}, and MPL was 500 Bq kg^{-1}

Table 8 Contamination of ^{90}Sr and ^{137}Cs wood and birch leaves

Test	Specific activity, Bq kg^{-1}		C_a		C_t	
	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs
Leaves	119	6.5	1.00	0.126	8.32	1.054
Branches	63.3	15	0.53	0.292	4.42	2.433
Trunk	32.4	6	0.27	0.117	2.26	0.973

Table 9 Contamination of ^{90}Sr and ^{137}Cs fresh mushrooms on EURT

Place of selection of test (distance from Chelyabinsk in km)	Test	Specific activity, Bq kg^{-1}		C_a		C_t	
		^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs
99	1	0.47	0.58	0.0039	0.0113	0.0328	0.0941
	2	1.2	0.97	0.0101	0.0189	0.0839	0.1573
	3	0.7	0.9	0.0059	0.0175	0.0489	0.1460
100	1	0.34	4.6	0.0041	0.0176	0.0305	0.1447
	2	0.59	19.9	0.0071	0.0762	0.0529	0.6259
	3	0.63	18.5	0.0076	0.0709	0.0565	0.5819
	4	1.4	8.2	0.0169	0.0314	0.1255	0.2579
102	1	0.7	3.9	0.0092	0.0169	0.0749	0.1383
104	1	1.7	18.8	0.0531	0.0450	0.2798	0.3705
The wood near the Lake Alabuga	1	9.8	39.0	0.0017	0.124	0.0133	0.9476
	2	9.0	1.43	0.0009	0.0035	0.004	0.0145
On a place of the former village Russian Karabolka	1	5.5	10.9	0.0065	0.0586	0.0396	0.4950
	2	8.9	2.0	0.0106	0.0108	0.0641	0.0908

(SanPiN2.2.2.1078-01). The average accumulation coefficient of ^{137}Cs in mushrooms in 2011—0.011 (in 2008—0.011, 2009–2010 the samples of mushrooms were taken from a large area and the accumulation coefficient was not calculated). The activity of ^{90}Sr was from 0.14 to 9.8 Bq kg^{-1}, and MPL was 50 Bq kg^{-1} (SanPiN2.2.2.1078-01). The average accumulation coefficient of ^{90}Sr in mushrooms in 2011 was 0,007 (in 2008, it was 0.041). C_a and C_t of ^{90}Sr in mushrooms are considerably lower than in the grass, and even lower than those in vegetables and cereal crops. C_a and C_t of ^{137}Cs in mushrooms are higher than of ^{90}Sr, but in the studied area, high levels of soil contamination with ^{137}Cs occur only on the floodplain bogs in the Techa River headwaters. We can assume that the mushrooms are not dangerous for the population; their contribution to the dose of internal irradiation is negligible.

Table 9 shows the values of the specific activity of ^{90}Sr and ^{137}Cs in mushrooms collected in the territory of EURT. Since mushrooms picked in the area of former village Russkaya Karabolka and the Lake Alabuga, and in areas with contamination density of 140, 700 and 2,400 kBq^{-1}m^{2} have accumulated 8.9, 9.0, and 9.8 Bq kg^{-1} of ^{90}Sr, it is possible that under certain conditions, there may be mushrooms that do not meet sanitary–hygienic standards. In the other territory

Table 10 Contamination of ^{90}Sr and ^{137}Cs of berries on EURT

Place of selection of test	Species	Specific activity, Bq kg^{-1}		C_a		C_t	
		^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs
The wood near the Lake Alabuga	Wild strawberry	813	5.2	0.140	0.0165	1.10	0.126
	Stone bramble	243	2.4	0.042	0.0076	0.33	0.058
On a place of the former village Russian Karabolka	Wild strawberry	213	1.0	0.254	0.0054	1.53	0.045

(outside EURT), wild mushrooms from the areas of now existing settlements can be considered as harmless.

In the whole area of study, the specific activity of ^{137}Cs in 15 samples of wild berries (Fragaria viridis, Fragaria vesca, cranberries) in 2008–2011 ranged from 0.34 to 5.2 Bq kg^{-1}, on the average, it was 1.58 Bq kg^{-1}, and MPL was 160 Bq kg^{-1} (SanPiN2.2.2.1078-01). The activity of ^{90}Sr in berries outside EURT was also low—from 1.5 to 12 Bq kg^{-1}, on the average, it was 5.5 Bq kg^{-1}, and MPL was 60 Bq kg^{-1}(SanPiN2.2.2.1078-01). The accumulation coefficients of ^{137}Cs in berries are almost the same as in mushrooms, and the accumulation coefficients of ^{90}Sr are significantly higher than in mushrooms and greater than in vegetables and cereal crops. In the berries of Fragaria vesca near the Lake Alabuga, the activity of ^{90}Sr in 2008 was 813 Bq kg^{-1}, and in the bramble, it was 243 Bq kg^{-1}. In the area of the former village of Russkaya Karabolka in a mixture of berries of Fragaria vesca and Fragaria viridis, the ^{90}Sr activity was 213 Bq kg^{-1}. It should be considered that wild berries from the territory of EURT pose the greatest danger from the perspective that ^{90}Sr enters into food. It is necessary to examine the nature of ^{90}Sr accumulation in berries more closely (Table 10).

3.4 Study of the Soil Content of Radionuclides Forms that are Available for Plants

Long-term studies of various authors prove that the soil content of ^{137}Cs and ^{90}Sr in forms that are available for plants changes over time. Their accumulation coefficients in the marketable part of agricultural products change accordingly. In particular strongly expressed is the decrease in mobility of radionuclides in the first years after the accident.

The studies of the behavior of radionuclides in soils show that a significant part of ^{90}Sr and ^{137}Cs changes quite rapidly into immobile forms. An immobile form is a form in which the radionuclide is bound in the root systems of plants or soil adsorption complex as a result of adsorption and precipitation (EMCRA 2001).

Table 11 The contents in the soil of forms ^{90}Sr available to plants in percentage

Soil	Layer, m^2	Soluble in water	Capable to an exchange	Soluble in acid	Insoluble
Gray forest soil, the natural	0–5	3.4 ± 0.3	67.2 ± 2.4	21.8 ± 2.1	7.61 ± 0.07
	5–10	3.9 ± 0.5	63.6 ± 4.2	25.6 ± 3.2	6.9 ± 0.6
Gray forest soil, the dried up	0–5	5.0 ± 1.2	64.3 ± 1.6	23.6 ± 0.8	7.1 ± 2.0
	5–10	1.7 ± 0.4	65.0 ± 7.5	26.5 ± 8.6	6.8 ± 1.6
Sod-podzolic soil, the dried up	0–5	2.9 ± 0.4	77.2 ± 2.4	14.2 ± 1.2	5.7 ± 0.8
	5–10	2.2 ± 0.4	85.3 ± 2.7	8.9 ± 2.5	3.6 ± 0.2

Table 12 The contents in the soil of forms ^{137}Cs available to plants in percentage

Soil	Layer, m^2	Soluble in water	Capable to an exchange	Soluble in acid	Insoluble
Gray forest soil, the natural	0–5	5.0 ± 0.7	2.7 ± 0.5	2.8 ± 1.4	89.4 ± 2.4
	5–10	13.7 ± 6.4	16.5 ± 5.4	36.6 ± 14.4	33.1 ± 7.5
Gray forest soil, the dried up	0–5	2.8 ± 0.5	10.8 ± 1.4	4.3 ± 2.0	82.1 ± 2.6
	5–10	16.5 ± 1.4	17.9 ± 5.3	16.2 ± 5.8	49.4 ± 4.2
Sod-podzolic soil, the dried up	0–5	9.8 ± 1.7	16.1 ± 8.1	17.4 ± 7.3	56.7 ± 16.6
	5–10	13.8 ± 2.9	22.6 ± 5.1	36.0 ± 6.6	27.5 ± 7.9

Since the processes of adsorption and precipitation are reversible, the ratio of mobile and immobile forms is determined by the ratio of the speed of bonding and release of radionuclides. The elements bound in the root system and aboveground biomasses are released as far as plant litter decomposes. Elements bound in the soil adsorption complex move into the soil solution as a result of exchange reactions.

We have previously shown that in case of simulation of the washing water regime for a long time, the release of radionuclides from the alluvial soil with gravitational waters ranged from 10.8 to 12.4 % of the contained ^{90}Sr and from 0.08 to 0.52 % of ^{137}Cs.

In 2008, we measured the content of water-soluble, exchange, and acid-soluble forms of ^{90}Sr and ^{137}Cs in the gray forest and sod-podzolic soil. We compared the content of bioavailable forms in layers of 0–5 and 5–10 cm in a naturally moist and air-dry gray forest soil, air-dry gray forest soil, and sod-podzolic soil. The results are shown in Tables 11 and 12.

We failed to reveal significant differences of content of biologically available forms of strontium in the studied samples of naturally moist and air-dry gray forest soil. There are also practically no differences between layers of 0–5 and 5–10 cm. It was found that in the sod-podzolic soil, the content of exchange form is higher and the content of acid-soluble form is lower than in the gray forest soil.

The content of bioavailable forms of ^{137}Cs varies more. In naturally moist gray forest soil in comparison with air-dry soil, the content of exchange form is decreased slightly in a layer of 0–5 cm. In the sod-podzolic soil higher is the content of acid-soluble form of ^{137}Cs. However, the greatest differences were observed not between the soil types, but between the layers of 0–5 and 5–10 cm. In

Table 13 Release of water-soluble radionuclides from the inundated soil at different modes of extraction, percentage of the grass

Variant	Condition of the soil	^{137}Cs	^{90}Sr
Extracted three times. a soil and water 1:15 ratio	The dry	1.21 ± 0.10	3.4 ± 0.7
	The damp	2.37 ± 0.21	6.0 ± 0.1
Extracted one time. a soil and water 1:200 ratio	The dry	0.73 ± 0.18	3.8 ± 0.04
	The damp	3.68 ± 0.31	3.4 ± 1.3
Extracted one time. a soil and water 1:30 ratio, centrifuged	The dry	0.24 ± 0.1	1.8 ± 0.6
	The damp	1.6 ± 0.4	2.8 ± 0.4
Extracted one time. a soil and water 1:30 ratio, did not centrifuge	The damp	2.7 ± 0.9	4.3 ± 1.9

all cases, the content of bioavailable forms of ^{137}Cs is higher in the 5- to 10-cm layer and the content of strongly bound forms that remain in the solid residue is significantly lower in this layer. Perhaps a high content of mobile forms explains the sharp decline in contamination with ^{137}Cs of this layer, with the assumption that in the underlying soil layer goes more ^{137}Cs than ^{90}Sr. We also compared different modes of extraction of ^{90}Sr and ^{137}Cs with distilled water from the floodplain soil.

It follows from Table 13 that the amount of ^{137}Cs extracted with distilled water from the floodplain soils when using the normal mode of extraction is lower than from the automorphic soils (gray forest and sod-podzolic soil). Apparently, this is due to the fact that the waterlogged floodplain soil quickly loses water-soluble forms of ^{137}Cs. The content of radionuclides in the aqueous extract, as was to be expected, depends on the extraction mode and soil condition. When using dry soil, we observed statistically significant differences in the amount of ^{137}Cs extracted in the ratio of 1:15, 1:30, and 1:200. The greatest amount of ^{137}Cs is extracted in case of threefold rinsing, although the amount of water in this variation is the least. Apparently, in case of long 3-h mixing takes place a more intensive dispersion of soil particles.

Quantity of ^{90}Sr extracted in the ratio of 1:15 and 1:200 does not vary, but it is significantly statistically greater than when extracting in the ratio of 1:30.

When moist soil is used, the amount of ^{137}Cs extracted in different modes is also statistically different. The extraction was the best at the ratio of 1:200 and the worst at the ratio of 1:30. It is important to note that from the moist soil in all modes of extraction was released 2–6 times more ^{137}Cs than from the dry soil. The differences are statistically significant. For ^{90}Sr, this dependence is less expressed, and at the ratio of 1:200, differences between moist and dry soil were not observed at all.

To study the possibility of recovery of content of water-soluble fractions of ^{137}Cs and ^{90}Sr when moistening the dried soil, we used the same soil sample that was used for the determination of content of water-soluble fractions of ^{137}Cs and ^{90}Sr. The results of analysis of aqueous extracts are shown in Table 14.

It follows from Table 14 that when soil is moistened during 1–16 days, there is no recovery of water-soluble ^{137}Cs. The quantity of extractable ^{137}Cs after

Table 14 The content of radionuclides in the inundated soil and water extracts from the inundated soil after drying and moistening, percentage of the contents in the soil

Variant	^{137}Cs	^{90}Sr
Natural soil	1.6 ± 0.4	2.8 ± 0.4
The dried-up soil	0.24 ± 0.1	1.8 ± 0.6
The soil dried up and humidified within 1 day	0.46 ± 0.3	3.4 ± 1.3
The soil dried up and humidified within 2 day	0.34 ± 0.03	2.04 ± 0.5
The soil dried up and humidified within 4 day	0.42 ± 0.1	2.12 ± 0.2
The soil dried up and humidified within 8 day	0.53 ± 0.13	1.6 ± 0.3
The soil dried up and humidified within 16 day	0.48 ± 0.06	1.6 ± 0.2

moisturization is slightly higher than when the dry soil is used. When soil is moistened during 4–16 days, this difference is statistically significant. When soil is moistened during 1 day, the amount of extractable ^{90}Sr is apparently restored. In the future, it reduces. The mechanism of this phenomenon is not entirely clear. We attempted to estimate the amount of ^{137}Cs and ^{90}Sr that enter into an aqueous solution of soil in case of a longtime continuous extraction.

The soil sample was collected from the 0–20 cm layer of alluvial meadow bog soils in the floodplain of the Techa River. In the moist condition, the soil was rubbed through a 0.5-mm sieve to remove fragments of plants and large mineral particles, thoroughly mixed and divided into two parts.

Part 1 (S—sterilized) was irradiated in the wet condition at a dose of 2,800 Gy (70 h at a dose rate of 0.011 Gy s^{-1}) to kill microorganisms. Part 2 (US—unsterilized) was not irradiated. From each part in the wet condition were made three different samples, 10 g each, and they were put into centrifuge tubes. In the tubes were added 50 ml of distilled water, and then, they were stirred for 60 min on a magnetic stirrer, then centrifuged for 60 min at the velocity of 2,500 rpm, and then poured off and filtered the supernatant fluid. To the rest of soil again were added 50 ml of water, and the cycle was repeated. Three cycles were made during 1 day. After 60 cycles, into the collected filtered supernatant were poured up to 5 l of distilled water, and it was stirred and separated into two parts.

In one part, we precipitated colloids using $FeCl_3$ (0.2 g l^{-1}) and filtered them in 1 day. Thereafter, we measured the content of ^{90}Sr and ^{137}Cs in the filtrate after precipitation of colloids (F), in the colloids sediment (C), and in the second part of supernatant liquid with unprecipitated colloids (NPC).

The quantity of ^{137}Cs and ^{90}Sr that entered into aqueous solution during 60 cycles is shown in Table 15.

From Table 15 follows that when using this method of extraction, about 12–20 % of ^{90}Sr and ^{137}Cs contained in soil can move into aqueous solution. Differences between the release of radionuclides from sterilized and unsterilized soil were not found. ^{90}Sr does not practically precipitate with colloids and, apparently, moves primarily into regular solution in ionic form. ^{137}Cs precipitates almost completely, and there are reasons to assume that in the extract it is in the form of a colloidal solution.

Table 15 Relative quantity of ^{137}Cs and ^{90}Sr arrived in water solution for 60 cycles. Percentage of the initial contents in the soil

Variant	Fraction	^{137}Cs	^{90}Sr
Sterilized	NPC	18.9 ± 2.4	12.0 ± 4.2
	F	0.49 ± 0.14	12.0 ± 3.3
	C	18.1 ± 1.0	1.6 ± 1.8
Unsterilized	NPC	19.4 ± 0.5	15.2 ± 4.4
	F	0.53 ± 0.16	12.1 ± 4.9
	C	17.7 ± 4.0	0.98 ± 0.3

4 Conclusion

1. The content of ^{90}Sr and ^{137}Cs in agricultural products and forest mushrooms in the entire territory within a radius of 30–35 km from the PA "Mayak" does not exceed the maximum permissible levels and poses no danger to the population.
2. The accumulation of ^{90}Sr in wild berries and grass on the territory of EURT may be higher than the radiation-hygienic standards and poses a danger to the population and farm animals.
3. The content of ^{90}Sr and ^{137}Cs in the soil in the form that is available for plants depends on soil moisture and can vary considerably.

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