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Vertical distribution of ^{137}Cs in forest soil after the ground fires

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We studied the influence of forest fires on vertical pattern of ^{137}Cs specific activity concentration in forest soils. Our experiments were organized in Bazar forestry of State Enterprise (SE) "Narodychi Forestry" (Ukraine). We sampled soil in the study sites where grassfires occurred at different times, and determined the specific activity of ^{137}Cs in all soil horizons. We determined that the forest fires and burned forest litter intensify mineralization of forest litter nutrients and increase the radionuclide content in upper layers of soil mineral part. In the following years, the radionuclides gradually move to deeper soil horizons and the difference between the burned and control areas decreases. We determined the depth of soil layer, where the changes in ^{137}Cs specific activity occur caused by the forest fires. The time required for restoration of the original distribution is calculated. The results obtained allow us to identify a group of plants (by the location of the root system) that may have increased levels of contamination in the years following a forest fire and to determine the period when we must conduct additional radiological control of them. We suggested the recommendations on usage of non-timber forest products on the territories contaminated with radionuclides.
Key words: forest plantations; forest fires; soil; forest litter; soil layers; radionuclides; specific activity

Introduction

The accident at the Chernobyl nuclear power plant (ChNPP) caused radiation contamination of large areas in Ukraine. More than 43,000 km^2 (almost 7 % of the total territory) were contaminated with ^{137}Cs isotope with deposition density higher than 37 kBq/m^2 (Krasnov et al., 2016). The location of a nuclear power station and weather conditions at the time of the accident stipulated the highest intensity and the extent of the territorial distribution of accidental releases in one of the most wooded regions, in Polissia.

Before the accident at ChNPP sustainable forestry activity aimed at maintaining the proper sanitary condition of forests and the formation of forest stands was conducted. As the result of ChNPP a significant part of radiation contaminated forests were excluded from the sphere of intensive forestry. Any forestry activity in Ukraine (mainly in Polissia) has been banned so far on the territory of 6.39 * 10^4 ha. The use of non-timber forest products on the territory of 1.14 * 10^6 ha (Krasnov et al., 2013) has been either conserved or regulated. Insufficient measures of stands control created favorable conditions for the increase of pest populations and forests diseases, as well as the reduction in wood quality. This has also accelerated the self-thinning process of forest stands and has increased accumulation of deadwood and formation of windfall (Melnik et al., 2016). These caused the high fire danger of forest stands. The situation is complicated by the fact that the machinery and equipment for dowsing fires is extremely outdated and deteriorated. Besides, their quantity is not sufficient for such forest areas. Thus, before the fire is localized and dowsed it can be spread to very large territories. Dry weather conditions seen on the territory of Ukraine for several recent years also contribute to the mentioned above facts. As a result, the number and the extent of forest fires in forest areas contaminated with radionuclides have significantly increased in recent years. In general, about 3,000 forest fires (Reports, (2007-2014) occur each year in the area over 3000 hectares in the forests of Ukraine (Fig. 1). A significant part of these forest fires occurs in the territory contaminated with radionuclides due to the poor sanitary condition.

Crown fires are dangerous, since they spread on big areas and are very intensive. High temperatures allow radionuclides penetrating the atmosphere through suspension of gases and ashes, thus, wind currents can spread radiation pollution of adjacent territories (Amiro et al., 1996). Nevertheless, the bigger part of fires in zone of radiation contamination belong to ground fires and are not considered to be intensive. As the result of these fires shrubs, grass and partly forest litter burn out. This type of fires is not characterized by intensive formation and spread of radiation contaminated particles but contributes to the redistribution of radionuclides on the territories where fires occur. Mineralization of organic remains, accumulated in forest for the last several years, speeds up due to burning out. Radionuclides release from remains and can penetrate the upper horizons of soil mineral part together with products of burning (Johansen et al., 2003). Thus, the assumption can be made that under standard functioning of forest ecosystems some amount of radionuclides could penetrate soil mineral part within 5 – 7 years due to its natural disintegration, but under mentioned above conditions the same amount of radionuclides can penetrate soil mineral part within 1 year. As the result, amount of radioactive elements in upper soil horizons increased in the first years after forest fires. From then on, radionuclides distribution renews, since fresh leaf litter accumulated in the first years after forest fires does not manage to decompose and radionuclides transferring in soil practically does not occur.

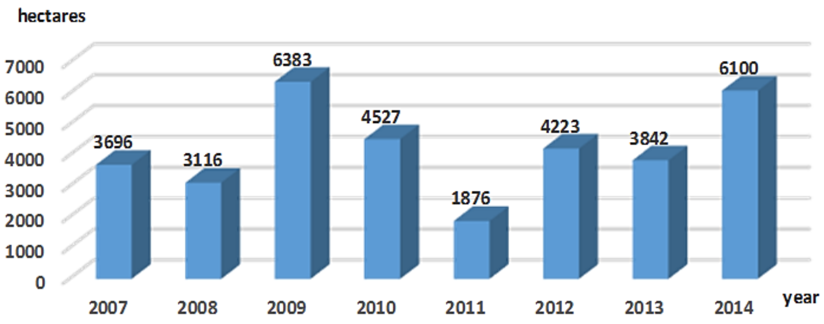


Fig.1. The areas of forest fires on the territory of Ukraine

In the first years after the fire radionuclides penetrate plants, especially herblike species, more easily. It can induce the higher level of radiation contamination, compared to the background observed in the territory. All these facts call for more detailed study of the radionuclides vertical distribution in forest soils in post-fire period in the territory contaminated with radionuclides. Reconsideration of the use of certain types of non-timber forest products in these areas in the coming years after the fires is the end result of the study.

Extensive radioecological investigation in forest ecosystems began after the Chernobyl accident. Scientists have studied radionuclides distribution in forest litter and soil mineral part (Garbaruk, 2015), radionuclides migration in different forest conditions (Pronevych, 2014), as well as radionuclides accumulation in forest products (Kudyn, 2015). External and internal exposure of population on the territories (Jönsson et al., 2017) contaminated with radionuclides have been estimated. Non-timber forest products (berries, edible mushrooms, meat of game animals) (Weimer, 2015) constitute a considerable part of food for local population living in the territories contaminated with radionuclides. That’s why a serious study on the ways of radionuclides penetration into non-timber forest products was conducted. Nevertheless, the Fukushima accident gave scientists data to compare consequences after this and the Chernobyl accident (Yoschenko et al., 2015). Based on the conducted investigations, Ukrainian scientists developed a number of normative documents and recommendations for the industry, including the Recommendations on forestry activity in the conditions of radioactive contaminations of territories (Recommendations, 2008). The Recommendations are regulating any forestry activity on the territories contaminated after the Chernobyl accident.

The latest investigations of Ukrainian and Belarusian scientists are concentrated mostly on the study of radiation contamination reduction in forests suffered after the Chernobyl accident, which was facilitated by the natural disintegration of radionuclides and radionuclides content in the forestry products (Dvornyk et al., 2016). The investigation results allow scientists substantiating the possibility of bringing forests into economic use (Krasnov et al., 2013; Bulko et al., 2016). Scientific research conducted further is considered to be the basis for developing a new edition of the Recommendations on forestry activity. Previous edition of Recommendations did not take into account the process of radionuclides distribution in forest ecosystems after fires, which is unacceptable. Such data should be included into renewed Recommendations, as far as forest fires can cause more intensive penetration of radionuclides into non-timber forest products and, thus, increase the risk of population exposure. All mentioned above calls for the necessity of further studies of the issue.

The first scientifically substantiated complex data on the character of forest fires in the conditions of radioactive contamination of the territories were presented at the international meeting under the auspices of the UN FAO in 1993. Further research on the issue was carried out by scientists from All-Russian Research Institute of Chemicalization of Forestry and All-Russian Research Institute for Fire Protection. The project was headed by S. I. Dusha-Gudym. Developments in this research direction were generalized and published in the overview (Dusha-Gudym, 1993) and reference book (Dusha-Gudym, 1999) for a relatively wide range of forestry experts. This reference book provides information on spatial location of radioactive trail, level of contamination, and the degree of fire danger of forests in zone of radioactive contamination. The study results on specific activity of radionuclides in combustible forest materials, their combustion products and smokes were presented. However, the processes of radionuclides penetration into forest ecosystems along with the products of combustion were not studied. There is no investigation on the vertical distribution of radionuclides in forest soils and their penetration into forest plants.

In 2006, Ukrainian scientists carried out experiment on the control of burning out forest areas contaminated with radionuclides (Yoschenko et al., 2006). Main attention was paid to the radionuclides transformation into suspension state and to the probability of their transportation with air currents. Scientist estimated the influence of forest fires on radioactive contamination of adjacent territories. The resuspension coefficient for each radionuclide, as well as the additional inhalation dose for firefighters working in forests contaminated with radionuclides, were estimated. Canadian scientists (Paliouris et al., 1995), who compared ^{137}Cs concentrations on burned and unburned stands, studied radionuclides redistribution in forest ecosystems where fires occurred. The study results showed that fires caused ^{137}Cs mobilization bound to the above-ground matter and with its concentration in the ash layer of the burned soil.

Study of long-term effects of forest fires did not give positive results (Dowdall et al., 2017). Even 10 years after forest fires there was no difference in ^{137}Cs distribution in soil profile and timber on burned and unburned forest stands. Probably, the difference could be observed in the period after forest fires, and such difference could mitigate with time. While the radionuclides migration in forest ecosystems is thoroughly studied, the problem of radionuclides distribution in forest ecosystems is still under consideration.

Methods

The experimental area was located in Bazar Forestry State Enterprise "Narodichi Forestry", Zhytomyr region, Ukraine (Fig. 2), about 70 km from Chernobyl NPP (51°5'35'' N, 29°18'56'' E) in the most typical forest conditions for this region – fresh subory (B2) (Fig. 3). ^{137}Cs deposition in this area varies between 177–395 kBq/m^2 as it was determined during the preliminary surveys (Krasnov et al., 2015).

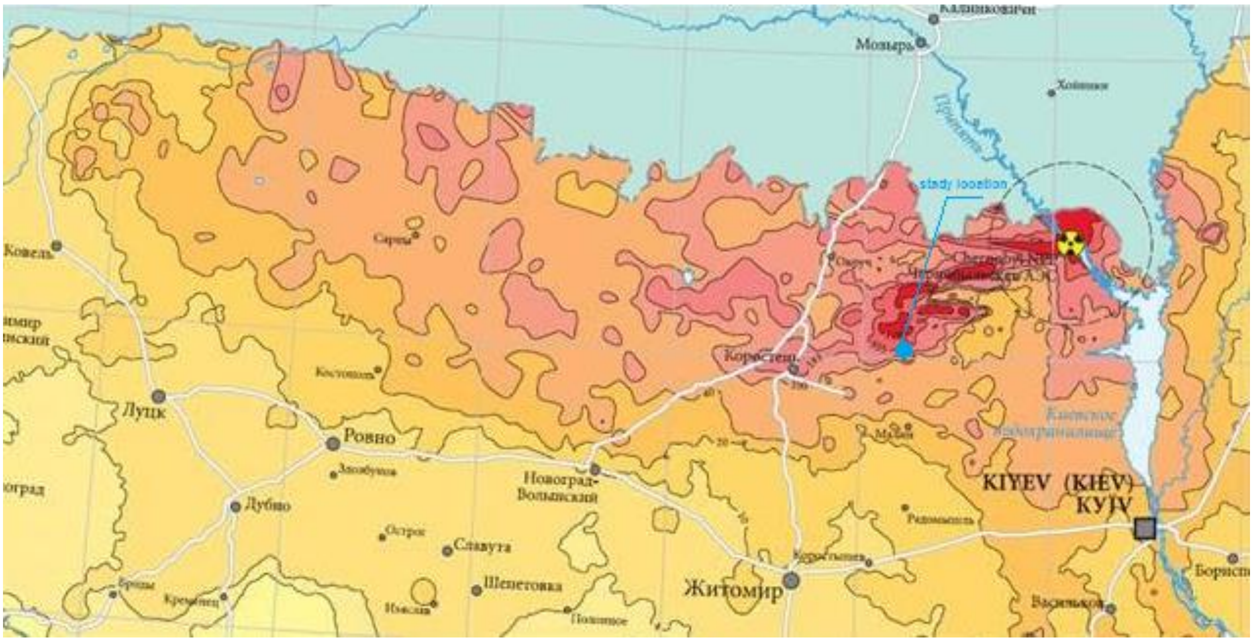


Fig. 2. Are of 137Cs contamination in Northern Ukraine after the Chernobyl accident

Soddy podzolic soil is the major soil type within the experimental area. The thickness of the organic horizon did not exceed 3-5 cm. To determine soil chemical characteristics the samples were selected in each separate stratum by quadrate method. According to generally accepted techniques, soil samples were selected with sampler to the depth of 15 cm. The analysis of samples average (20 sampling points in each separate stratum) was conducted on the basis of certified laboratory at Zhytomyr sanitary-epidemiological station. Main chemical characteristics of studied soil to the depth of 0-15 cm were as follows: pH of 4.25 ± 0.47, Tot-C 2.96 ± 1.93 %, Tot-N 0.12 ± 0.09 %, C/N 24.76 ± 2.78, K-AL 7.03 ± 6.36 mg/100g, Ca-AL 16.82 ± 19.22 mg/100g, K-HCl 15.63 ± 6.31 mg/100g, Ca-HCl 22.85 ± 21.70 mg/100g (mean ± SD, n = 14).

As far as forest fires is a spontaneous phenomenon, and burning out forests for conducting experiments is impermissible in Ukraine without special allowance, it was impossible to conduct research of ^{137}Cs vertical distribution in soils of experimental areas in the period before fires. That's why experimental areas were selected from the territories burnt after fires. The conditions for selecting the areas were their close location, minor differences in the density of radioactive contamination, the same type of soils, forest conditions and composition of the forest stand, as well as similar structure of vegetation cover. In the result of preliminary analysis, three experimental areas suffered after ground fires in different years were selected in the quadrant 45 of Bazar forestry (Fig. 3). Forest fires occurred within all areas in the most dry summer period. Research was conducted in 2014. We provided the onservations in one year after the fire at the experimental area 1. Two years after the fire the research was conducted in the experimental area 2, and three years after the fire the research was done in the experimental area 3. The choice of these areas allows to study the temporal radionuclide distribution in soil.

Since the survey of the burnt areas was not conducted before the fires, the experimental area 4 was selected as the control plot where there were no fires. The distance between the experimental areas was 50-100 m. Considering the flat relief of the territory, such distance is enough to exclude the possibility of the radionuclides transition between areas with direct runoff. When selecting experimental areas, the prevailing wind direction during the fire was taken into account. None of the experimental areas was contaminated by radioactive ash during the fires in neighboring ones. The same applies to the control area.

The density of soil radioactive contamination in the period of study (2018) was the following: the experimental area 1 – 376.4 kBq/m^2, the experimental area 2 – 164.2 kBq/m^2, the experimental area 3 – 182.9 kBq/m^2, and the experimental area 4 – 224.9 kBq/m^2.

Fig. 3. Forest stands in the experimental areas (quadrant 45, Bazar forestry of State Enterprise (SE) "Narodychi Forestry")

The experimental areas (before the fire) had the same characteristics of the tree layer (pure stands of 90 year old Scotch pine (*Pinus* sylvestris L.). Besides, they were characterized by a high homogeneity both of soil and floristic composition of vegetation mantle. Forest understorey is represented by oppressed specimens of Scotch pine, common oak (*Quercus robur* L.), and one of European mountain ash (*Sorbus aucuparia* L.). Shrub plants were quite numerous and consisted of a Yellow Rhododendron (*Rhododendron luteum* Sweet.), Labrador tea (*Ledum palustre* L.), alder buckthorn (*Frangula alnus* Mill.) and European dewberry (*Rubus caesius* L.). The basis of grass and shrub layer was blueberry (*Vaccinium myrtillus* L.), cowberry (*Vaccinium vitis-idae* L.), common heather (*Calluna vulgaris* L.), sedge helobius (*Carex limosa* L.) and fibrous tussock-sedge (*C. appropinquata* Schum.). To conduct research within selected experimental areas (compartments) four sample plots were put. The size of each sample plot is 100x100 m.

At each sampling plot, three soil samples (Fig. 4) were randomly collected. Such quantity of soil profiles on each sample plot allows making representative sampling, which is evidenced by obtained results (fluctuation of ^{137}Cs specific activity from the average value within separate horizons does not exceed tolerance limits). Both the description and the measurement of thickness of selected soil horizons within each soil profile were carried out. After that, soil samples were selected from all profiles for determining ^{137}Cs specific activity. The technique for selecting samples was the following: point samples were selected from each of soil horizons. As far as thickness of forest litter and humus-eluvial horizon is insufficient (not more than 3 cm), just one point sample was taken from each of these horizons. Three point samples were taken from other soil horizons (from their upper, middle and lower parts). The maximum depth of sampling was limited to 60 cm. It is due to no necessity of studying radionuclides in deeper soil layers, whereas their redistribution could not take place at such depth after the fire in the forest (Krasnov et al., 2015). Soil samples were taken using a drill PD-25-15 (hand sampler of point type with a head of 3cm in diameter and 20 cm length). The weight of a selected soil sample was 300-400 grams. There were 108 samples selected. Packaging, transportation, storage and disposal of radioactive samples of forest products were carried out according to NRBU -97 (Radiation safety standards of Ukraine). The formal note of selection and a passport were made for each sample.

^{137}Cs content was measured in all selected samples. Samples preparation and measurements were conducted on the basis of specialized radioecological laboratory at Zhytomyr State Technological University.

The preparation of samples for spectrometric analysis was the following: drying to air-dry state, grinding and homogenization, filling of measuring vessels, and their weighing. Measurement of ^{137}Cs specific activity in samples was made with the complete scintillation spectrometry system GDM-20 (Gammadata Instrument AB, Sweden), which is based on a 3"x3" NaI (Tl) detector on a 14-pin PM-tube. Measurement of ^{137}Cs with spectrometry system was automatically controlled by WinDAS software. Counting uncertainty for each of the analyzed sample did not exceed 5 %. Obtained data were automatically put into electronic database. Data were processed with application programs STATGRAPHICS and Microsoft Excel software.

Fig. 4. Soil profile

Results and Discussions

Studies have shown that the highest value of specific activity of ^{137}Cs was observed in the debris layer in all the experimental areas (Table 1). A similar consistency is observed on the areas where different amount of time from the moment of the fire has elapsed (number of years). Probably these circumstances are explained by the fact that during burning in all cases, mainly the upper inert part of the debris layer burnt out. Semidecomposed and decomposed parts of debris layer usually were not exposed to fire, their rate of mineralization did not increase under its influence, and so they continued to hold radioactive elements. Part of the radionuclides after the burning out of the top debris layer got to its lower layers, thus creating the prerequisites for their transition to the mineral soil.

However, comparing the values of specific activity of ^{137}Cs in debris layer and in hummus-eluvial horizon of different test areas, we found certain non-compliance. So, the distribution of ^{137}Cs between the two horizons is practically identical on experimental area No. 4 that had not experienced burning and on areas where forest fires took place 2 and 3 years ago (No. 2 and No. 3).

The values of the specific activity of the radionuclide in the hummus-eluvial horizon are 12 to 15 per cent from those established for the debris layer. At the same time, the test area №1, where the fire occurred a year ago, the specific activity of ^{137}Cs in hummus-eluvial horizon towards the debris layer was 40 %. Perhaps this is due to the greater intensity of the fire in the test area No. 1, which led to a partial burnout of semidecomposed part of the debris layer.

Table 1. The specific activity of ^{137}Cs in the soil layers on the sample areas, crops of which have been exposed to forest fires

Horizon	The area №4 (control)		No. 1 (1 year after fire)		No. 2 (2 years after the fire)		No. 3 (3 years after the fire)	
	the depth of sampling, cm	specific activity, Bq/kg	the depth of sampling, cm	specific activity, Bq/kg	the depth of sampling, cm	specific activity, Bq/kg	the depth of sampling, cm	specific activity, Bq/kg
Debris layer H0		15569.0		5428.7		7505.3		9521.0
HE	2.5	2419.0	1.7	2005.0	1.8	1134.0	1.7	1118.0
E	5.5	479.7	4.8	406.3	4.7	271.0	4.8	355.0
	9.5	215.5	8.8	198.0	8.8	89.8	8.8	119.7
	13.7	68.2	12.3	95.6	13.2	52.1	12.3	61.9
EI	18.5	29.7	14.5	34.5	17.5	45.4	15.5	33.4
	28	14.3	24.3	20.7	26	19.2	25	18.2
	38	12.0	35.8	14.2	34.2	15.7	34.8	9.2
I	48	11.3	52.5	6.1	44.5	10.6	51.7	7.4

On all test areas it is possible to trace the decrease of specific activity of ^{137}Cs with depth. However, the analysis of the peculiarities of the vertical distribution of ^{137}Cs in forest soils after fires is complicated by the significant initial pattern structure of radioactive contamination of forests. Therefore, for each sample area relative values of specific activity of ^{137}Cs were calculated according to soil layers, which were determined as a percentage of the sum of the values of the specific activity of the radionuclide in the soil profile (table 2 – 5).
The analysis of distribution of specific activity of ^{137}Cs in soil layers on the sample area № 4, that were not affected by forest fires shows a natural decrease in the content of the radionuclide with depth (table 2). Almost 96% of the sum of the values of specific activity of ^{137}Cs in the soil is concentrated in the debris layer (83 %) and hummus-eluvian horizon (13 %).

Table 2. Specific activity of ^{137}Cs in the soil layers (area №4 - control)

Horizon	The depth of sampling, cm	Specific activity of ^{137}Cs, Bq/kg	Specific activity of ^{137}Cs in a layer of the soil profile, %
Debris layer H0		15569.0	82.73
HE	2.5	2419.0	12.85
E	5.5	479.7	2.55
	9.5	215.5	1.15
	13.7	68.2	0.36
EI	18.5	29.7	0.16
	28	14.3	0.08
	38	12.0	0.06
I	48	11.3	0.06
Total		18818.7	100

On sample area № 1, where since the fire until the beginning of researches a year has passed, there has been a significant decrease in the content of 137Cs in debris layer (16% versus control). It is explained by more intense, deep burnout of the top debris layer and the transition of greater part of the radionuclides in the hummus-eluvial layer of the mineral soil (table 3). This is confirmed by the fact that the sum of the relative specific activity of 137Cs in the debris layer and hummus-eluvial soil horizon is approximately 91 %. The obtained data demonstrate that in this experimental area, the significant amount of 137Cs was recovered from the debris layer and got to the hummus-eluvial horizon and migrated to deeper soil horizons.

Table 3. Specific activity of 137Cs in the soil layers (sample area No. 1, 1 year after fire)

Horizon	The depth of sampling, cm	Specific activity of 137Cs, Bq/kg	Specific activity of 137Cs in a layer of the soil profile, %
Debris layer H0		5428.7	66.13
HE	1.7	2005.0	24.42
E	4.8	406.3	4.95
	8.8	198.0	2.41
	12.3	95.6	1.16
EI	14.5	34.5	0.42
	24.3	20.7	0.25
	35.8	14.2	0.17
I	52.5	6.1	0.07
Total		8209.0	100

The experimental areas No. 2 and No. 3, where 2 and 3 years have passed since the fire, patterns of vertical distribution of 137Cs in the soil layers that we set in the control plot (Tables 4-5) are observed. However, in the third year after the fire the inter-relation between the content of 137Cs in the debris layer and hummus-eluvian horizon has disrupted (table 5). Thus, the total value of the relative specific activity of 137Cs in hummus-eluvial soil horizon for the area No. 3 is only 10 % as opposed to 12-13 % for site No. 2 and control. This peculiarity can be explained by the fact that in the first years after the fire 137Cs continues to get to the hummus-eluvial horizon at the expense of destruction composed and semicomposed layers of hummus horizon, which almost were not damaged by fire. Further, the thickness of these layers decreases, but their natural recovery is disturbed as undecomposed tree waste was destroyed by the fire three years ago. It is likely that in the next (fourth year after the fire) there will be a gradual restoration of the initial distribution due to intensive decomposition of the debris layer, appearing in the following year after the fire.

Table 4. Specific activity of 137Cs in the soil layers (sample area №2, 2 years after the fire)

Horizon	The depth of sampling, cm	Specific activity of 137Cs, Bq/kg	Specific activity of 137Cs in a layer of the soil profile, %
Debris layer H0		7505.3	82.09
HE	1.8	1134.0	12.40
E	4.7	271.0	2.96
	8.8	89.8	0.98
	13.2	52.1	0.57
EI	17.5	45.4	0.50
	26	19.2	0.21
	34.2	15.7	0.17
I	44.5	10.6	0.12
Total		9143.1	100

Table 5. Specific activity of 137Cs in the soil layers (sample area №3 - 3 years after the fire)

Horizon	The depth of sampling, cm	Specific activity of 137Cs, Bq/kg	Specific activity of 137Cs in a layer of the soil profile, %
Debris layer H0		9521.0	84.68
HE	1.7	1118.0	9.94
E	4.8	355.0	3.16
	8.8	119.7	1.06
	12.3	61.9	0.55
EI	15.5	33.4	0.30
	25	18.2	0.16
	34.8	9.2	0.08
I	51.7	7.4	0.07
Total		11243.8	100

After analyzing the relative specific activity of 137Cs in eluvial horizon of the different test areas, it is possible to track the gradual increase in the 137Cs content in the upper layers of eluvial horizon with the time passed since the fire, which is caused by its gradual migration from hummus-eluvial horizon.

As can be seen from the generalized graph of the distribution of 137Cs in the soil layers on the test areas, since forest fires where different number of years passed (Fig. 5), redistribution of the content of the radionuclide can be traced to a depth of 10 cm and does not affect the deeper soil horizons.

Forest fires and the vertical redistribution of radionuclides in the upper layers of the soil profile can lead to changes in the intensity of accumulation of 137Cs by herbaceous and shrub plants root systems which are located in the upper 10-cm soil layer and debris layer. This stipulates a necessity of a ban or more stringent regulation of gathering wild berries and medicinal plants in the contaminated areas after forest fires.

To develop recommendations regarding limitations on the use of non-timber forest products after the fires, it is necessary to determine how much time is necessary to a full recovery of the vertical distribution of radionuclides in forest soils to its original condition (before the fire). Whereas, deflection of the vertical distribution of 137Cs between soil layers from the initial one is traced on sample area (3 years after the fire), it is necessary to apply the tools of mathematical processing of the data to obtain predictive results. With this purpose, graphs of dependence of specific activity of 137Cs in soil to the depth of its placement for each sample area (Fig. 6) were constructed and mathematical relationships that describe them were determined (table. 6).

Mathematical relationships for all test areas with high confidence (R2= 0,98-0,99) are described by the exponential equation of the type

$$A = a_0 \cdot h^{a_1}, \qquad (1)$$

where *A* is the specific activity of 137Cs in soil, Bq/kg;

h is depth of soil sample selection, cm;

a_0 and a_1 are parameters of the regression equation.

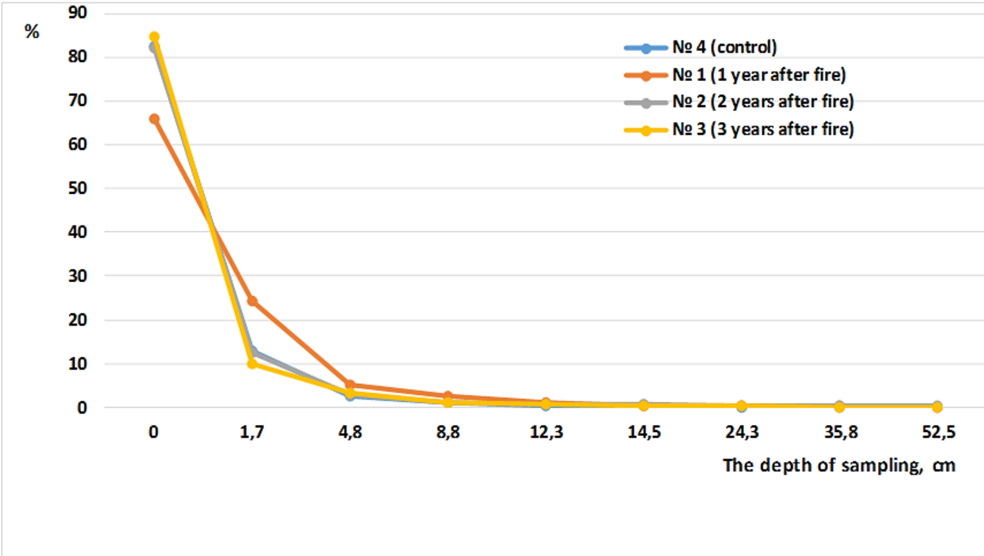


Fig. 5. The vertical distribution of 137Cs in the soil layers

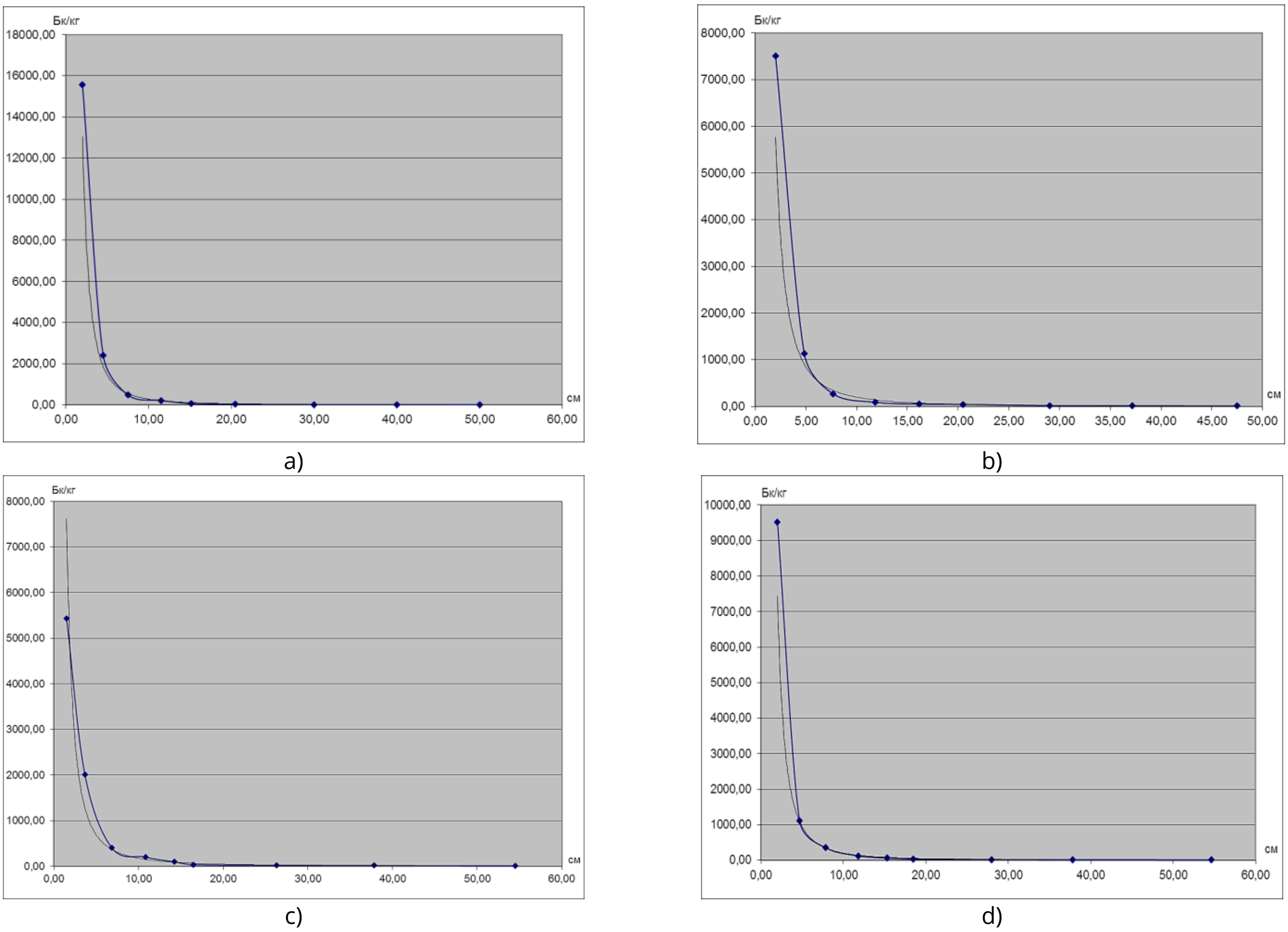


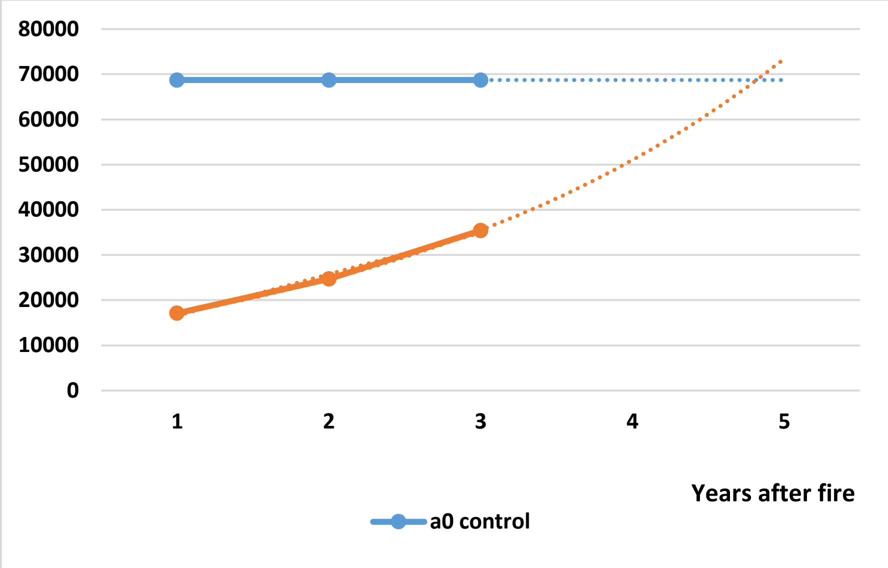
Fig. 6. The dependence of specific activity of ^{137}Cs in soil and sampling depth: a) No. 4 (control); b) No. 1 (1 year after fire); c) No. 2 (2 years after a fire); d) No. 3 (3 years after the fire)

Despite the same type of equation (exponential) for all test areas that describes the mathematical relationship between specific activity of ^{137}Cs in the soil (*A*) and depth of sampling (*h*), variations in the parameters a_0 and a_1 for the regression equations (Table 6) are traced. The largest differences are observed between the corresponding parameters for the test area (No. 4) and the area that suffered from burnout a year ago (No. 1).

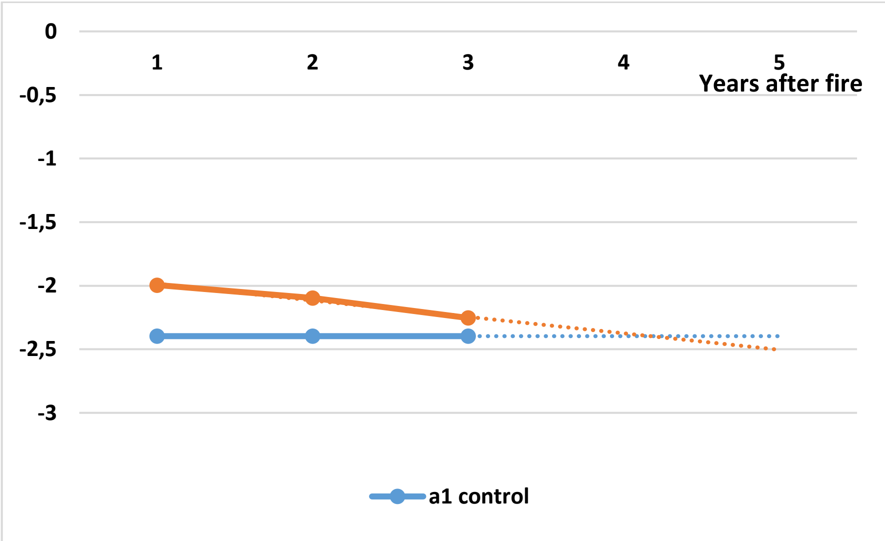
Table 6. Regression parameters for specific activity of ^{137}Cs in the soil and sampling depth

No.	Time after burning	regression equation	equation parameter a_0	equation parameter a_1
1	1 year	$A = 17104 \cdot h^{-1.995}$	17104	-1.995
2	2 years	$A = 24683 \cdot h^{-2.098}$	24683	-2.098
3	3 years	$A = 35427 \cdot h^{-2.254}$	35427	-2.254
4	control	$A = 68724 \cdot h^{-2.397}$	68724	-2.397

For test areas where the fire was 2-3 years ago (No. 2 and No. 3) the gradual approximation of the equation parameters with the parameters of the equation of a test area was observed, and therefore the restoration of the original vertical distribution of ^{137}Cs in soil horizons is evident. This allows us to forecast future changes and calculate the approximate return time of the vertical distribution of 137Cs in soils of forest ecosystems after the fires to their original state. We did it by plotting the regression equation of test areas (No. 1-3) in accordance with a time elapsed after the fire, and by analyzing the change of the parameters of these equations. We draw the graphs demonstrated the changes in parameters a0 and a1 depending on the time after the fire (Fig. 7). The value of corresponding parameters for control test area that did not experience fire was taken as the control. Proceeding from the simulation results, we assumed that vertical distribution of ^{137}Cs in forest soils after the fires will occur for a time that does not exceed 5 yearse. Therefore, it is necessary to introduce tougher regulation of procurement of berries and medicinal raw materials in the forests contaminated by radionuclides after the fires during this period.



a)



b)

Fig. 7. Dynamics of parameters a0 and a1 versus the time after the fire. a) parameter a0; b) parameter a1

Conclusions

Radiological analysis of soils in forest ecosystems after the ground fires showed differences in the vertical distribution of total activity of 137C regards the time after the fire. Our results testify that crown fires caused the vertical distribution pattern of radionuclides in forest soils, namely the decrease of their content in the debris layer and increase in the upper horizons of the mineral soil. We traced vertical distribution of 137Cs in soils after the crown fires up to a depth of 10 cm, its deeper concentration was not detected. Initial distribution of radionuclides in the soil profile is restored within 5 years after the forest fire. We observed the content of radionuclides slightly increased in the upper soil layers by this time. We thought this could be threat of more intense submission to the plant root system which is located in the soil layer up to 10 cm and in debris layer.

Thus, the plants that can potentially have high content of radionuclides after the fires are herbs and berries. Therefore, in it is necessary to organize serious regulation of their procurement this period.

References

Amiro, B.D., Sheppard, S.C., Johnston, F.L., Evenden, W.G., Harris, D.R. (1996). Burning question: what happens to iodine, cesium and chlorine in biomass fires? The science of the total environment, 187, 93–103.

Bulko N.Y., Mashkov Y.A., Tolkacheva N.V., Moskalenko N.V., Kozlov A.K. (2016. On the state of forests and forest lands of resettlement zones in the context of their rehabilitation possibilities. Problemy lesovedenyja i lesovodstva. Proceedings of Forest Institute, National Academy of Science of Belorussia, 76, 363–370 (in Russian).

Dowdall M., Bondar Y., Skipperud L.. (2017), Investigation of the vertical distribution and speciation of ^{137}Cs in soil profiles at burnt and unburnt forest sites in the Belarusian Exclusion Zone, Journal of Environmental Radioactivity, 175–176, 60–69.

Dusha-Gudym S.I. (1993). Forest fires in territories contaminated with radionuclides, Nauchno-issledovatelskij i informacionnyj centr po lesnym resursam, Moscow (in Russian).

Dusha-Gudym S.I. (1999). Radioactive forest fires, Nauchno-issledovatelskij i informacionnyj centr po lesnym resursam, Moscow (in Russian).

Dvornyk A.M., Dvornyk A.A. (2016). Complex model of behavior of long-lived radionuclides in forest ecosystems, Problemy lesovedenyja y lesovodstva, Proceedings of Forest Institute, National Academy of Science of Belorussia, 76, 380–385 (in Russian).

Garbaruk, D.K. (2015). Distribution of ^{137}Cs in forest litter and soil of the dominant types of forest in a pine formation near the Chernobyl nuclear power plant accident zone, Problemy lesovedenyja y lesovodstva. Proceedings of Ynstytut lesa Nacionalnoj akademii nauk, Gomel, 75, 412–419 (in Russian).

Johansen M.P., Hakonson T.E., Whicker F.W., Breshears D.D. (2003). Pulsed redistribution of a contaminant following forest fire: cesium-137 in runoff. Journal of environmental quality, 32, 2150–2157.

Jönsson M., Tondel M., Lsaksson M., Finck R., Wålinder R., Mamour A. and Rääf, C. (2017). Modelling the external radiation exposure from the Chernobyl fallout using data from the Swedish municipality measurement system, Journal of Environmental Radioactivity, 178–179, 16–27.

Krasnov V.P., Kurbet T.V., Davydova I.V. (2015), Analysis of the results of forest survey on radioactive contamination for their rehabilitation, Naukovyj visnyk Nacionalnogo lisotehnichnogo universitetu Ukrainy, 4, 52–55 (in Ukrainian).

Krasnov V.P., Kurbet T.V., Davydova I.V., Shelest Z.M. and Bojko O.L. (2015), Vertical distribution of total activity of ^{137}Cs in soils of the Polissya of Ukraine. Naukovyi visnyk Nacionalnogo lisotehnichnogo universitetu Ukrainy, 5, 123–129 (in Ukrainian).

Krasnov, V.P., Kurbet, T.V., Korbut, M.B. and Bojko, O.L. (2016). Distribution of ^{137}Cs in the forest ecosystems of the Polissya of Ukraine, Agroekologichnyj zhurnal, 1, 82–87 (in Ukrainian).

Krasnov, V.P., Landin, V.P. (2013). Methodological bases for rehabilitation of forest ecosystems contaminated with radionuclides, Zbalansovane pryrodokorystuvannja, 2–3, 33–39 (in Ukrainian).

Kudyn M.V. (2015). The current state of the pine forests of the Belarusian sector of the exclusion zone of the Chernobyl nuclear power plant, Problemy lesovedenyja y lesovodstva, Proceedings of Ynstytut lesa Nacionalnoj akademii nauk, Gomel, 75, 468–479. (in Russian).

Melnik V.V., Kurbet T.V., (2016). Sanitarnyy stan sosnovykh nasadzhen' v zoni bezumovnoho vidselenny. Proceed. All-Ukrainian Sci. Conf. devoted to the Day of Science, Zhytomyr, 181–182 (in Ukrainian).

Paliouris G., Taylor H.W., Wein R.W., Svoboda J., Mierzynski B. (1995). Fire as an agent in redistributing fallout ^{137}Cs in the Canadian boreal forest, The science of the total environment, 161, 153–166.

Pronevych, V.A. (2014). Migration of ^{137}Cs in forest biocenoses of Polissya, Naukovyj visnyk Nacionalnogo lisotehnichnogo universitetu Ukrainy, 24 (7), 145–150 (in Ukrainian).

Recommendations on forestry activity in the conditions of radioactive contaminations of territories. (2008). Kyiv (in Ukrainian).

Reports of Zhytomyr Regional Department of Forestry and Hunting (2007-2014). Printed and stored in one hard copy. (in Ukrainian).

Weimer R.N. (2015). Temporal and Spatial Variation of Radiocaesium in Moose (*Alces alces*) Following the Chernobyl Fallout in Sweden, Licentiate Thesis. Swedish University of Agricultural Science, Upsala. SLU Service/Repro. Upsala.

Yoschenko V., Nanba K., Konoplev A., Takase T., Zheleznyak, M. (2015). Radiocesium distributions and fluxes in the forest ecosystems of Chernobyl and Fukushima, Geophysical Research Abstracts, 17, 235-241.

Yoschenko V.I., Kashparov V.A., Protsak V.P., Lundin S.M., Levchuk S.E., Kadygrib A.M., Zvarich S.I., Khomutinin Y.V., Maloshtan I.M., Lanshin V.P., Kovtun M.V., Tschiersch J. (2006). Resuspension and redistribution of radionuclides during grassland and forest fires in the Chernobyl exclusion zone: part I. Fire experiments, Journal of Environmental Radioactivity, 86 (2), 143–163.

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