ECOLOGY

Forest ecosystems are complex areas in terms of rehabilitation of radioactively contaminated areas, so conducting an up-to-date examination of these areas for radioactive contamination is relevant. The paper considers the improvement of methods of soil sampling for obtaining representative materials in the estimation of vertical migration of ^{137}Cs in the soil profile and the level of soil contamination with ^{137}Cs. The density of radioactive soil contamination was studied by reducing the number of selected samples from 30 to 3 in the layers of 10, 20, and 30 cm. The results show that when the number of soil samples decreases, the average magnitudes of soil contamination with ^{137}Cs are not significantly different within each analyzed layer. It was noted that at sampling in the 10-centimeter layer, the studied indicator was 1.3–1.4 times lower than in the layers of 20 and 30 cm, and there is no difference between the latter. To obtain reliable levels of radioactive contamination of the territory, it is necessary to perform 10-time repeated sampling in the forest soil layer of 30 cm. At a decrease in the number of soil samples from 10 to 3, the fluctuation of average values of the specific activity of ^{137}Cs in different layers of soil profile is low. To obtain representative magnitudes of ^{137}Cs content in each layer of the soil profile, it is necessary to make various samplings. Thus, for 4-time repeated sampling, is sufficient for all layers of forest litter, and 6-time repeated sampling is enough for the humus-eluvial horizon. It is necessary to perform 8-time repeated sampling for the eluvial and illuvial horizon, and 10-time repeated sampling for illuvial sand and parent rock. The obtained results make it possible to carry out up-to-date examination of forests for radioactive contamination based on the updated methodology and using the obtained data on ^{137}Cs migration in forest soils

Keywords: ^{137}Cs, density of radioactive soil contamination, forest ecosystems, soil sampling

UDC: 630:574*631.4(477.42)
DOI: 10.15587/1729-4061.2020.209873

SOIL SAMPLING WHEN EXAMINING FORESTS FOR RADIOACTIVE CONTAMINATION

V. Melnyk
Assistant*
E-mail: melnyk_vika91@ukr.net
T. Kurbet
PhD, Associate Professor*
E-mail: meraviglia@ukr.net
Z. Shelest
PhD, Associate Professor*
E-mail: szm05121960@gmail.com
I. Davydova
PhD, Associate Professor*
E-mail: davydvairina2@gmail.com
*Department of Ecology
Zhytomyr Polytechnic State University
Chudnivska str., 103,
Zhytomyr, Ukraine, 10005

Received date 05.06.2020
Accepted date 03.08.2020
Published date 25.08.2020

1. Introduction

The accident at the Chernobyl Nuclear Power Plant (CNPP) radically changed the radiation situation on the European continent. Significant areas of the countries of the former Soviet Union and Europe suffered intensive radioactive contamination, which substantially changed the living conditions of people in these territories. The first radioecological research revealed that forest arrays had much higher levels of radioactive contamination compared with other forms of landscapes [1, 2]. Research results of [3] show that the forest areas kept by 20–30 % more radionuclides compared to the open terrain. Due to various natural factors and inhomogeneity of radioactive falls in terms of composition and physical-chemical properties, the mosaic, focal and high-gradient character was noticed during the examination of forest grounds for radioactive contamination [3, 4]. This caused a significant difference between the minimum and maximum magnitudes of soil contamination density within one forest area or a taxation area [5]. Such discrepancies essentially complicated the forest examination in order to determine the scale of radioactive contamination of forest ecosystems. The examination of forest arrays was conducted at several stages, which differed among themselves both by volume of works and by methodological approaches. However, they all had some (objective and subjective) methodological flaws, which influenced the accuracy of executed works.

30 years have passed since the Chernobyl accident, the radiation situation in forest ecosystems has changed, which is related to natural decomposition of ^{137}Cs, its redistribution in soil and consolidation in the main components of forest ecosystems. That is why it is advisable to examine forest areas for radioactive contamination in order to resume separate forestry activities, which will contribute to the improvement of the state of incompletely degraded plantations. However, the above-mentioned examinations require the solution of particular methodical issues, namely, the perfection of the procedure that would allow obtaining reliable results and would not require excess costs and consumption of working time. That is why determining the optimum number of soil samples and the required depth of their sampling for the objective characteristic of the current radiation situation in forests is necessary and relevant. Results obtained using this procedure will make it possible to develop a modern map of

radiation situation on the territories contaminated as a result of the accident at the CNPP and will contribute to solving the problem of rehabilitation of forest areas.

2. Literature review and problem statement

Soils are the initial section of all biogeochemical cycles in forest ecosystems. Vertical redistribution of radionuclides in the soils is characterized by certain peculiarities. The results of research [6, 7] show that in the first years after the accident, forest litter contained the major number of radionuclides. Over time, the bulk of the gross stock of ^{137}Cs in forest soil has moved into the mineral part of the soil [8, 9]. Based on the conducted research [10], inhomogeneity of radioactive contamination of forest soils, regularities of distribution of radionuclides between the forest litter and mineral layers of soil were described fairly well. The researchers proposed prognostic models for migration and distribution of radionuclides in soils, but these models had a theoretical basis and were based on the half-life of radioactive elements. Paper [11] studied the distribution of ^{137}Cs in soddy podzolic soils in different types of forest-vegetative conditions. The authors found that the forest litter remains a geochemical barrier on the way of radionuclide migration in soil, and maximum magnitudes of the specific activity of radionuclide were found in the humus-eluvial horizon. Other authors obtained similar results concerning the peculiarities of vertical migration of radioactive elements in soils of different types of forest-vegetative conditions. Thus, the transition of a significant amount of ^{137}Cs to the mineral part of the soil was detected in article [12]. It was established that the highest content of ^{137}Cs was observed in 12-centimeter layers, in the fresh boreal forest, it is 54.0 %, in fresh subors – 40.0 % and in wet subors – 52.8 % of the total activity of radionuclide in soil. During the monitoring study [13] of the content of radionuclides in soils and vegetation, researchers found that evergreen coniferous vegetation kept up to 80 % radionuclides. In addition, scientists argue that after three years, the major amount of radionuclides moved to the soil. The process of ^{137}Cs transition into deeper soil layers is quite rapid in peat soils and considerably slower in the automorphic sandy soils. Thus, the maximum depth of radionuclides penetration in automorphic soils is from 30 to 70 cm, in hydromorphic, it is by 2–3 times deeper [14, 15]. In papers [16, 17], it was found that the biological accessibility of ^{137}Cs in the soil increases with depth. The result of research [18] was a thorough description of the modern redistribution of radionuclides among the main components of forest ecosystems. In addition, the authors underlined that the bulk of ^{137}Cs is still concentrated in forest litter and mineral layers of soil. As studies [19, 20] show, there is a slower radionuclides migration in deep layers of soil than in the upper ones. Research [21, 22] focused on studying the forms of finding and fixing radionuclides in soil. In recent years, some publications compare the materials of ^{137}Cs distribution in forest ecosystems as a result of the accidents at Chernobyl and Fukushima nuclear power plants [23]. Paper [24] deals with the sorptive capacity of ^{137}Cs to be retained in clay minerals of forest soils. These studies were conducted to predict further potential health risks and environmental pollution during radionuclides migration in soils. Various methods of soil sampling were used during these studies. Despite the sufficiently full research into the processes of migration and distribution of radionuclides in soils, there are still unsolved issues that are related to the sampling procedure to characterize the current density of radioactive soil contamination.

After the accident, researchers analyzed the radioactive contamination of agricultural land in more detail. This was due to the need to prevent external and internal irradiation of the population during agricultural work and the consumption of products from these lands. The scientists of the agricultural industry developed a unified approach to studying the radiation situation, which was based on two stages. The first stage involved gamma shooting, the results of which allowed choosing the optimum places for sampling, and the second stage – soil sampling in specified locations. All works at the first stage were carried out using the SRP-68-01 at the height of 1 m from the soil surface. The use of this approach allowed inspection of agricultural land in all areas affected by radioactive contamination. Based on the obtained results, the maps-schemes of radioactive contamination of land were compiled, which enabled the organization of farming [25, 26].

Examination of forests to determine the extent of radioactive contamination of territories took place at several stages and was much more complex compared to agricultural areas. The reason for this was significant areas of radioactive contamination of forest arrays, an insignificant number of skilled professionals, the lack of proper material base for research, and insufficient state funding. The first procedure of forest inspection was based on measuring the capacity of the exposure dose of gamma radiation using the military device DP-5V. Due to the need for obtaining urgent data, measurements of the exposure dose were carried out in 16 azimuth directions from the CNPP at certain intervals, linking these directions to forest roads and quarterly gaps. Conducted studies resulted in obtaining the configuration of radioactive contamination of forests, the power of exposure dose of gamma radiation in certain quarters, and a considerably mosaic character of contamination. The obtained materials described in detail radioactive contamination of forest areas and allowed taking a series of organizational measures to prevent irradiation of workers of the forest industry. In addition, forestry was prohibited in these areas or the use of forest products was regulated. However, such examinations covered small areas, were not sufficiently detailed, and the obtained results reflected the general regularities of radioactive contamination of the territory, which were used at the following stages of research.

The second stage of examination (1987–1988), characterized by other methodical approaches, covered significant forest areas, and needed significant labor resources. The studies were carried out in stationary forest sites, where soil was sampled and subsequently analyzed for the ^{137}Cs content on spectrometric devices. The power of the exposure dose was measured in soil sampling places. After receiving a sufficient amount of statistical material, the dependence between the power of the exposure dose of gamma radiation and the magnitude of the density of radioactive soil contamination was established. Northern forestry of Zhytomyr and Kyiv oblasts and a part of Rivne and Chernihiv oblasts were examined using this approach.

The next stage of the study lasted from 1989 to 1992. Within this period, a sufficient number of laboratories with a powerful instrumental base were created in Ukraine. The forests were examined by soil sampling and measuring the specific activity of radionuclides in soils. According to the results of research conducted in 1991–1992, it was found that 39 %

of the State Forest fund of Ukraine had the density of radioactive soil contamination with ^{137}Cs of more than kBk/m^2 [27]. The cartographic materials that reflected the accumulation of radioactive elements in forest ecosystems were developed based on the obtained data. The results of the examination of forest arrays for radioactive contamination of that time in general characterized the radiological situation in forests, however, there were many questions concerning the methodical approaches and the number of samples to assess the radioactive contamination of the territory.

According to other methodological approaches [10], the studies were conducted to determine the levels of radioactive soil contamination on permanent or temporary test areas. The first way to study the non-uniformity of radioactive contamination in forest quarters was based on the selection of a different number of samples, depending on the analyzed area. The second method is based on the use of a surveying compass and a measuring tape, where the power of the exposure dose was measured at the intersection of moves and mixed soil samples were selected to determine the density of radioactive contamination.

The developed procedure for the inspection of radioactively contaminated forests for the purpose of their rehabilitation (from 2010 through 2015) [28] was based on the results of the research conducted in 1991–1992. This procedure included obtaining current information on the density of radioactive soil pollution in forest quarters. However, this procedure involved soil sampling at the depth of 10 cm, and analysis of literary sources shows that radionuclides migrated to deeper layers of soil.

The accidents at the nuclear power plant in Fukushima prefecture caused radioactive contamination of significant areas of densely populated Japan, which is why the studies of overcoming the consequences of this accident are becoming increasingly important nowadays. Publication [29] deals with the possibility of decontamination of landscapes affected by the Fukushima accident. The activities on deactivation are mainly focused on agricultural and residential areas and do not relate to forest areas that cover 75 % of the region. In paper [30], the cost and effectiveness of radiation decontamination of forest arrays were assessed. Although the introduction of deactivation of all forest arrays ensures a significant decrease in the dose of external irradiation for an average resident, decontamination costs can potentially make up significant sums. As study [31] shows, in order to provide protection of the population during their stay in radioactively contaminated forest territories, it is necessary to perform constant analysis of a change in the dose of external irradiation of the population in these areas.

Paper [32] considers the need to establish beforehand the reference sampling sites with known background radiation for timely and reliable assessment of irradiation received by people in the affected zone and to determine the extent of environmental pollution. Research [33] considers the procedure of operative mapping of the territories contaminated with radionuclides, based on the use of correlative dependences between previously obtained results of the examination of radioactively contaminated territories. The use of this approach is informative and efficient for agricultural land under conditions of a limited amount of data about direct measurements and the time limit. However, radioactive contamination of forest areas is significantly different from the agricultural, which is why the use of this approach requires a different methodological basis.

More than 30 years have passed since the accident at the CNPP, and the radiation situation in the forests has stabilized. The radionuclides migration in soils, ^{137}Cs distribution in the main components of forest ecosystems, and its accumulation in various forest products were studied. The obtained research results made it possible to develop a series of normative documents [34, 35] aimed at harmonization of forestry management and the use of forestry products. However, despite the above studies regarding the examination of forest areas for radioactive contamination, many issues remain unresolved. Their main part is related to the lack of reliable information about the required quantity and the depth of soil sampling, which would most fully and accurately characterize current levels of radioactive soil contamination. All this gives reasons to argue that it is expedient to conduct research aimed at the improvement of the soil sampling procedure during the examination of forests for radioactive contamination.

3. The aim and objectives of the study

The purpose of this research was to improve the procedure of soil sampling to establish current magnitudes of the density of radioactive soil contamination in forest ecosystems and in assessing the vertical migration of ^{137}Cs in the soil profile.

To achieve the set goal, it is necessary to solve the following tasks:

– to study the necessary repeatability of soil sampling to obtain representative values of density of radioactive soil contamination with ^{137}Cs;

– to analyze different depths of soil sampling to characterize the current density of radioactive soil contamination in forest plantations;

– to establish the optimum number of soil samples, which is required to characterize the specific activity of ^{137}Cs in different layers of forest soils in the soil profile.

4. Materials and methods for research into soil sampling during the examination of forests for radioactive contamination

The research was conducted in 2018 at the state enterprise «Narodytske specialized forestry», in quarter 40, section 8 of Narodytsky forestry, Ukraine. A test area of 50×50 m was established to improve the methodological peculiarities of soil sampling during the study of redistribution of radionuclides in the soils of forest ecosystems and determining current levels of radioactive soil contamination. The type of forest plant conditions is fresh boreal forest (A_2). 56-year-old pine plantations (composition 10 *P. sylvestris*) with closeness 0.7, bonitet 2, medium height of 16 m and diameter of 20 cm grow on the test area. The regrowth is absent. The underbrush is isolated, about 1 m in height, formed by the Rowan ordinary (*Sorbus Aucuparia L.*). The projative coverage of the grass-shrub tier is 50–55 %. It is co-dominated by cranberries (*Vaccinium vitids-idaea L.*), Scotch heather (*Calluna vulgaris (L.) Hull*), melampyrum (*Melampyrum pretense L.*). The mossy tier has projection coating of 85–90 %. It is dominated by variable-leaved crestwort (*Dicranum polysetum Sw.*) and Schreber's big red stem moss (*Pleurozium schreberi (Willd ex Brid.) Mitt*). Association: green mossy pine forest. The density of radioactive soil contamination was 266.5±11.8 kBk/m^2 (7.2±0.3 Ki/km^2), maximum values reached 477.5 kBk/m^2

(12.9 Ki/km^2), and minimum – 163.6 kBk/m^2 (4.2 Ki/km^2). The soil is soddy-podzol sandy soil on fluvioglacial sands.

To characterize the specific activity of ^{137}Cs in different layers of forest soils in the soil profile, the soil pit was established. The soil profile was established in typical places that were characterized by homogeneous relief elements, moisturizing conditions, types of plant associations, soil-forming rocks, and the lack of influence of forestry activities. The establishment and description of the soil profile were carried out according to the procedures that are generally accepted in soil science [36]. The following morphological features were studied in detail: power of genetic horizons, humidity, coloration, mechanical (granulometric) composition, structure, density, fissuring, neoformations, inclusions, consistence, root system of plants and character of transition to the following horizons. After completion of the soil profile description, the soil was sampled to measure the specific activity of ^{137}Cs. The description of the genetic horizons of the soil pit by morphological characteristics is given in Table 1. First, the samples were selected from the lowest horizon, then from the previous one, and so on, bottom up on the soil profile. Compliance with this sampling sequence is necessary because when the sample is taken from the pit wall, the soil crumbles and clogs the horizons that are lower on the ground profile. To determine the content of ^{137}Cs on the ground profile, we took samples ten times:

– forest litter with the use of the template of 20×30 cm by mineralization degree (modern litter, semi-decomposed, and decomposed layer);

– the soil was sampled layer-by-layer by 4-centimeter layers to the depth of 1 m with a special sampler.

To determine the depth and sufficient repeatability of soil sampling, the territory of the trial area was broken into equal rectangles using the transect method. 6 vertical and 5 horizontal lines were established in order to get the 30-time repeated sampling. At the intersections of the vertical and the horizontal lines, the soil was sampled using a cylindrical drill with a diameter of 40 mm at different depths (Fig. 1).

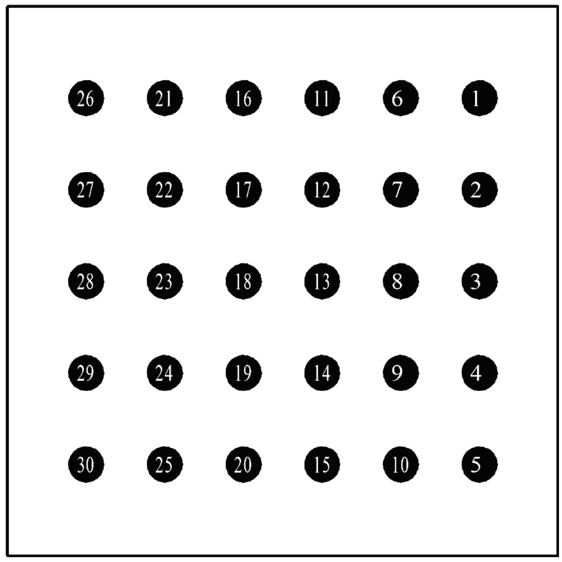

Fig. 1. Layout of soil sampling points

Analysis of the publications indicates that in the periods following the accident at the CNPP, soil sampling in radioecological research was conducted at different depths [9–12, 37]. To establish the actual levels of soil contamination with ^{137}Cs in the first years after the accident, the soil samples were taken at the depth of 10 cm. At present, the main stock of radionuclides is concentrated in the 30-centimeter soil layer. That is why we conducted soil sampling in the 10-, 20- and 30-centimeter layers. All the selected soil samples were dried to the air-dry state, crushed, and homogenized. The specific activity of ^{137}Cs in the samples was measured on a scintillation gamma-spectrometric device (GDM–20) with the multi-channel pulse analyzer (PA). The relative error of measurement of the specific activity of ^{137}Cs in the samples did not exceed 5 %. Statistical treatment of the received data was carried out by the generally accepted methods using the application program package Microsoft Excel and Statistica 10.0. After measuring the specific activity of ^{137}Cs in the selected soil samples, the magnitude of the density of radioactive soil contamination was computed according to the sampling points. Using the technique of random (Table 2) and uniform (Fig. 2–8) sampling, the points for analysis were selected. In both techniques, the number of the studied points was reduced from 30 to 3 within one trial area for all studied soil layers.

When comparing the magnitudes of the density of radioactive soil contamination and specific activity of ^{137}Cs in the soil profile, the focus was on analyzing the values of variance factor (V) and significance factor (p). These statistical parameters informatively reflect variability and give a qualitative assessment of a degree of confidence that results are true.

Table 1

Descriptions of genetic horizons of a soil pit by morphologic features in a fresh boreal forest

Soil layer	Characteristic
H_0 – 0...8 cm	forest litter consists of a layer of dead pine residues, the fresh litter of pine, residues of green mosses and herbaceous vegetation; permeated with plant roots; sharp transition
HE – 0...12 cm	humus-eluvial horizon is gray, sandy, fresh, loose, permeated with plant roots, the transition is gradual in color
E – 12...16 cm	eluvial horizon is light gray, sandy, fresh, loose, rarely permeated with plant roots, the transition is gradual in coloration
I – 16...36 cm	illuvial horizon is light brown, sandy, fresh, loose, the transition is gradual by coloration
PI – 36...68 cm	illuvial sand is light yellow, sandy, loose, fresh, transition gradual by coloration
P – 68... cm	the parent rock is white sand, sandy, loose, fresh
Soil type: soddy medium-podzol sandy soil	

Notes: H_0 – forest litter; HE – humus-eluvial horizon; E – eluvial horizon; I – illuvial horizon; PI – illuvial sand; P – parent rock

Table 2

Scheme of a random sampling of soil

	Quantity of points						
Numbers of soil sampling points	**30**	**25**	**20**	**15**	**10**	**5**	**3**
	6	30	10	2	1	25	20
	11	4	18	4	14	9	6
	8	27	4	27	27	20	22
	26	16	14	21	2	18	–
	29	22	23	20	20	2	–
	7	4	21	22	3	–	–
	17	12	1	27	24	–	–
	5	7	24	11	19	–	–
	13	29	10	8	11	–	–
	19	1	16	9	21	–	–
	5	10	22	28	–	–	–
	15	2	7	18	–	–	–
	22	20	16	16	–	–	–
	1	18	5	4	–	–	–
	15	22	27	24	–	–	–
	22	29	11	–	–	–	–
	23	13	5	–	–	–	–
	17	22	17	–	–	–	–
	19	6	22	–	–	–	–
	7	26	6	–	–	–	–
	16	19	–	–	–	–	–
	11	22	–	–	–	–	–
	2	29	–	–	–	–	–
	30	8	–	–	–	–	–
	6	17	–	–	–	–	–
	23	–	–	–	–	–	–
	8	–	–	–	–	–	–
	12	–	–	–	–	–	–
	27	–	–	–	–	–	–
	14	–	–	–	–	–	–

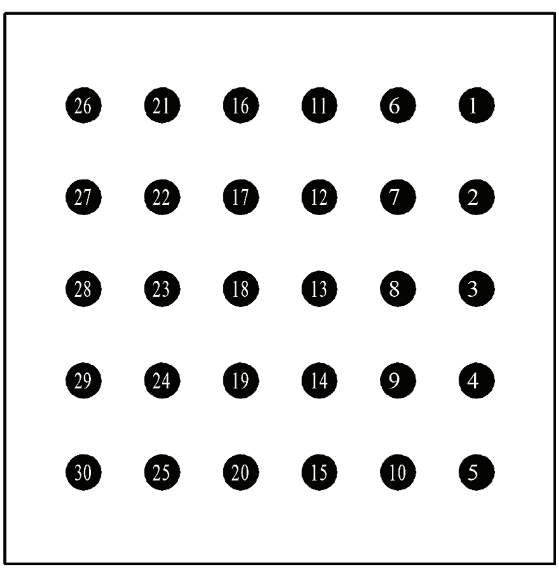

Fig. 2. Scheme of uniform sampling of soil at 30-time repeated sampling

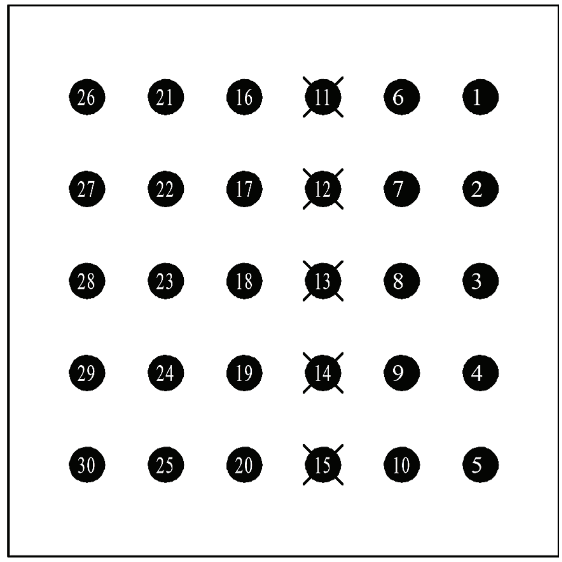

Fig. 3. Scheme of uniform soil sampling at 25-time repeated sampling (✖ – the point that was not used in this technique)

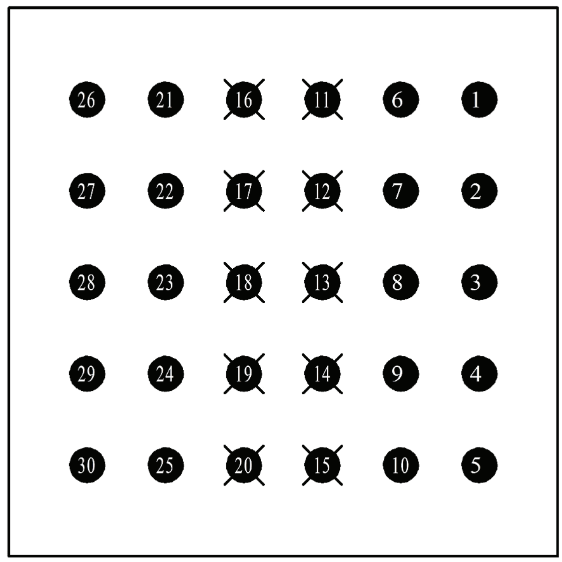

Fig. 4. Scheme of uniform soil sampling at 20-time repeated sampling (✖ – the point that was not used in this technique)

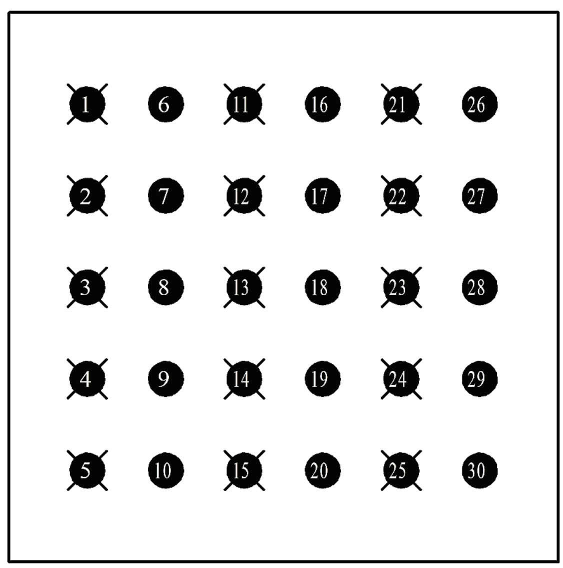

Fig. 5. Scheme of uniform soil sampling at 15-time repeated sampling (✖ – the point that was not used in this technique)

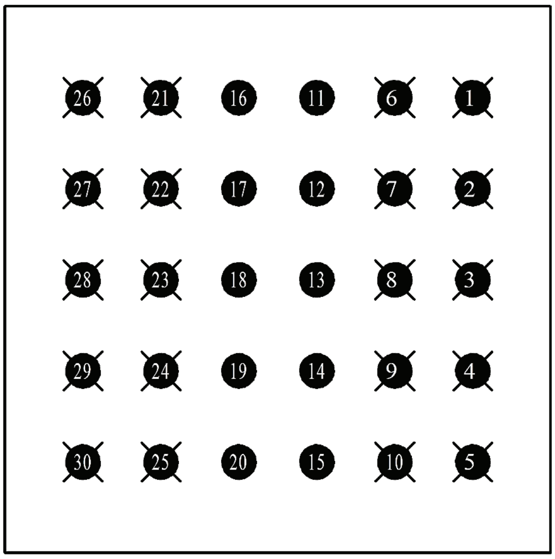

Fig. 6. Scheme of uniform soil sampling at 10-time repeated sampling (✕ – the point that was not used in this technique)

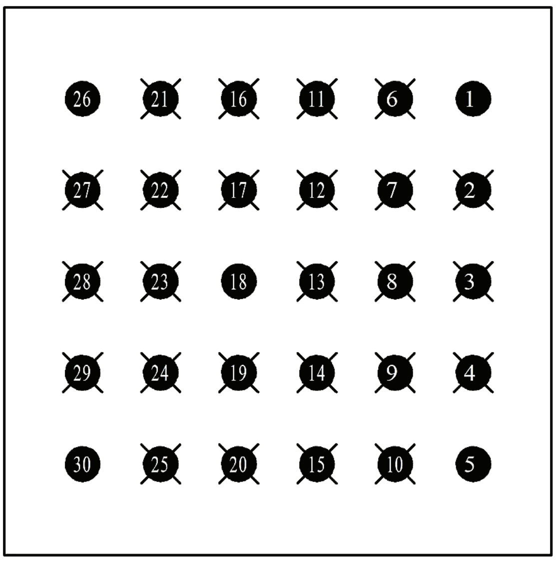

Fig. 7. Scheme of uniform soil sampling at 5-time repeated sampling (✕ – the point that was not used in this technique)

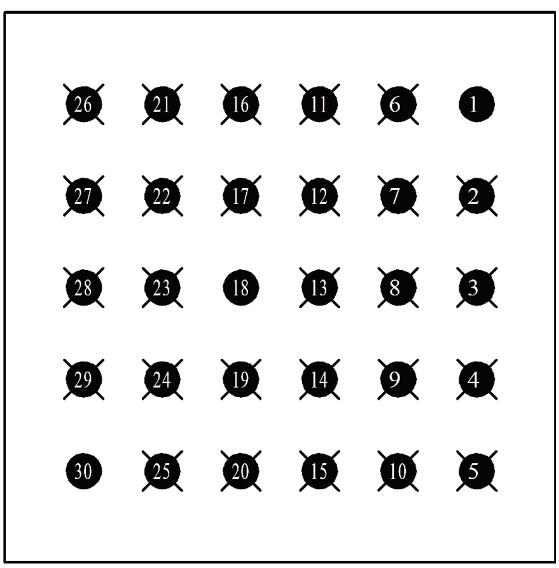

Fig. 8. Scheme of uniform soil sampling at 3-time repeated sampling (✕ – the point that was not used in this technique)

5. Improvement of the soil sampling procedure in forest ecosystems

5. 1. Fluctuations of magnitudes of the density of radioactive soil contamination at different soil sampling repeatability

At random sampling, the density of radioactive soil contamination fluctuated within a considerable range in all the studied layers. When sampling in the soil layer of 10 cm, this indicator has the fluctuation amplitude from 107 to 137 kBk/m^2. In the layer of 20 cm, the levels of soil contamination with ^{137}Cs varied from 154 to 174 kBk/m^2, and in the layer of 30 cm – from 152 to 177 kBk/m^2. Analysis of the basic statistical parameters of the density of radioactive soil contaminations at a random reduction of the number of the studied points in 10-, 20- and 30-centimeter layers are shown in Table 3. The obtained results indicate that when reducing the number of soil sampling points from 30 to 3, the average magnitudes of radioactive soil contamination in the 10-centimeter soil layer do not differ substantially. Reliability of the obtained data is proved by a single-factor dispersion analysis – $F_{fact.}=0.6<F_{(6;107;0,95)}=2.2$. However, in the case of rather similar average magnitudes of the levels of soil contamination with ^{137}Cs at the change in the number of analyzed points, the fluctuations of variance factor and significance factor were recorded. At 30-time repeated sampling, variance factor was 24.9 %, and at 3-time repeated sampling, there was an increase in this parameter by 1.3 times. Similar regularities are also traced for significance factor that at a decrease in the number of points for analysis up to 3 was 10 %, which is 2.2 times higher than at 30-time repeated selection.

Table 3

Statistical parameters of determining the average density of radioactive soil contamination at different number of sampling points (random sampling method)

Number of observations, pieces	Statistical parameters				
	M	*m*	ð	*V*, %	*P*, %
10-centimeter soil layer					
30	122	5.6	30	24.9	4.6
25	120	6.0	30	25.1	5.0
20	128	7.1	32	25.0	5.6
15	120	8.7	34	28.0	7.2
10	137	12.7	40	29.4	9.3
5	107	10.1	32	30.0	9.5
3	124	12.4	39	31.5	10.0
20-centimeter soil layer					
30	167	5.3	29	17.4	3.2
25	174	6.5	33	18.7	3.7
20	169	5.6	25	14.9	3.3
15	163	7.7	30	18.2	4.7
10	171	11.4	36	21.0	6.7
5	154	15.5	35	22.4	10.0
3	170	3.4	6	3.5	2.0
30-centimeter soil layer					
30	170	5.4	30	17.3	3.2
25	176	6.2	31	17.6	3.5
20	173	6.1	27	15.7	3.5
15	161	7.6	29	18.2	4.7
10	172	7.4	23	13.5	4.3
5	152	10.6	24	15.6	7.0
3	177	24.3	42	14.5	6.6

When analyzing the samples taken in the 20-centimeter soil layer, the patterns similar to the above were recorded. However, the values of the density of radioactive soil contamination in this layer were considerably higher. The results of single-factor dispersion analysis show that between the magnitudes of the levels of radioactive soil contamination in a 20-centimeter layer, there is no reliable difference, which is proved by Fisher criterion – $F_{fact.}=0.5<F_{(6;107;0,95)}=2.2$. Analysis of the 20-centimeter soil layer showed that at a random decrease in the number of points from 30 to 15, the variance factor has medium variability and varies from 14.9 to 18.7 %. The factor of significance in this situation did not exceed 5 %. When taking 10 and 5 samples, there is an increase in these indicators, so the variation factor continues to be characterized by medium variability, and the reliability factor approaches 10 %.

There was also a similar analysis of the results of determining the density of radioactive soil contamination at soil sampling in a 30-centimeter layer. The levels of soil contamination with ^{137}Cs at a decrease in the number of points for analysis in this soil layer fluctuated, but this variation was not significant – $F_{fact.}=0.8<F_{(6;107;0,95)}=2.2$. In addition, for the 30-centimeter soil layer, the lowest values of indicators of variance and significance were recorded. Thus, at a decrease in the number of points for analysis from 30 to 3, the variance factor has medium variability and is in the range from 14.5 to 18.2 %. The significance factor of the resulting magnitudes of the density of radioactive soil contamination does not exceed 7 %.

The results indicate that average magnitudes of the density of radioactive soil contamination in 10-, 20- and 30-centimeter layers at a random decrease in analyzed points ranged within small limits, which was proved by Fisher criterion, $F_{theor.}<F_{fact.}$ However, at a decrease in the number of analyzed points, the factor of variance and significance increased. Based on the obtained results, it can be noted that in order to study the density of radioactive contamination, 10-time repeated sampling will be sufficient for 20- and 30-centimeter soil layers (significance factor will not exceed 8 %). For a 10-centimeter soil layer, it is necessary to perform 15-time repeated sampling ($p\leq8$ %) in order to obtain representative data.

Similar results were obtained when using a uniform technique for reducing the number of the studied sampling points (Table 4). The density of radioactive soil contamination during sampling in a 10-centimeter layer and their gradual decrease from 30 to 3 was in the range from 111 to 148 kBk/m^2. The results of the single-factor dispersive analysis show that a reliable difference between the magnitudes of radioactive soil contamination was not found – $F_{fact.}=1.0<F_{(6;107;0,95)}=2.2$). It was established that in the given soil layer variance factor during the analysis of 30, 25, 20, and 15 points is characterized by strong variability, which ranges from 25.6 to 28.6 %, whereas the significance indicator does not exceed 7.5 %. At 10, 5, and 3 sampling points, the first statistical parameter decreases and varies from 16.7 to 21.7 %, and the second increases up to 9.7 %.

The density of radioactive soil contamination at sampling in the 20-centimeter layer amounted to 165–216 kBk/m^2. When reducing the number of sampling points from 30 to 10, the magnitudes of levels of soil contamination with ^{137}Cs do not differ significantly. The reliability of the obtained results is proved by a single-factor dispersion analysis at the 95 % confidence level – $F_{fact.}=0.3<F_{(4;99;0,95)}=2.5$. During the comparison of statistical parameters in the analysis of points from 5 to 30, it was found that the accuracy indicator does not exceed 5.3 %. The variance factor is characterized by medium variability and varies in the range from 11.8 to 18.1 %. When sampling in the 30-centimeter soil layer, the density of radioactive soil contamination was within 162–197 kBk/m^2. Research results are quite similar to the previous ones. Thus, at a decrease in the number of points for analysis from 30 to 3, the variance factor has the fluctuation amplitude from 6.1 to 18.2 %, and the significance factor does not exceed 5 %.

Table 4

Statistical parameters of determining the average density of radioactive soil contamination at a different number of sampling points (uniform sampling method)

Number of observations	Statistical parameters				
	M	*m*	ð	*V*, %	*P*, %
10-centimeter soil layer					
30	128	6.1	33.4	26.2	4.8
25	129	7.1	35.3	27.5	5.5
20	136	7.8	34.8	25.6	5.7
15	124	9.2	35.6	28.6	7.4
10	111	7.6	24.1	21.7	6.8
5	148	13.6	30.3	20.5	9.2
3	141	13.6	23.6	16.8	9.7
20-centimeter soil layer					
30	170	5.4	29.6	17.4	3.2
25	174	6.2	31.1	17.9	3.6
20	173	7.0	31.3	18.1	4.1
15	166	7.4	28.6	17.3	4.5
10	165	8.4	26.6	16.1	5.1
5	199	10.5	23.5	11.8	5.3
3	216	6.4	11.0	5.1	3.0
30-centimeter soil layer					
30	170	5.4	29.6	17.4	3.2
25	174	6.2	31.1	17.9	3.6
20	173	7.0	31.3	18.1	4.1
15	166	7.4	28.6	17.3	4.5
10	165	8.4	26.6	16.1	5.1
5	199	10.5	23.5	11.8	5.3
3	216	6.4	11.0	5.1	3.0

In order to obtain reliable and representative magnitudes of radioactive soil contamination, it is necessary to make sampling in 15 points ($p\leq8$ %) in a 10-centimeter layer. For 20- and 30-centimeter soil layers, soil sampling in 10 points is enough ($p\leq5$ %) both with the uniform and random technique.

5. 2. Analysis of soil sampling depth to determine the density of radioactive contamination of forest soils

The vertical distribution of ^{137}Cs in different layers of forest soils was analyzed by means of determining the content of radionuclides in 10-, 20- and 30-centimeter soil layers (both randomly and uniformly). The results of the studies suggest that using the random sampling technique, the density of radioactive soil contamination in the analyzed layers fluctuated. Thus, in the 10-centimeter soil layer, the studied indicator was 1.3–1.4 times lower than in the 20- and 30-centimeter layers (Fig. 9). The reliability of the difference of obtained results was proved by a single-factor dispersion analysis at a 95 % confidence level at a different number of samplings. Thus, during sampling at 30 points, the proof had the following form for 10- and 20-centimeter layers – $F_{fact.}=34.6>F_{(1;59;0,95)}=4.0$ and for 10- and 30-centimeter layers – $F_{fact.}=38.9>F_{(1;59;0,95)}=4{,}0$. During sampling at 25 points for the 10- and 20-centimeter layer – $F_{fact.}=36.7>F_{(1;49;0,95)}=4.0$ and for 10- and 30-centimeter layer – $F_{fact.}=41.2>F_{(1;49;0,95)}=4.0$. Comparison during sampling at 20 points reflects that for 10- and 20-centimeter layer – $F_{fact.}=20.4>F_{(1;39;0,95)}=4.1$ and 10- and 30-centimeter layer – $F_{fact.}=23.1>F_{(1;39;0,95)}=4.1$. For sampling at 15 points: 10- and 20-cm layers – $F_{fact.}=13.6>F_{(1;29;0,95)}=4.2$ and 10- and 30-centimeter layers – $F_{fact.}=12.6>F_{(1;29;0,95)}=4.2$. When comparing the levels of radioactive soil contamination at the random sampling technique, in the 20- and 30-centimeter layers we found out that there was no reliable difference between the average values of the studied indicators. The obtained results are proved by single-factor dispersion analysis for sampling points of 30, 25, 20, 15: $F_{fact.}=0.15<F_{(1;59;0,95)}=4.0$, $F_{fact.}=0.04<F_{(1;49;0,95)}=4.0$, $F_{fact.}=0.24<F_{(1;39;0,95)}=4.1$ and $F_{fact.}=0.02<F_{(1;29;0,95)}=4.2$. Similar results were also obtained at a subsequent decrease in the number of selected samples. Thus, if we had 10 sampling points in 20- and 30-centimeter layers, the densities of radioactive soil contamination with ^{137}Cs among them were not significantly different ($F_{fact.}=0.007<F_{(1;19;0,95)}=4.4$). However, in both cases, it is by 1.5 higher than in the 10-centimeter soil layer. Since the Chernobyl accident, there has been a certain deepening of ^{137}Cs into the soil, which is why in order to obtain an objective density of radioactive soil contamination, it is necessary to make sampling in the layer of the 30-centimeter depth.

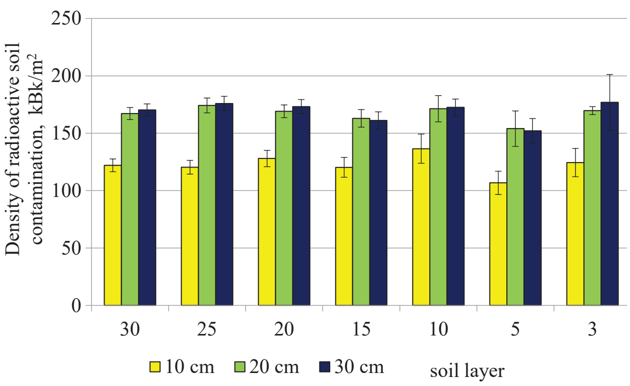

Fig. 9. Density of radioactive soil contamination with ^{137}Cs in different layers at a random decrease in sampling points

When comparing the magnitude of the density of radioactive soil pollution, obtained at uniform sampling at different depths, similar patterns to those at random sampling were observed. Thus, at a gradual decrease in the number of the studied points (Fig. 10), it was revealed that this indicator in the 20- and 30-centimeter soil layers is 1.3 times higher than in the 10-centimeter layer. Reliable difference of average values was proved by Fisher criterion for the selection of 30 points in the 10- and 20-centimeter layer – $F_{fact.}=27.4>F_{(1;59;0,95)}=4.0$ and in the 10- and 30-centimeter layer – $F_{fact.}=27.3>F_{(1;59;0,95)}=4.0$. Similar regularities were also observed at the selection of 25 points: 10- and 20-centimeter layers – $F_{fact.}=23.0>F_{(1;49;0,95)}=4.0$ and 10- and 30-centimeter layers – $F_{fact.}=19.5>F_{(1;49;0,95)}=4.0$. For sampling at 20 and 15 points, reliability looked as follows: for 10- and 20-centimeter layers – $F_{fact.}=12.5>F_{(1;39;0,95)}=4.1$ and $F_{fact.}=12.4>F_{(1;29;0,95)}=4.2$; for 10- and 30-centimeter layer – $F_{fact.}=12.1>F_{(1;39;0,95)}=4.1$ and $F_{fact.}=11.8>F_{(1;29;0,95)}=4.2$, respectively.

At uniform sampling in the 20- and 30-centimeter layer, it was found that there is no reliable difference between average values of density of radioactive soil contamination. Reliability of the obtained results is proved by Fisher criterion, for 30-, 25-, 20- and 15-time repeated sampling, respectively: $F_{fact.}=0.009<F_{(1;59;0,95)}=4.0$, $F_{fact.}=0.17<F_{(1;49;0,95)}=4.0$, $F_{fact.}=0.002<F_{(1;39;0,95)}=4.1$ and $F_{fact.}=0.17<F_{(1;29;0,95)}=4.2$. That is why in order to obtain representative values of the levels of soil contamination with ^{137}Cs at the uniform decrease in the number of points, it is necessary to make sampling in a 30-centimeter soil layer.

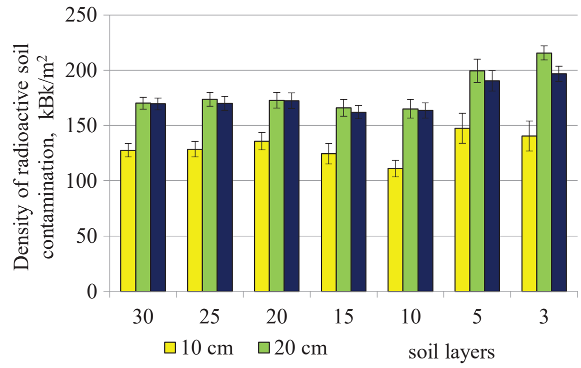

Fig. 10. Density of radioactive soil contamination with ^{137}Cs in different layers at a uniform decrease in the number of points for analysis

Analysis of the obtained magnitudes of the density of radioactive soil contamination at the uniform and random sampling in 10-, 20- and 30-centimeter soil layers revealed certain patterns. Thus, at soil sampling in a 10-centimeter layer, the indicator of radioactive soil contamination was 1.3–1.5 times lower than when sampling at the depth of 20 and 30 cm. After studying the results, it is possible to note that currently, a considerable mass of radionuclides migrated to deeper layers of forest soils. Comparing the analyzed indicator in 20- and 30-centimeter soil layers, no significant difference in the obtained magnitudes was observed, but the statistical parameters of the indicator were better for a deeper layer. Thus, to obtain representative magnitudes of soil contamination with ^{137}Cs, it is necessary to make sampling in the 30-centimeter soil layer.

5. 3. The optimal number of soil samplings to study the distribution of ^{137}Cs in the soil profile

At a gradual reduction of the number of samples from 10 to 3, certain patterns were identified in different layers of forest litter of fresh boreal forest (Table 5) [38]. Thus, the variance factor in the current litter at 10-time repeated sampling is 7.2 %, and significance factor is 2.3 %. At a decrease in the number of samples up to 3, the first parameter increased by 1.3 times, and the second – by 2.3 times. Similar tendencies were found for semi-decomposed and decomposed layers of forest litter. Thus, the variance factor expressed weak variability and did not exceed 7.5 % (fluctuation amplitude was from 4.0 to 5.9 % and from 3.7 to 7.4 %, respectively). The significance factor for semi-decomposed layers of forest litter ranged from 1.6 to 2.7 %, and for decomposed layers, it was in the range from 1.6 to 3.7 %. That is, the parameter that characterizes the reliability of the experiment does not exceed 4 %, which testifies to the high accuracy of the results. Thus, it can be noted that for all layers of forest litter, factors of variance and significance increase at a decrease in the number of samples from 10 to 3. That is why in order to obtain reliable results of magnitudes of the specific activity of radionuclide in all layers of forest litter, it is necessary to make sampling 4 times.

Estimation of variance and significance factors at a change in the number of soil samplings in mineral layers of humus-eluvial horizon revealed certain specific features. Thus, the values of variance factor fluctuated as follows: at the depth of 0–4 cm – from 4.8 to 10.3 %, at the depth of 4–8 cm – from 4.1 to 12.1 %, and at the depth of 8–12 cm – from 12 to 15.0 %. At a decrease in the number of samplings up to 4, the significance factor exceeded 5 % and at the depth of 0–4 cm was 5.1 %, at the depth of 4–8 cm – 5.6 %, at the depth of 8–12 cm 7.5 %. The highest accuracy of the studied indicators was when sampling was made 10 times and amounted to 2.5 %, 3.0 %, and 3.8 %, according to the above-mentioned depths. However, when comparing the significance factor and variation factor in the humus-eluvial horizon of a fresh boreal forest, it is necessary to make sampling not less than 6 times to obtain representative results.

For the eluvial horizon in the conditions of a fresh boreal forest at the depth of 12–16 cm, the value of the variance factor reflected high variability results and fluctuated from 22 to 35 %. The values of significance factor exceeded 5 % and were in the range from 7.8 to 17.4 %. The most accurate results were observed when soil sampling was repeated 10 times. The illuvial horizon had a capacity of 20 cm (16–20 cm, 20–24 cm, 24–28 cm, 28–32 cm, 32–36 cm). The variance factor in this horizon is characterized by medium variability and is in the range from 9 to 21 %. Thus, at the sampling depth of 16–20 cm, variance factor had the fluctuation amplitude from 12.7 to 19.5 %, and at the depth of 20–24 cm varied from 12 to 19 %. At subsequent deepening of sampling, we noticed an increase in this factor, which at the depth of 24–28 cm was from 15 to 21 % and at the depth of 32–36 cm – from 11 to 15 %. However, at the depth of 28–32 cm, there was the weakest fluctuation of variance factor – from 9 to 12 %. The value of significance factor at the studied depths did not exceed 12 %. The peculiarity is that the highest values of this factor were observed when sampling was repeated 3 times. At an increase in the number of samples, this indicator decreased, and when sampling was repeated 5 times, it did not exceed 8.4 %, and when it was repeated 10 times – 4.5 %.

Table 5

Average values of the specific activity of ^{137}Cs (Bk/kg) in soil layers in fresh boreal forests

h	Number of samples							
	10	9	8	7	6	5	4	3
H_1	7,048±161	7,027±178	7,052±200	6,969±210	7,042±233	7,042±285	7,234±273	7,235±385
H_2	11,481±179	11,536±19	11,473±205	11,441±233	11,441±276	11,616±261	11,801±239	11,727±322
H_3	22,131±355	22,179±394	22,114±440	22,114±508	22,001±586	22,242±654	22,361±830	23,116±487
HE 0–4	1,450±36	1,448±40	1,438±44	1,445±50	1,461±56	1,430±57	1,427±73	1,358±38
HE 4–8	729±22	726±24	728±27	732±31	746±33	742±40	717±40	678±16
HE 8–12	650±24	650±27	646±31	663±30	673±33	671±41	658±50	682±61
E 12–16	361±30	367±32	377±35	364±37	347±40	336±46	342±59	285±22
I 16–20	93±3.9	94±4.2	94±4.7	95±5.3	94±6.1	94±7.5	91±8.9	83±6
I 20–24	70±3.4	70±3.8	68±4.0	67±4.4	69±4.7	69±5.8	74±4.5	72±5.8
I 24–28	66±3.3	65±3.3	64±3.5	65±4.0	65±4.7	67±4.8	67±6.2	69±8.3
I 28-32	77±2.0	77±2.3	77±2.5	76±2.8	75±3.2	75±3.9	77±4.4	74±4.0
I 32-36	63±2.8	63±3.2	62±3.2	59±2.4	60±2.6	60±3.2	62±3.2	63±4.4
PI 36–40	59±3.2	59±3.5	60±3.9	58±4.0	57±4.7	58±5.7	60±7.0	63±8.3
PI 40–44	32±1.1	32±1.3	32±1.4	33±1.6	33±1.7	33±1.9	33±2.5	33±3.5
PI 44–48	35±4.5	35±5.0	36±5.6	38±6.2	38±7.3	40±8.6	41±11	44±15
PI 48–52	56±3.3	56±3.7	56±4.1	59±4.0	61±3.8	62±4.5	62±5.9	62±8.3
PI 52–56	43±2.9	43±3.2	44±3.6	45±4.0	45±4.7	45±5.7	45±7.4	43±10
PI 56–60	13±1.0	13±1.1	13±1.3	13±1.5	12±1.4	12±1.7	12±2.2	10±1.7
PI 60–64	11±1.1	11±1.2	11±1.4	10±1.1	10±0.8	9±1.0	9±1.2	10±1.3
PI 64–68	10±0.4	10±0.5	10±0.5	10±0.6	10±0.7	10±0.8	10±1.1	10±1.5
P 68–72	15±1.9	15±2.1	15±2.4	15±2.7	16±2.9	15±3.4	15±4.4	15±6.2
P 72–76	15±3.8	16±4.3	16±4.8	18±5.3	16±6.0	17±7.2	20±8.8	11±2.2
P 76–80	10±0.6	10±0.6	10±0.7	10±0.8	10±0.7	9±0.8	9±1.0	10±1.3
P 80–84	14±1.8	14±2.1	15±2.3	15±2.6	14±3.0	14±3.7	14±4.8	14±5.8
P 84–88	11±0.7	11±0.8	10±0.8	10±0.9	10±1.1	10±1.3	11±1.0	11±1.2

Note: h – sampling depth; H_0 – forest litter (H_1 – current litter; H_2 – semi-decomposed layer; H_3 – decomposed layer); HE – humus-eluvial horizon; E – eluvial horizon; I – illuvial horizon; PI – illuvial sand; P – parent rock

Analysis of the statistical parameters of ^{137}Cs distribution by the depth of the soil profile, starting from illuvial sand, indicates a significant fluctuation of factors of variance and significance. Variance factor at different depths has either medium or strong variability. Thus, at the depth of 36–40 cm, it ranges from 17 to 24 %, at the depth of 40–44 cm – from 11 to 19 %. Beginning from the depth of 44–48 cm, the values of the factor are distributed over a wider range – from 15 to 35 %. Significance factor at 10-time repeated sampling does not exceed 10 %, at a decrease in the number of samplings up to 3, it increases by more than 20 %. That is why to get more reliable research results, it is necessary to make soil sampling 10 times at the depth from 36 to 68 cm. Parent rock begins at a depth of 68 cm. The values of significance factor in determining specific activity range from 6 to 40 % and the variance factor has the fluctuation amplitude from 18 to 92 %. In this soil horizon, the lowest values of factors of variance and significance are observed when sampling is repeated 10 times. Thus, at sampling at the depth of 76–80 cm, they are 21 % and 6.5 %, and at the depth of 84–88 cm – 22 % and 6.9 %, respectively. During sampling at the depths of 68–72 cm, 72–76 cm, and 80–84 cm, the variance factor has a strong variability and fluctuates from 39 to 80 %. The value of significance factor for the above-stated sampling depths varies from 12 to 25 %.

To get more reliable results of sampling in the soil profile for each soil layer, it is necessary to make different samplings. The minimum number of samples is typical for all layers of forest litter and is repeated 4 times, and the maximum number of sampling for 10 times was observed for illuvial sand and parent rock. For the humus-eluvial layer, it is enough to make soil sampling 6 times, and for eluvial and illuvial horizons 8 times.

6. Discussion of results of improving the soil sampling procedure in forest ecosystems

Despite all the difficulties that arose at different stages of examination of forest areas for radioactive contamination, the obtained materials sufficiently reliably characterize the mosaic character and density of radioactive contamination of forest areas. According to the results of research [27], cartographic materials and recommendations for forestry enterprises were developed. Based on them, forestry activities or the possibility of logging were prohibited or limited. Despite a rather high-quality description of the radiological situation in the forests of that time, there were many unresolved issues. Thus, in the earlier existing procedures of examination of forest areas for radioactive contamination [10, 27, 28], a sufficient number of samplings were not determined. In addition, according to these procedures, soil sampling was made at a depth of 10 cm. Materials of publications [11, 12] prove that over time there was migration and redistribution of radionuclides in the deeper soil layers, that is why the above-specified sampling depth does not reflect the current content of radioactive elements in soils. The procedures that were developed for the examination of agricultural lands for radioactive contamination [25, 26, 33] cannot be used for forest lands. After all, the above procedures do not give the qualitative characteristic of radioactive contamination of forest arrays, which have significant mosaic pollution and a more complex spatial structure.

The results presented in this study make it possible to eliminate a series of shortcomings of the existing procedures. In particular, it is possible to determine the optimum number of soil samples and the required sampling depth for the objective characteristic of the current radiation situation in forests. This is the merit of this study.

The obtained results of research regarding the improvement of the soil sampling procedure to establish current magnitudes of the density of radioactive soil contamination in forest ecosystems were achieved by solving a series of tasks. Thus, the following results were obtained when studying the necessary repeatability of soil sampling to obtain representative values of the density of radioactive soil contamination with ^{137}Cs. In both random and uniform technique of soil sampling, average values of density of radioactive soil contamination in 10-, 20- and 30-centimeter layers did not change substantially (Tables 3, 4). However, at a decrease in the number of analyzed points from 30 to 3, there is an increase in statistical parameters (variance and significance factors). That is why in order to obtain representative magnitudes of the levels of radioactive soil contamination in 20- and 30-centimeter soil layers, it is enough to repeat sampling 10 times, and for a 10-centimeter layer – 15 times. When making the given number of samplings in all analyzable soil layers, the significance factor will not exceed 8 %, and the variance factor will have medium variability.

By analyzing the vertical distribution of radionuclides at different soil sampling to characterize the current density of radioactive soil contamination, it was observed that ^{137}Cs migrated into deeper layers of soil. According to research results (Fig. 9, 10), it was found that in the case of random and uniform sampling techniques, it is necessary to make sampling in a 30-centimeter layer of soil. The results of sample analysis in a 20-centimeter soil layer have the same values as in a 30-centimeter layer, but it is characterized by a greater variance of statistical parameters. To establish the density of radioactive soil contamination, the 10-centimeter soil layer is not representative, because it does not characterize the current redistribution of radionuclides in soil [10, 12]. Thus, for the up-to-date examination of forest areas for radioactive contamination, it is necessary to make sampling 10 times repeated in a 30-centimeter soil layer (at uniform and random sampling technique).

When assessing the vertical migration of ^{137}Cs in the soil profile, the optimum number of soil samplings required to characterize the specific activity of ^{137}Cs in different layers of forest soils was studied. In the process of solving this problem, it was found that it is necessary to make different sampling for each layer of soil. Thus, analysis of the obtained results (Table 5) shows that the minimum number of soil samples to characterize the specific activity of ^{137}Cs necessary for all layers of forest litter is repeated 4 times. With an increase in the sampling depth by profile, the number of samplings increases, and it must be repeated 6 times repeated for the humus-eluvial horizon, 8 times for eluvial and illuvial horizon. The maximum 10-time repeated soil sampling is observed for illuvial sand and parent rock.

The use of the optimum quantity of soil samples and the established depth of their sampling during examination for radioactive contamination of forest areas will make it possible to obtain representative results. In addition, due to the improvement of methodological approaches to sampling for forest examination will reduce labor intensity and time consumption to carry out this research. The use of the obtained materials on the depth and the number of soil samplings is representative to examine the forest areas in boreal and subor forests, which are characterized by soddy podzol sandy and sandy loam soils. During the examination of forest arrays of other types of forest-vegetative conditions, these results are informative, however, they need the adjustment of sampling depth, due to the physical and mechanical properties of soils.

7. Conclusions

1. In the process of studying the vertical migration of ^{137}Cs in forest soils under current conditions, it should be noted that the bulk of radionuclides migrated to deeper layers of forest soils. That is why in order to obtain representative data (at the random and uniform technique) of the current level of radioactive soil contamination in forest ecosystems, it is necessary to make sampling in a 30-centimeter soil layer.

2. The number of samplings is determined by the aim of the research. To obtain representative results during the examination for radioactive contamination of forest areas (at the uniform and random sampling techniques), it is enough to repeat soil sampling 10 times ($p \leq 8$ %). To conduct more accurate scientific research, the number of samples should be increased up to 25 ($p \leq 5$ %).

3. To obtain reliable results of vertical migration of ^{137}Cs in the soil profile, it is necessary to make different sampling for each horizon. Thus, for all layers of forest litter, it is enough to repeat sampling 4 times. For the humus-eluvial horizon – 6 times, for eluvial and illuvial horizon – 8 times. The maximum number of soil sampling repetitions is necessary for illuvial sand and parent rock.

References

1. Tihomirov, F. A., Sidorov, V. P., Shcheglov, A. I. (1994). Les i lesnoe hozyaystvo v usloviyah radioaktivnogo zagryazneniya. Lesnoe hozyaystvo, 1, 26–29.
2. Tikhomirov, F. A., Shcheglov, A. I., Sidorov, V. P. (1993). Forests and forestry: radiation protection measures with special reference to the Chernobyl accident zone. Science of The Total Environment, 137 (1-3), 289–305. doi: https://doi.org/10.1016/0048-9697(93)90395-m
3. Shcheglov, A. I., Tihomirov, F. A., Tsvetnova, O. B., Klyashtorin, A. L., Mamihin S. V. (1996). Biogeohimiya radionuklidov chernobyl'skogo vybrosa v lesnyh ekosistemah evropeyskoy chasti SNG. Radiatsionnaya biologiya. Radioekologiya, 36 (4), 469–478.
4. Kaletnyk, M. M., Landin, V. P. Krasnov, V. P. et. al. (1991). Radiolohichna obstanovka v lisakh Ukrainskoho Polissia. Oikumena, 2, 61–66.
5. Kashparov, V. A. (2009). Radioecological significance of a fuel соmponent of снernobyl radioacтive fallout. Problems of Chernobyl Exclusion Zone, 9, 5–22. Available at: http://uiar.org.ua/Russ/3.pdf
6. Shcheglov, A. I., Tsvetnova, O. B. (2002). Ekologicheskaya rol' lesnyh podstilok pri radioaktivnom zagryaznenii. Aktual'nye problemy lesnogo kompleksa, 5, 151–153.
7. Shcheglova, A. I., Tsvetnova, O. B. (2001). Rol' lesnyh ekosistem pri radioaktivnom zagryaznenii. Priroda, 4, 23–32. Available at: http://elib.biblioatom.ru/text/chernobyl-i-problemy-radiobiologii_2001/go,2/
8. Boyko, O. L. (2012). Distribution of ^{137}Cs total activity in forest phytocenoses. Lisivnytstvo i ahrolisomelioratsiya, 120, 87–94. Available at: http://forestry-forestmelioration.org.ua/index.php/journal/issue/view/13/120-pdf
9. Krasnov, V. P., Kurbet, T. V., Davydova, I. V., Shelest, Z. M., Boyko, O. L. (2015). Vertical Distribution of ^{137}Cs Total Activity in Forest Soils of Ukrainian Polissya. Scientific Bulletin of UNFU, 25.5, 123–129. Available at: https://nv.nltu.edu.ua/index.php/journal/article/view/1014
10. Perevolotskiy, A. N. (2006). Raspredilenie ^{137}Cs i ^{90}Sr v lesnyh biogeotsenozah. Gomel': RNIUP «Institut radioekologii», 256.
11. Krasnov, V. P., Kurbet, T. V., Shelest, Z. M., Boyko, A. L. (2015). ^{137}Cs distribution in sod-podzol forest soil of Ukrainian Polissia. Nuclear Physics and Atomic Energy, 16(3), 247–253. doi: https://doi.org/10.15407/jnpae2015.03.247
12. Melnyk, V., Kurbet, T. (2018). Current distribution of ^{137}Cs in sod-podzolic soils of different types of forest conditions. Eastern-European Journal of Enterprise Technologies, 5 (10 (95)), 65–71. doi: https://doi.org/10.15587/1729-4061.2018.142613
13. Gonze, M.-A., Calmon, P. (2017). Meta-analysis of radiocesium contamination data in Japanese forest trees over the period 2011–2013. Science of The Total Environment, 601-602, 301–316. doi: https://doi.org/10.1016/j.scitotenv.2017.05.175
14. Bulko, N. I., Shabaleva, M. A., Kozlov, A. K. (2009). Osobennosti povedeniya ^{137}Cs v sosnovyh nasazhdeniyah raznyh tipov lesa na territorii zapadnogo sleda avarii na ChAES. Vestnik MDPU imeni I. P. Shamyakina, 2 (23), 3–14. Available at: https://cyberleninka.ru/article/n/osobennosti-povedeniya-137cs-v-sosnovyh-nasazhdeniyah-raznyh-tipov-lesa-na-territorii-zapadnogo-sleda-avarii-na-chaes/viewer
15. Bulko, N. I., Shabaleva, M. A., Mitin, N. V., Tolkacheva, N. V., Kozlov, A. K. (2015). Osobennosti dlitel'nyh protsessov migratsii chernobyl'skogo ^{137}Cs v avtomorfnyh i gidromorfnyh pochvah sosnovyh fitotsenozov v dal'ney zone avarii na ChAES. Sb. nauch. Tr. IL NAN Belarusi, 75, 391–404.
16. Bulko, N. I. (2009). Fiziko-himicheskoe sostoyaniya ^{137}Cs v pochvah sosnovoy formatsii regionov s razlichnymi tipami chernobyl'skih vypadeniy spustya 20 let posle avarii na ChAES. Problemy lesovedeniya i lesovodstva, 69, 516–534.
17. Bulko, N. I. (2014). Transformatsiya form nahozhdeniya ^{137}Cs v pochvah nasazhdeniy razlichnogo sostava v dal'ney zone chernobyl'skoy katastrofy spustya chetvert' veka. Problemy lesovedeniya i lesovodstva, 74, 380–391.
18. Krasnov, V. P., Kurbet, T. V., Korbut, M. B., Boiko, O. L. (2016). Rozpodil ^{137}Cs u lisovykh ekosystemakh Polissia Ukrainy. Agroecological Journal, 1, 82–87. Available at: http://nbuv.gov.ua/UJRN/agrog_2016_1_14
19. Markina, Z. N., Glazun, I. N. (2005). Raspredelenie fiziko-himicheskih pokazateley ^{137}Cs po profilyu pochv lesnyh ekosistem zony otchuzhdeniya ChAES Bryanskoy oblasti. Problemy lesovedeniya i lesovodstva, 63, 487–489.

20. Averin, V. S. et. al. (2007). Radioekologicheskie posledstviya CHernobyl'skoy avarii. 20 let posle Chernobyl'skoy katastrofy: posledstviya v Respublike Belarus' i ih preodolenie. Natsional'nyy doklad. Minsk: Komitet po problemam posledstviy katastrofy na CHernobyl'skoy AES pri Sovete Ministrov Respubliki Belarus', 13–35.
21. Didenko, L. G. (2001). O soderzhanii i formah nahozhdeniya ^{137}Cs i kaliya v hvoe i drevesine sosny. Problemy lesovedeniya i lesovodstva, 52, 150–157.
22. Didenko, L. G. (2000). K voprosu o formah nahozhdeniya ^{137}Cs v lesnyh pochvah. Problemy lesovedeniya i lesovodstva, 51, 223–228.
23. 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
24. Pratama, H. A., Yoneda, M., Shimada, Y., Satoshi, F., Ikegami, M. (2019). Correlation between Different Type of Caesium Carrier in The Radiocaesium Interception Potential Measurement for Forest Soils. Journal of Physics: Conference Series, 1198 (2), 022026. doi: https://doi.org/10.1088/1742-6596/1198/2/022026
25. Metodychni rekomendatsiyi «Vedennia silskoho hospodarstva v umovakh radioaktyvnoho zabrudnennia terytoriyi Ukrainy vnaslidok avariyi na Chornobylskiy AES na period 1999–2002 rr. (1998). Kyiv, 105.
26. Deysan, M., Didkivskyy, M., Dankevych, Ye. et. al. (2011). Recommendations on agricultural production in the radioactive contamination of the northern regions of Zhytomyr, victims of the Chernobyl accident for 2011–2016. Zhytomyr: In-t silskoho hosp-va Polissia NAAN Ukrainy, 34. Available at: http://ir.znau.edu.ua/handle/123456789/4728
27. Krasnov, V. P. (1998). Radioekolohiya lisiv Polissia Ukrainy. Zhytomyr: Volyn, 112.
28. Krasnov, V. P., Orlov, O. O., Kurbet, T. V. (2010). Metodyka obstezhennia radiatsiyno zabrudnenykh lisiv z metoiu yikh reabilitatsiyi na period 2010–2015 rr. Zhytomyr, 16.
29. Yasutaka, T., Naito, W. (2016). Assessing cost and effectiveness of radiation decontamination in Fukushima Prefecture, Japan. Journal of Environmental Radioactivity, 151, 512–520. doi: https://doi.org/10.1016/j.jenvrad.2015.05.012
30. Evrard, O., Laceby, J. P., Nakao, A. (2019). Effectiveness of landscape decontamination following the Fukushima nuclear accident: a review. SOIL, 5 (2), 333–350. doi: https://doi.org/10.5194/soil-5-333-2019
31. Kato, H., Onda, Y., Yamaguchi, T. (2018). Temporal changes of the ambient dose rate in the forest environments of Fukushima Prefecture following the Fukushima reactor accident. Journal of Environmental Radioactivity, 193-194, 20–26. doi: https://doi.org/10.1016/j.jenvrad.2018.08.009
32. Almgren, S., Isaksson, M. (2009). Long-term investigation of anthropogenic and naturally occurring radionuclides at reference sites in western Sweden. Journal of Environmental Radioactivity, 100 (7), 599–604. doi: https://doi.org/10.1016/j.jenvrad.2009.04.009
33. Khomutinin, Y., Levchuk, S., Protsak, V., Pavliuchenko, V., Kashparov, V. (2019). Prompt Mapping of Radioactively Contaminated Areas. Nuclear and Radiation Safety, 3 (83), 51–57. doi: https://doi.org/10.32918/nrs.2019.3(83).06
34. Krasnov, V. P., Orlov, O. O., Landin, V. P. et. al. (2008). Rekomendatsiyi z vedennia lisovoho hospodarstva v umovakh radioaktyvnoho zabrudnennia. Kyiv: Derzhkomlishosp, 82.
35. Pro zatverdzhennia Derzhavnoho hihienichnoho normatyvu «Hihienichnyi normatyv pytomoi aktyvnosti radionuklidiv (137)Cs ta (90)Sr u derevyni ta produktsiyi z derevyny». Zareiestrovano v Ministerstvi yustytsiyi Ukrainy 16 lystopada 2005 r. za N 1384/11664. Available at: https://zakon.rada.gov.ua/laws/show/z1384-05#Text
36. DSTU ISO 10381-1:2004. Yakist gruntu vidbir prob. Chastyna 1. Nastanovy shchodo skladannia prohram vidbyrannia prob (2006). Kyiv: derzhspozhyvstandart Ukrainy, 62.
37. Krasnov, V. P., Kurbet, T. V., Shelest, Z. M., Boiko, O. L. (2016). 137-Cs redistribution in time in wet bory and sugrudy soils in forests of Ukrainian Polissia. Nuclear Physics and Atomic Energy, 17 (1), 63–68. doi: https://doi.org/10.15407/jnpae2016.01.063
38. Melnyk, V. V. (2019). Kolyvannia velychyn pytomoi aktyvnosti ^{137}Cs u riznykh sharakh lisovykh gruntiv v umovakh svizhoho boru Ukrainskoho Polissia. Zbirnyk naukovykh prats II Vseukrainskoi naukovo-praktychnoi konferentsiyi. Ekolohichna bezpeka: suchasni problemy ta propozytsiyi. Vol. II. Kyiv: Interservis, 133–140.