LONG-TERM DYNAMICS OF RADIONUCLIDE VERTICAL MIGRATION IN SOILS OF THE CHERNOBYL NUCLEAR POWER PLANT EXCLUSION ZONE

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ABSTRACT

The radioactive fallout from the Chernobyl Nuclear Power Plant (ChNPP) accident consisted of fuel and condensation components. An important radioecological task associated with the late phase of the accident is to evaluate the dynamics of radionuclide mobility in soils. Identification of the variability (or invariability) in the radionuclide transfer parameters makes it possible to 1) accurately predict migration patterns and biological availability of radionuclides and 2) evaluate long-term exposure trends for the population who may reoccupy the remediated abandoned areas. In 1986-1987, a number of experimental plots were established within various tracts of the fallout plume to assist with the determination of the long-term dynamics of radionuclide vertical migration in the soils.

The transfer parameters for ^{137}Cs, ^{90}Sr, and ^{239,240}Pu in the soil profile, as well as their ecological half-time of the radionuclide residence ($T_{1/2}^{ecol}$) values in the upper 5-cm thick soil layers of different grasslands were estimated at various times since the accident. Migration characteristics in the grassland soils tend to decrease as follows: $^{90}\text{Sr} > ^{137}\text{Cs} \geq ^{239,240}\text{Pu}$. It was found that the ^{137}Cs absolute $T_{1/2}^{ecol}$ values are 3–7 times higher than its radioactive decay half-life value. Therefore, changes in the exposure dose resulting from the soil deposited ^{137}Cs now depend only on its radioactive decay. The ^{90}Sr $T_{1/2}^{ecol}$ values for the 21st year after the fallout tend to decrease, indicating an intensification of its migration capabilities. This trend appears consistent with a pool of mobile ^{90}Sr forms that grows over time due to destruction of the fuel particles.

Key words: Chernobyl, Ecological half-time, Soil migration, Transfer parameters

INTRODUCTION

The radioactive fallout in the Chernobyl Exclusion Zone (ChEZ) from the Chernobyl Nuclear Power Plant (ChNPP) Reactor Unit Number 4 accident consisted of two major components: fuel and condensation components. The contamination of the affected area included a superposition of the plumes of these two components, their ratio of which depended on the direction and distance from the release source (1, 2). This resulted in different dynamics of the fallout transformations and radionuclide migration characteristics in the soils at various distances along the fallout plume.

One of the important radioecological tasks associated with the late phase of the accident is to evaluate the dynamics of radionuclide mobility in soils. Identification of the variability (or invariability) in the radionuclide transfer parameters makes it possible to 1) accurately predict migration patterns and biological availability of radionuclides and 2) evaluate long-term exposure trends for the population who may reoccupy the remediated abandoned areas upon completion of remediation activities.

In 1986-1987, a number of experimental plots were established within various tracts of the fallout plume associated with the ChNPP accidental release. The following criteria were taken into account for the selection of the plots:

- Topography and geochemical conditions (chemical and physical properties of soils, granulometric and mineralogical compositions of soils, aqueous modes of soils, etc.);
- Types of land (soils previously used for agricultural needs and naturally developed soils);
- Physical and chemical properties of the fallout (fuel and condensation components ratio);
- Density of contamination with long-lived radionuclides.

Some of the experimental plots were located in the area where self-remediation had been proceeding very intensely (3). Some 15-20 y after the fallout, soil sampling was no longer possible due to intense growth of vegetation.

MATERIALS AND METHODS

The description of the experimental plots is summarized in Table 1, which presents the ^{137}Cs and ^{90}Sr contamination values for May 1986. Selected physico-chemical properties and granulometric composition of soils at the experimental plots in 1991 are shown in Table 2. Two or three holes in the soil were dug at each experimental plot (up to 0.5 m deep) and two soil cores were sampled from each hole using a specially designed dismountable sampler. In each core, the soil was sampled at 0-2 cm, 2-5 cm, 5-10 cm, 10-15 cm, and up to 40-50 cm deep, taking into account specific conditions at the sampling point. The soil samples taken at the same level in each hole were combined.

A high purity germanium semiconductor detector and gamma-spectrometer ORTEC® ADCAM®-300[§] were utilized to measure the content of gamma-emitting radionuclides in the soil samples. ^{90}Sr and Pu isotopes content were measured radiochemically using standard procedures (4, 5).

The ^{137}Cs and $^{239, 240}$Pu transfer parameters in the soil profiles were calculated using the convective and diffusion transfer model:

[§] ORTEC® website: http://www.ortec-online.com/products.htm

$$C(x,t) = C_0 \cdot \left\{ \frac{1}{\sqrt{\pi \cdot D \cdot t}} \exp\left(-\tfrac{(x-V\cdot t)^2}{4D\cdot t} \right) - \tfrac{V\cdot x}{2D} \exp\left(-\frac{V \cdot x}{D} \right) \left[1 - \operatorname{erf}\left(\frac{x + V \cdot t}{2\sqrt{D \cdot t}} \right) \right] \right\} \qquad (1)$$

where C_0 is the radionuclide content in the *x* soil layer at the initial moment of time *t*; D is the diffusion coefficient for the radionuclide (cm^2 y^{-1}); and V is the velocity of the radionuclide directional transfer with moisture flow (cm y^{-1}).

Due to the complex nature of the ^{90}Sr redistribution in the soil resulting from its fallout as fuel particles, ^{90}Sr transfer parameters were calculated using a two-component convective and diffusion transfer model:

$$\begin{aligned} C(x,t) = {} & C_0 \cdot a \cdot \left\{ \frac{1}{\sqrt{\pi \cdot D_1 \cdot t}} \exp\left(-\tfrac{(x-V_1\cdot t)^2}{4D_1\cdot t} \right) - \tfrac{V_1\cdot x}{2D_1} \exp\left(-\frac{V_1 \cdot x}{D_1} \right) \left[1 - \operatorname{erf}\left(\frac{x + V_1 \cdot t}{2\sqrt{D_1 \cdot t}} \right) \right] \right\} + \\ & + C_0 \cdot (1-a) \cdot \left\{ \frac{1}{\sqrt{\pi \cdot D_2 \cdot t}} \exp\left(-\tfrac{(x-V_2\cdot t)^2}{4D_2\cdot t} \right) - \tfrac{V_2\cdot x}{2D_2} \exp\left(-\frac{V_2 \cdot x}{D_2} \right) \left[1 - \operatorname{erf}\left(\frac{x + V_2 \cdot t}{2\sqrt{D_2 \cdot t}} \right) \right] \right\} \end{aligned} \qquad (2)$$

where C_0 is the radionuclide content in the *x* soil layer at the initial moment of time *t*; D_1 and V_1 are a diffusion coefficient and a velocity of the directional transfer of the “fast” component of the radionuclide with moisture flow; D_2 and V_2 are a diffusion coefficient and a velocity of the directional transfer of the “slow” component of the radionuclide with moisture flow; and *a* is the share of the “fast” component of the radionuclide ($0 \le a \le 1$). The assessments were made using the computer software developed in the Ukrainian Research Institute of Agricultural Radiology (6) and the StatSoft® STATISTICA** software.

RESULTS AND DISCUSSION

The dynamics of the ^{137}Cs and ^{90}Sr redistribution in soils at the experimental ChEZ plots are shown in Figs. 1 and 2, respectively. The experimental data on ^{137}Cs redistribution in the soils of the experimental plots demonstrate a relatively low intensity of ^{137}Cs vertical transfer. Twenty one years after the fallout, 90-97% of the total ^{137}Cs inventory deposited in the upper 5-cm thick soil layer of the grassland formed on automorphous mineral soils. A more intense ^{137}Cs transfer occurred in the grasslands formed on hydromorphous organogenic soils where, within the same period of time, the upper 5-cm thick soil layer contained 50-89% of ^{137}Cs (Fig. 1: Plots 2 and 5). ^{90}Sr migration in the soils appeared to be much more intense. As early as five to six years after the fallout, the upper 5-cm thick layer of the grassland soils contained 65-91% of the entire ^{90}Sr inventory of the soil profile. Nine years after the accident, the upper soil layer contained 46-88% of the ^{90}Sr inventory and 21 y after the accident, it contained 32-87% of its inventory. The maximum ^{90}Sr migration was observed in the automorphous mineral soils (Fig. 2: Plots 4, 5, 8, and 11). The minimum ^{90}Sr and ^{137}Cs migration was observed in the soddy-podzolic sandy soil, the significant part of which was covered with moss. Migration of Pu isotopes appeared to be the least intense. Four to six years after the fallout, the upper 5 cm thick grassland soil layer contained 91-99% of the Pu inventory in the soil profile.

** StatSoft® STATISTICA software website: http://www.statsoft.com/

Physico-chemical properties of the ChNPP fallout played a significant role in the migration of radionuclides. In 1986-1988, the migration of radioisotopes of various chemical elements (Cs, Ce, Sr, and others) was fairly similar, regardless of ratios between the fuel and condensation components of the fallout plume. It probably resulted from a mechanical transfer of these radionuclides with fuel particles. In 1989, the radionuclide distribution differentiated (7), with their chemical properties, as well as physical and chemical properties of soils affecting the radionuclide transfer more significantly.

^{90}Sr, ^{137}Cs, and ^{239,240}Pu distributions in soils of the experimental plots with various ratios of the fuel and condensation components of the fallout (Plots 1 and 5) shows that ^{90}Sr and ^{239,240}Pu may migrate as part of the finely dispersed fuel particles. Fig. 3 shows radionuclide distribution profiles in the soils where the fuel component comprises about 80% and 45%. The ^{137}Cs distribution in the soils profiles at both experimental plots is similar, confirming the fact the fuel component does not contain a large amount of this radionuclide at these particular plots. Similarity of the radionuclide distributions in the soil profiles with a large share of the fuel component in the initial contamination shows that mechanical transfer of the radionuclides with the finely dispersed fuel particles might have prevailed. The radionuclide distribution (Fig. 3B) confirms their vertical migration in mostly soluble forms, likely resulting from a faster destruction of the fuel particles under these soil conditions.

The experimental data on the radionuclide distribution in the soil profiles of the experimental plots made it possible to estimate transfer parameters for ^{137}Cs and Pu isotopes using a one-component convective diffusion transfer model (Table 3) and for ^{90}Sr using a two-component convective diffusion model (Table 4). The estimated radionuclide transfer parameters help assess variability of the radionuclide transfer estimates. Table 5 shows the mean and mean square deviations of the diffusion coefficient and velocity of directional ^{137}Cs transfer in the soil profile of the grassland formed on soddy-podzolic sandy-loam soils seven and eight years after the fallout. The variability of the estimates ranges from 10 to 33%.

The dynamics of the ^{137}Cs transfer parameters (Table 3) shows that, practically at every experimental plot, the transfer parameters decrease as a function of time, specifically the diffusion coefficient decreases by factors of 1.5-3 and decrease of the velocity of the directional transfer ranges from several times to several orders of magnitude. Based on assessments of radionuclides transfer parameters specific for the period 6-9 y after the fallout, the authors estimated the values of ecological half-time[††] ($T_{1/2}^{ecol}$) of radionuclides residence in the upper 5 cm soil layer of grassland. These periods were as follows: 60-150 y for the automorphous mineral soils, 11-20 y for the hydromorphous organogenic soils, and 17-80 y for the organogenic drained soils (8). Table 3 shows estimated values of the $T_{1/2}^{ecol}$ for ^{137}Cs calculated using the radionuclide transfer parameters for the 21st year after the ChNPP accident. The averaged values of the ^{137}Cs $T_{1/2}^{ecol}$ is 180-320 y for the grassland formed on automorphous mineral soils of a light granulometric composition and 90-110 y for the grassland formed on hydromorphous organogenic soils. These values illustrate that the ^{137}Cs vertical migration in the grassland soils during the late phase of the accident significantly decreased. The absolute values of the ^{137}Cs ecological half-time of ^{137}Cs residence in the upper 5-cm thick soil layer are 3-7 times higher than the ^{137}Cs radioactive decay half-life of 30.17 y (e.g., during the late phase of the ChNPP accident, changes in dose resulting from deposition of ^{137}Cs on the soil only depended on its radioactive decay). This factor must be considered for development of predictive assessments,

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[††] The time during which half of the activity of the radionuclide is removed from the soil layer, without taking into account its physical decay.

including dose exposures for the hypothetical population in case of their reoccupation of the abandoned areas.

For most grassland formed on automorphous mineral soils of a light granulometric composition, ^{137}Cs migration intensity does not significantly vary within the limit of error, which means that, at the late phase of the accident, physical and chemical characteristics of the soils are not as significant for ^{137}Cs vertical migration as they were in the short term.

The values shown in Table 4 demonstrate a more intense ^{90}Sr transfer in the soil profiles, in comparison with the ^{137}Cs and Pu isotopic transfer. The ^{90}Sr transfer parameters (Table 4) show that the radionuclide migration is significantly more intense than ^{137}Cs transfer at practically all experimental plots. Since ^{90}Sr in the fallout was mostly deposited in the fuel particles matrix and the rate of destruction of the fuel particles and ^{90}Sr leaching varied under various chemical conditions of soil, forms of ^{90}Sr transfer and their ratios in the soils changed throughout the post-ChNPP accident period, making it necessary to use the two-component convective diffusion model for evaluating the ^{90}Sr migration in soils. To compare ^{90}Sr and ^{137}Cs migration characteristics, the authors used ^{90}Sr and ^{137}Cs $T_{1/2}^{ecol}$ for the upper 5-cm thick grassland soil layers (Tables 3 and 4). The ^{90}Sr $T_{1/2}^{ecol}$ values are by factors of 2-40 lower than those for ^{137}Cs.

The $T_{1/2}^{ecol}$ values for ^{90}Sr during the 21st year after the fallout vary in a wide range; specifically, from 7.5-150 y. The ^{90}Sr $T_{1/2}^{ecol}$ values equal 11-18 y for the grassland formed on hydromorphous organogenic soils. The ^{90}Sr $T_{1/2}^{ecol}$ values equal 150, 65, 7.5, and 9 y for the grassland formed on automorphous mineral soils of a light granulometric composition. The maximum ^{90}Sr $T_{1/2}^{ecol}$ value was observed for the soddy-podzolic sandy soil area, the significant area of which was covered with moss. As stated above, the ^{137}Cs migration in this area was the least intense as well.

Based on assessments of the ^{90}Sr transfer parameters specific for the period 6-9 y after the fallout, the authors estimated the $T_{1/2}^{ecol}$ values for various grasslands. The ^{90}Sr $T_{1/2}^{ecol}$ values equal 11-19 y for the automorphous mineral soils of a light granulometric composition and 100–160 y for the hydromorhous organogenic soils (5). Comparison of these values based on the ^{90}Sr transfer parameters during the 6th to 9th and the 21st year after the ChNPP accident (Table 4) shows that the ^{90}Sr $T_{1/2}^{ecol}$ values tend to decrease at approximately half of the experimental plots; i.e., its migration capability increases. The intensity of the radionuclide transfer depends on the rate of destruction of the fuel particles, especially for ^{90}Sr because its absorption is by an order of magnitude slower than absorption of ^{137}Cs or Pu isotopes. This trend appears consistent with a pool of mobile ^{90}Sr forms that grows as a function of time due to destruction of the fuel particles (9). The ^{90}Sr, ^{137}Cs and ^{239,240}Pu vertical transfer parameters indicate that, for 1990-1992, the migration capability of the radionuclides decreases as follows: $^{90}\text{Sr} > {}^{137}\text{Cs} \geq {}^{239,240}\text{Pu}$.

CONCLUSIONS

1. Long-term dynamics of radionuclides vertical migration in grassland soils of the ChEZ was assessed. The transfer parameters for ^{137}Cs, ^{90}Sr, and ^{239,240}Pu in the soil profile, as well as ecological half-time values of these radionuclides in residence in the upper 5-cm thick soil layers of different grasslands were estimated.

2. Migration characteristics of radionuclides in the grassland soils of the ChEZ tend to decrease as follows: $^{90}\text{Sr} > {}^{137}\text{Cs} \geq {}^{239,240}\text{Pu}$.

3. The ^{137}Cs vertical migration was shown to significantly decrease in the grassland soils during the late phase of the accident. The ^{137}Cs average $T_{1/2}^{ecol}$ values equal 180-320 y for the grassland formed on automorphous mineral soils of a light granulometric composition and 90-110 y for the grassland formed on hydromophous organogenic soils, which is significantly higher than for the period of 6–9 y after the fallout.

4. The ^{137}Cs absolute $T_{1/2}^{ecol}$ values are by factors of 3-7 higher than its radioactive decay half-life value, i.e., during the late phase of the accident, changes in the exposure dose resulting from the soil deposited ^{137}Cs depend only on its radioactive decay. This factor should necessarily be considered for development of predictive assessments, including dose exposures for the hypothetical population in case of their reoccupation of the abandoned areas.

5. For most grassland formed on automorphous mineral soils of a light granulometric composition, ^{137}Cs migration intensity does not significantly vary within the limit of error, which means that, in the long term after the ChNPP accident, physical and chemical characteristics of the soils are not as significant for ^{137}Cs vertical migration as they were in the short term.

6. The estimated ^{90}Sr $T_{1/2}^{ecol}$ values for the 21st year after the fallout have a wide range: 7.5-150 y for the grassland formed on automorhous mineral soils of a light granulometric composition and 11–18 y for the grassland containing hydromorphous organogenic soils.

7. The ^{90}Sr $T_{1/2}^{ecol}$ values for the 21st year after the fallout tend to decrease at a number of experimental plots, indicating an intensification of its migration capabilities. This trend appears consistent with a pool of mobile ^{90}Sr forms that grows as a function of time due to destruction of the fuel particles.

8. The obtained results have to be considered for predictive assessments, including those for dose exposures for the hypothetical population in case of their reoccupation of the exclusion areas if implementation and/or planning of remediation activities at the ChEZ are considered reasonable and appropriate.

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Table 1. Description of the Experimental Sites.

Plot	Description	Turf Characteristics	^{137}Cs Contamination[a] (MBq m^{-2})	^{90}Sr Contamination[a] (MBq m^{-2})	Location from the ChNPP	Comments
1	Grassland formed on soddy-podzolic sandy-loam soil.	Loose, poorly defined or occasionally absent.	34±2	16±4	4 km west	In the last few years, this plot was eliminated due to development of the ChNPP infrastructure.
2	Wet grassland formed on peat soils, with the peat soil layer of 20-25 cm.	4-5 cm thick and dense.	79±3	57±12	4 km west	
3	Grassland formed on soddy-podzolic sandy soil.	Loose, poorly defined or occasionally missing. A significant part of the area is covered with moss.	28±1	17±7	4 km west	
4	Grassland forming on soddy-podzolic sandy-loam soil used as a cropland prior to the ChNNP accident.		3.0±0.2	2.9±0.2	6 km south	
5	Grassland forming on soddy-podzolic gleyed soil used as a cropland prior to the ChNPP accident.		3.2±0.1	2.0±0.1	4 km north	Currently, it is a thin birch tree forest.
6	Grassland forming on soddy-podzolic gleyed soil used as a cropland prior to the accident.	Loose or occasionally absent.	3.9±0.2	2.4±0.1	4 km north	Currently, it is a birch tree thin forest.
7	Wet grassland formed on soddy gleyed soil.	Dense. The humus layer is approximately 20-30 cm thick.	1.4±0.3	0.8±0.2	8 km north-east	Currently, this area is heavily covered with shrubs.
8	Grassland forming on soddy-podzolic sandy-loam soil used as a cropland prior to the accident.	Loose and poorly defined.	4.4±0.2	2.8±1.0	12 km west	
9	Grassland cultivated prior to the accident formed on soddy-podzolic sandy loam soil with a high humus content.		13.7±0.2		16 km north	
10	Grassland formed on soddy-podzolic sandy-loam soil on the edge of a pinewood.	Loose.	11.9±0.3		60 km west	In 1986, a large amount of lime was introduced in the soil after the ChNPP accident.
11	Cultivated grassland formed on soddy-meadow soil.		1.3±0.1	0.12±0.03	23 km west	Currently, the area is heavily covered with deciduous trees.

[a] ^{137}Cs and ^{90}Sr contamination values are for May 1986.

Table 2. Agrochemical Characteristics of the Experimental Sites.

Plot	Depth of soil layer (cm)	Organic matter %	pH_{H_2O}	pH_{KCl}	Hydrolitic acidity (mEq/100 g of soil)	Ca (mEq/100 g of soil)	Mg (mEq/100 g of soil)	K_2O (mg/100 g of soil)	Sand[a], %	Clay[b], %
1	0-20	0.80	4.7	4.0	6.0	0.8	0.14	0.8	85.3	-
	20-30	0.38	4.5	4.1	1.0	0.8	0.15	1.1	89.5	1.2
2	0-20	23.16	5.9	5.5	9.5	34.6	1.98	2.2	44.0	9.6
	20-30	1.58	6.4	5.8	1.2	8.8	0.62	1.0	86.1	4.4
3	0-15	0.45	4.9	4.2	1.8	1.0	0.15	0.8	82.4	1.2
	15-30	0.06	5.2	4.5	0.7	0.7	0.15	0.8	88.7	-
4	0-20	0.71	5.1	4.0	2.1	1.0	0.26	3.0	80.4	2.0
	20-30	0.01	5..4	4.5	-	0.9	0.23	2.1	83.3	-
5	0-20	2.60	5.1	4.0	5.4	1.7	0.26	1.8	72.2	2.9
	20-30	traces	5.0	4.4	-	0.8	0.22	1.0	81.7	-
6	0-20	0.59	5.3	4.2	2.3	1.0	0.15	2.0	83.6	1.5
	20-30	traces	5.8	4.8	-	0.8	0.14	1.5	87.6	-
7	0-20	3.50	5.3	4.3	10.0	6.1	0.74	3.4	62.5	5.5
	20-30	0.63	5.8	5.1	0.8	3.9	0.47	1.1	85.1	3.4
8	0-20	3.85	5.6	4.7	5.2	4.0	0.36	1.8	82.3	4.9
	20-30	0.20	6.1	5.0	0.4	1.5	0.16	1.0	90.0	0.4
9	0-20	2.14	6.9	6.1	0.7	5.5	0.76	10.1	73.5	-
	20-30	2.27	7.3	6.6	0.4	6.5	0.93	8.8	70.9	1.3
10	0-3	1.36	8.6	8.3	-	35.4	0.23	4.4	61.0	3.7
	3-4.5	1.17	7.7	7.7	-	12.1	0.81	2.8	76.5	2.0
	4.5-8.5	0.25	7.8	7.5	-	3.0	0.35	1.8	80.8	0.5
	8.5-22	0.07	8.0	7.6	-	1.8	0.13	2.0	76.5	1.5

[a] Sand > 0.06 mm

[b] Clay < 0.001 mm

Table 3. Changes of ^{137}Cs Vertical Transport in Soil Profiles at the Experimental Plots and ^{137}Cs Ecological Half-Time ($T_{1/2}^{ecol}$) of the Residency in the Upper 5-cm Thick Soil Layer.

Time after deposition (y)	D (cm^2 y^{-1})[a]	V (cm y^{-1})[b]	$T_{1/2}^{ecol}$ (y)[c]
Plot 1			
2.33	0.22±0.03	0.06±0.01	
4.58	0.09±0.02	0.16±0.03	
5.17	0.29±0.04	<0.001	
6.17	0.08±0.01	0.14±0.03	
7.17	0.20±0.03	<0.001	
8.25	0.06±0.02	<0.001	
9.17	0.18±0.04	<0.001	
Plot 2			
6.25	0.44±0.10	<0.001	
7.17	0.46±009	<0.001	
9.17	0.21±0.06	<0.001	
21.4	0.21±0.05	0.012±0.010	110 (89-145)
Plot 3			
2.17	0.19±0.03	0.23±0.04	
5.5	0.08±0.01	0.15±0.02	
6.25	0.07±0.01	0.13±0.02	
7.17	0.05±0.01	0.09±0.02	
9.17	0.06±0.01	0.09±0.03	
21.3	0.07±0.004	0.02±0.002	210 (110-400)
Plot 4			
1.42	0.31±0.04	0.14±0.04	
4.58	0.13±0.02	0.08±0.02	
6.25	0.15±0.03	0.003±0.001	
7.17	0.23±0.03	<0.001	
8.25	0.20±0.03	<0.001	
9.17	0.13±0.02	<0.001	
21.3	0.15±0.03	<0.001	180 (130-300)
Plot 5			
1.42	0.17±0.03	0.09±0.02	
4.58	0.13±0.02	0.10±0.02	
6.25	0.11±0.01	0.10±0.03	
7.17	0.19±0.02	<0.001	
9.17	0.19±0.03	<0.001	
21.3	0.21±0.07	0.04±0.02	88 (62-123)
Plot 6			
1.42	0.19±0.03	<0.001	
4.58	0.14±0.02	0.06±0.02	
6.25	0.05±0.01	0.18±0.4	
7.17	0.28±0.04	0.07±0.02	
8.25	0.11±0.01	<0.001	
9.17	0.11±0.02	<0.001	
21.3	0.23±0.04	<0.001	130 (100-175)
Plot 7			
1.42	0.34±0.07	<0.001	
4.42	0.30±0.07	<0.001	
6.25	0.41±0.10	<0.001	
7.17	0.44±0.10	<0.001	
8.25	0.33±0.05	0.01±0.002	
9.17	0.13±0.03	<0.001	
Plot 8			
1.25	0.14±0.02	0.05±0.01	
4.58	0.07±0.01	0.05±0.01	
5.5	0.07±0.01	0.16±0.02	

6.25	0.12±0.02	<0.001	
7.17	0.14±0.02	<0.001	
9.17	0.05±0.01	0.001	
21.3	0.09±0.02	<0.001	320 (260-420)
Plot 11			
1.25	0.42±0.11	0.14±0.03	
2.4	0.68±0.12	0.18±0.03	
6.3	0.37±0.10	0.51±0.11	
7.17	0.39±0.12	<0.001	
8.25	0.12±0.02	0.02±0.01	
9.17	0.20±0.02	0.12±0.02	

[a] -D is the diffusion coefficient for the radionuclide (cm^{2} y^{-1}).

[b] -V is the velocity of the radionuclide directional transfer with moisture flow (cm y^{-1}).

[c] -Based on the ^{137}Cs transport parameters for the 21st year after the fallout (the minimum and maximum values are given in brackets).

Table 4. Changes of ^{90}Sr Vertical Transport in Soil Profiles at the Experimental Sites and ^{90}Sr Ecological Half-Time ($T_{1/2}^{ecol}$) of the Residency in the Upper 5-cm Thick Soil Layer.

Time after deposition, (y)	**a**	**D_1[a] ($cm^2\ y^{-1}$)**	**V_1[a] ($cm\ y^{-1}$)**	**D_2[b] ($cm^2\ y^{-1}$)**	**V_2[b] ($cm\ y^{-1}$)**	**$T_{1/2}^{ecol}$ (y)**
			Plot 1			
5.25	0.11±0.02	14.1±4.1	1.0±0.4	0.12±0.09	0.10±0.02	48
9.4	0.65±0.12	2.3±0.5	1.1±0.2	0.04±0.03	0.16±0.07	8
			Plot 2			
9.4	0.04±0.01	17.2±3.1	3.0±1.1	0.49±0.15	<0.001	60
21.4	0.60±0.14	3.3±0.9	1.6±0.4	0.46±0.16	0.19±0.08	18
			Plot 3			
21.3	0.14±0.04	3.6±0.8	0.82±0.12	0.07±0.02	0.03±0.01	150
			Plot 4			
9.2	0.08±0.02	3.1±0.5	0.35±0.11	0.53±0.11	0.03±0.02	38
21.3	0.3±0.04	5.9±1.0	1.2±0.2	0.31±0.14	0.04±0.01	65
			Plot 5			
9.2	0.27±0.10	2.5±0.4	0.20±0.06	0.2±0.07	0.06±0.02	44
21.3	0.22±0.03	11.0±2.0	1.2±0.2	1.10±0.14	0.30±0.08	11
			Plot 6			
21.3	0.75±0.12	3.3±0.4	0.70±0.21	0.40±0.12	0.10±0.05	7.5
			Plot 7			
9.4	0.20±0.02	7.4±1.3	1.4±0.3	0.51±0.14	0.05±0.02	42
			Plot 8			
6.25	0.10±0.03	7.0±2.2	0.60±0.13	0.55±0.16	0.05±0.02	35
21.3	0.67±0.12	3.5±0.5	0.70±0.18	0.40±0.11	0.10±0.03	9
			Plot 11			
6.25	0.28±0.09	7.5±1.2	3.1±0.7	0.53±0.16	0.08±0.02	41

[a] D_1 and V_1 are a diffusion coefficient and a velocity of the directional transfer of the “fast” component of the radionuclide with moisture flow.

[b] D_2 and V_2 are a diffusion coefficient and a velocity of the directional transfer of the “slow” component of the radionuclide with moisture flow.

Table 5. ^{137}Cs Transfer Variability and ^{137}Cs Ecological Half-Time ($T_{1/2}^{(ecol)}$) of the Residence in the Upper 5-cm Thick Soil Layer Based on the Experimental Data for Natural Grasslands Formed on Soddy-Podzolic Sandy-Loam Soil.

Soil layer	**D (cm^2 y^{-1})**[a]	**V (cm y^{-1})**[b]	**$T_{1/2}^{ecol}$ (y)**
	t=7.17 years		
1	0.12	<0.001	240
2	0.22	<0.001	135
3	0.11	<0.001	260
4	0.14	<0.001	320
mean± SD	*0.15±0.05*	<0.001	*215±55*
	t=8.26 years		
1	0.20	<0.001	145
2	0.21	<0.001	140
3	0.23	<0.001	125
4	0.19	<0.001	155
mean SD	*0.21±0.02*	<0.001	*140±15*

[a] D is the diffusion coefficient for the radionuclide (cm^2 y^{-1})

[b] V is the velocity of the radionuclide directional transfer with moisture flow (cm y^{-1}).

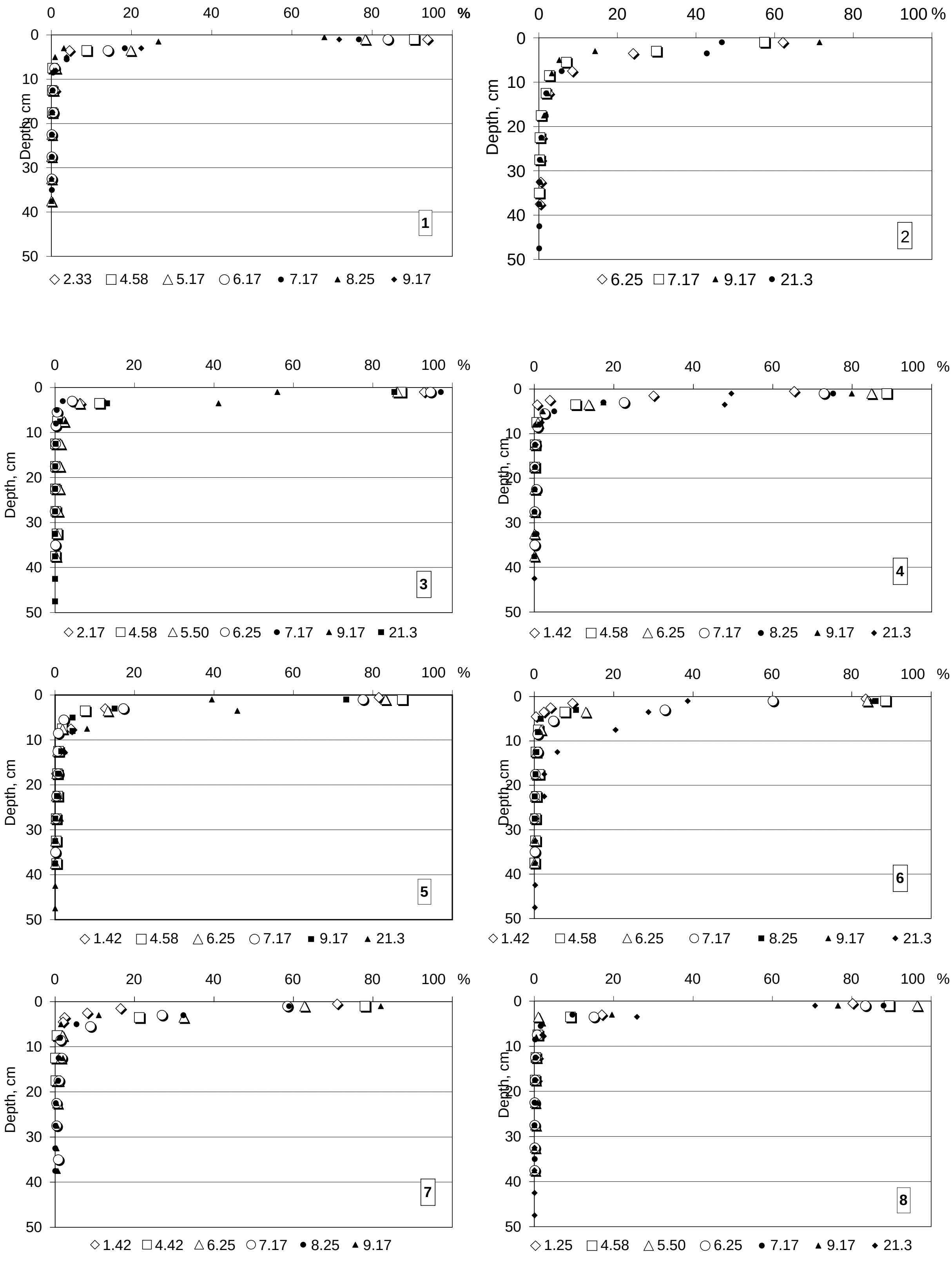

Fig. 1. ^{137}Cs distribution in soils profiles at the experimental plots at various times after the fallout (numbers below the diagrams show the number of years after the ChNPP accident).

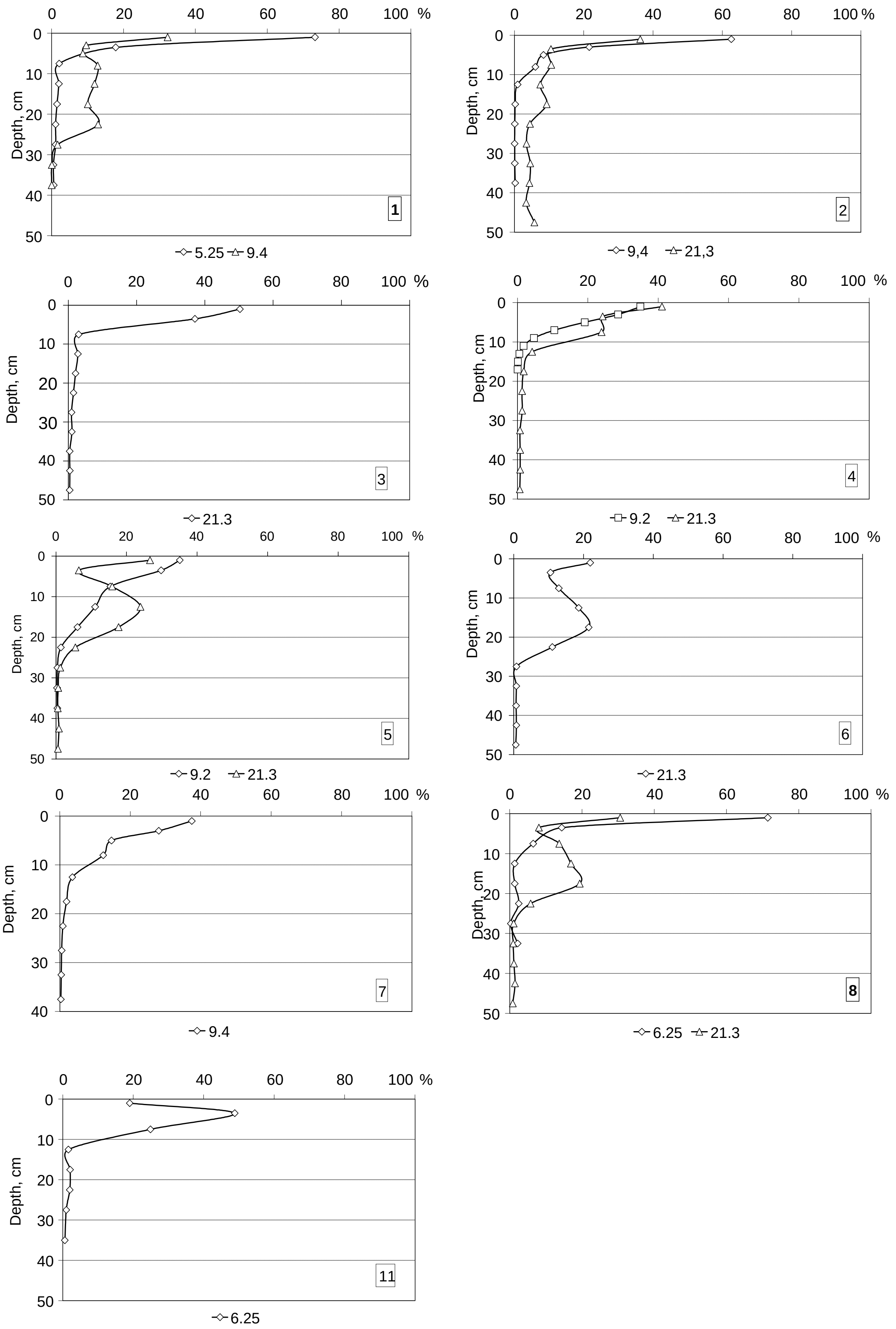

Fig. 2. ^{90}Sr distribution in soils profile at the experimental plots at various times after the ChNPP accident (numbers below the diagrams show the number of years after the fallout).

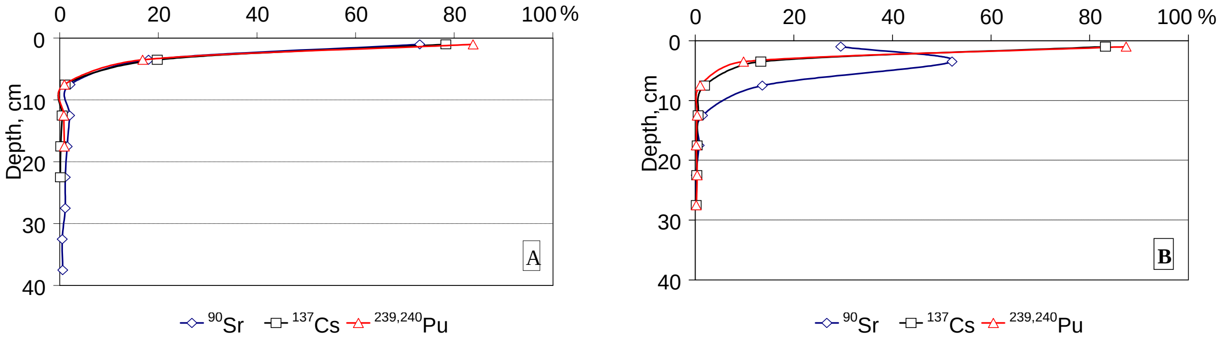

Fig. 3. ^{90}Sr, ^{137}Cs, and ^{239,240} Pu vertical distribution in soil profiles: A) sod podzol sandy soil (the fuel component share in the fallout is 80% for ^{137}Cs; 2-3 km West from the ChNPP); B) peat podzol gleyed soil previously used as a cropland (the fuel component share in the fallout is 45% for ^{137}Cs, 4 km North from the ChNNP).