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CURRENT DISTRIBUTION OF ^{137}Cs IN SOD-PODZOLIC SOILS OF DIFFERENT TYPES OF FOREST CONDITIONS

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Досліджено сучасний розподіл ^{137}Cs у дерново-підзолистих лісових ґрунтах різних типів лісорослинних умов. Аналіз перерозподілу ^{137}Cs у ґрунті через 30 років після аварії на ЧАЕС є необхідним для оцінки надходження радіонукліда у різні компоненти лісових екосистем та обґрунтування реабілітації лісових територій. Виявлено переміщення значної кількості ^{137}Cs до мінеральної частини ґрунту у всіх типах лісорослинних умов, у яких проводились дослідження. Встановлено максимальні величини питомої активності ^{137}Cs у лісовій підстилці, а також зменшення даного показника від верхньої її частини (сучасного опаду) до нижньої (розкладеної). У свіжих борах дане зменшення складає 3,1 разів, свіжих суборах – 1,2 разів, вологих суборах – 1,5 разів. За величиною питомої активності ^{137}Cs шари лісової підстилки у досліджуваних типах лісорослинних умов можна розмістити у порядку зменшення: розкладений шар > напіврозкладений шар > сучасний опад. У гумусово-елювіальному горизонті ґрунту потужністю 12 см сконцентровано у свіжих борах – 54,0 %, свіжих суборах – 40,0 % і вологих суборах – 52,8 % від загальної активності радіонукліду у ґрунті, а разом з вмістом ^{137}Cs у лісовій підстилці – 75,0 %; 65,8 % і 71,5 % (відповідно до типів лісорослинних умов). Відмічене поступове зменшення питомої активності ^{137}Cs по профілю до материнської породи. Так, до нижніх шарів ґрунтового розрізу (12–88 см) мігрувало відповідно 26,4 %, 35,7 % та 28,5 % від загального запасу радіонукліду у ґрунті. Отримані матеріали підтверджені за допомогою однофакторного аналізу на 95 %-му довірчому рівні. На основі отриманих результатів можна спрогнозувати майбутні рівні радіоактивного забруднення продукції лісового господарства

Ключові слова: ^{137}Cs, радіоактивне забруднення, питома активність, лісові насадження, дерново-підзолисті ґрунти

1. Introduction

It is known that the radionuclides, upon entering the components of forest ecosystems, gradually moved from the upper to the lower tiers of vegetation and the soil surface. Over time, the main volume of radioactive elements moved to the forest litter and, depending on the type of forest conditions and the composition of tree tier, the migration of radionuclides of different intensity into the mineral part of forest soils started. The result of the accident at the Chernobyl nuclear power plant (CHNPP) is the fixation of the radionuclides in soil and their penetration to the numerous components of forest biocenoses. These components of the forest ecosystems have been widely used in the practice of forest management, as well as by the local population for their own use. Traditionally, the local population uses the non-tree products of the forest: wild berries, mushrooms, and medicinal plants. The dosage of internal irradiation due to the consumption of the specified forest products varies from 12 to 40 % for the total population, and from 50 to 95 % for the critical groups of population [1]. Thus, along with the "forest gifts", the population receives a significant dosing load. Radioactive contamination of certain components of forest ecosystems, which are subsequently utilized as raw materials for the manufacture of food products, depends on the generic features and the type of forest conditions. For the time being, studies into the redistribution of radionuclides in forest soils have almost stopped; existing publications are based on the fragmented materials while data on the current distribution of ^{137}Cs in the turf-podzolic soils are lacking.

Therefore, it is a relevant task to study the current redistribution of ^{137}Cs in turf-podzolic soils of the most common types of forest conditions; this would make it possible to predict the migratory processes of the radionuclide in the chain "soil–plant–human".

2. Literature review and problem statement

The most common soils in forest ecosystems are the turf-podzolic, peaty, and peat soils. These soils are characterized by the low vegetation potential, which is explained by the light mechanical composition, high acidity, low content of exchanging cations and humus. In addition, there is a significant reserve of organic matter (in the form of forest litter and peat of various strength), which is very slow at mineralization [2]. The latter is due to the geographical location and climatic characteristics of the examined region. Thus, at the elevated terrain elements there forms the wash-through type of water regime, and at the low elements there is waterlogging. The role of climate manifests itself in the fact that precipitation exceeds evaporation. The process of soil formation and the presence of mostly pine forests greatly influence the processes that occur in the soil [3]. The existing characteristics of turf-podzolic soils allowed the radioecologists long before the Chernobyl disaster to refer them to those that reveal a significant migration of ^{137}Cs and ^{90}Sr. At that time, researchers were already aware that ^{90}Sr was characterized by a significantly greater migration capability in soil and in the system soil–plants. It was established that in the turf-podzolic soils the migration capability of both radionuclides was almost the same. That was due, according to researchers, to the above-specified features of the sandy turf-podzolic soils.

Over 10–15 years following the accident at CHNPP, several papers were published [4, 5] that reported research results on the following: the redistribution of mostly ^{137}Cs, and to a considerably lesser extent, ^{90}Sr in forest soils; the forms of existence of these radionuclides in soil; the rates of penetration of the most common radioactive elements. It was established [6] in the papers that the largest share of the activity of radionuclides out of its total quantity in the soil is found in forest litter. Over time, the radioactive elements had gradually penetrated from the top non-decomposed part of the forest litter deeper to the decomposed part. Papers [7, 8] noted a noticeable displacement of the radionuclides to the humus-eluvial horizon of the mineral layer of forest soils. Scientists have also found that in deciduous and mixed forests the displacement of the radioactive elements to the mineral part of the soil occurred at a faster pace than that observed in coniferous plantations. The results of studies conducted during that period proved that the main amount of ^{137}Cs in soil acquired a firmly fixed form. It should be noted that most of the research at that time were not of a long-term character. Those were the one-time or occasional observations, which failed to fully characterize the migratory processes in all varieties of the turf-podzolic soils, at plantations of various species, in areas with a varying degree of hydration, and over different periods. During the period that followed, studies into the redistribution of radionuclides in forest soils had significantly decreased. Only scientists in Ukraine and the Republic of Belarus continued periodic observation of the migration processes of certain radionuclides in forest soils over automorphic and hydromorphic landscapes.

Papers [9, 10] investigated peculiarities in the transformation of the form of existence of ^{137}Cs and described the dependence of radionuclide content in soil depending on the composition of vegetation. Furthermore, the authors examined the dynamics of ^{137}Cs content in the components of the litter-soil complex in automorphic turf-podzolic sandy soils. Based on the data obtained, it was substantiated that over the years specific radionuclide activity moves from forest litter to the mineral layer of soil [11, 12]. Paper [13] examined the distribution of ^{137}Cs in the forest litter and soil in the heather, moss, and bilberry types of forest. As a result, it was established that the most content of the radionuclide remains in forest litter and in a 0–5 cm mineral layer of soil. It was established in research [14] that the pine plantations (moss pine forest) on the turf-podzolic soils contained, in forest litter, as of 2014, only about 20 % of the total stock of radionuclide in the soil, while 80 % of its stock had been displaced to its mineral part (70.7 % are concentrated in a layer of 10 cm. As reported in study [15], the redistribution and migration capability of ^{137}Cs in soil depend on the conditions of wetting, the soil type, and phytocenosis. It was concluded in article [16] that a considerable amount of ^{137}Cs accumulates in the products from forest economy. That was explained by the presence of the radionuclide in the soil layer hosting the roots of plants.

Papers [17, 18] provided data about the features of the ^{137}Cs distribution in damp pine forests that grow on turf-podzolic soils. Studies [19, 20] analyzed the distribution of the total activity of ^{137}Cs in the ecosystem of a fresh pine forest. Based on the research conducted in 2012, the authors drew the following conclusion: the more intensive vertical migration of ^{137}Cs was observed from 2000 to 2012 in poor sandy soils of moist forests than in the relatively rich sandy loam moist soils [15, 21]. However, the richer conditions of sudubravas in the layers of the mineral part of soil with a capacity of up to 10 cm and 20 cm concentrate the greater percentage of the ^{137}Cs activity than those under poor conditions of forests. It was also noted that at the time of observation (2012–2014) the forest litter had ceased to be a major container of the radionuclides. The papers also prove that the process of the ^{137}Cs deepening into the soil occurs more intensively in hydromorphic soils in comparison with automorphic soils [11, 17, 22].

In recent years, some studies have compared materials of the distribution of cesium-137 in forest ecosystems resulting from accidents at nuclear power plants in Chernobyl and Fukushima [23]. Scientists have recently [24] been engaged in the search for ways to rehabilitate the radioactively contaminated forests, as well as find ways to enhance the stability of soils. Papers [25, 26] report results of research into the consolidation and redistribution of ^{137}Cs in different fractions of soil in the forest ecosystems and in mushrooms (macromycetes).

Common patterns in the migration of ^{137}Cs in forest soils have been established; the specified patterns were quantified under certain types of planting conditions. In recent years, no publications relating to the current redistribution of ^{137}Cs in the turf-podzolic soils of forest ecosystems have been found; in this case, especially important relating to different types of forest conditions. The process of the redistribution of radioactive elements in soil is dynamic and requires periodic observations. It was established that there is a close relationship between density of the radioactive contamination of soil and the concentration of ^{137}Cs in forest products. Based on studies into levels of radioactive contamination of soil, it is possible to predict the content of a given radionuclide in a forest product and to substantiate the rehabilitation of forest massifs in general. Such observations must be conducted first of all in the most common types of forest turf-podzolic sandy soils that would make it possible to obtain results on the current distribution of ^{137}Cs in forest soils. Based on the results to be obtained, one can predict the levels of radioactive contamination of different components of forest ecosystems, and hence – the produce from forests. That all would contribute to estimating the radiation situation in forest ecosystems aimed at restoring proper forest management.

3. The aim and objectives of the study

The aim of this work was to examine the current distribution of ^{137}Cs in turf-podzolic soils of the most common types of forest conditions.

To accomplish the aim, the following tasks have been set:

– to investigate the current redistribution of ^{137}Cs between forest litter and the mineral part of soil for different types of forest conditions;

– to analyze the migration of ^{137}Cs in turf-podzolic soils under different environmental conditions.

4. Materials and methods of research

We carried out our study in 2017, at the permanent test areas (PTA), laid out in the pine forests at Naroditske forestry of "Naroditske SLG", located in the north-eastern part of Zhytomyr Oblast (Ukraine). The territory of this forestry enterprise was exposed to significant radioactive contamination, which is why its forests include plots with a large range in the density levels of radioactive contamination of the soil. In addition, forests and soils on the territory of the DP "Naroditske SLG" are typical for Ukrainian Polissya.

Characteristics of PTA No. 1. It is located at the taxa plot No. 8 in quarter No. 40. Type of forest conditions – fresh forest (A_2). The PTA hosts a 56-year-old pine plantation (composition: 10 Ps) with a closeness of 0.7, a bonitet of 2, with an average height of 16 m and a diameter of 20 cm. Regrowth is missing. The underbrush is isolated, about 1 m tall, formed by ordinary mountain-ash (*Thusrbus aucuparia L.*). Projective covering of the herb-shrub layer is 50–55 %. It is predominated by bilberry (*Vaccinium vitids-idaea L.*), ordinary heather (Calluna vulgaris (L.) Hull), common cow-wheat (*Melampyrum pretense L.*). The mossy tier has a projective covering of 85–90 %. It is dominated by dicranum moss (*Dicranum polysetum Sw.*) and Schreber's big red stem moss (*Pleurozium schreberi*). Association: green-moss pine forest. Soil – sandy turf-podzolic, on fluvioglacial sands. The forest litter has a capacity of about 8 cm. The mineral part of the soil clearly demonstrates the following horizons: humus-eluvial – dark gray color, with a capacity of 12 cm; eluvial – light-gray color, with a capacity of 4 cm; illuvial – light brown, sandy, with a capacity of 20 cm; illuvial rock – light-yellow color, with a capacity of 32 cm. Parent rock started at the depth of 68 cm. The density of the radioactive contamination of the soil was 266.5±11.8 kBq/m2 (7.2±0.3 Ci/km^2), the maximum values reached 477.5 kBq/m2 (12.9 Ci/km^2), the minimum values amounted to 163.6 kBq/m2 (4.2 Ci/km^2).

Characteristics of PTA No. 2. It is located at taxa plot No. 30, quarter No. 10. The type of forest conditions – fresh subor (B_2). The PTA hosts a 60-year pine plantation (10 C_3) with a closeness of 0.8. a bonitet of 1, the average heights of 18 m and a diameter of 22 cm. The regrowth is represented by rare trees of ordinary pine (*Pinus sylvestris L.*), plain oak (*Quercus robur L.*) and silver birch (*Betula pendula Roth.*). The underbrush is rare, about 1.5 m tall, mountain-ash (*Thusrbus aucuparia L.*) and glossy buckthorn (*Frangula alnus Mill.*). The projective covering of the herb-shrub layer is 70–75 %. It is co-dominated by cowberry (*Vaccinium vitids-idaea L.*), heather (*Calluna vulgaris (L) Hull*), blueberry (*Vaccinium myrtillus L.*). The mossy tier has a projective covering of 85–90 %. It is dominated by dicranum moss (*Dicranum polysetum Sw.*) and Schreber's big red stem moss (*Pleurozium schreberi*). Association: green-moss pine forest. The soil is sod-medium podzolic, medium gleyed light-loamy, on fluvioglacial deposits. The forest litter has a capacity of about 12 cm. The mineral part of the soil clearly displays the following horizons: humus-eluvial – dark gray color, with a capacity of 12 cm; eluvial – light-gray color, with a capacity of 12 cm; illuvial – gray-brown, loamy, with a capacity of 8 cm; illuvial- gleyed – light-yellow color, with a capacity of 32 cm. The gleyed parent rock started at the depth of 64 cm. The density of the radioactive contamination of the soil was 422.8±24.3 kBq/m^2 (11.4±0.65 Ci/km^2), the maximum values reached 708.6 kBq/m^2 (19.1 Ci/km^2), and the minimum values were 318.0 kBq/m^2 (8.6 Ci/km^2).

Characteristics of PTA No. 3. It is located at taxa plot No. 7, quarter No. 10. The type of forest conditions – moist subor (B_3). The PTA hosts a 70-year-old pine plantation (composition: 9 Ps+1 Bp) with a closeness of 0.8, a bonitet of 1, the average height of 24 m and a diameter of 28 cm. The regrowth is represented by rare trees of ordinary pine (*Pinus sylvestris L.*), plain oak (*Quercus robur L.)* and silver birch (*Betula pendula Roth.*). The underbrush is clearly expressed, over 1.5 m tall, mountain-ash (*Thusrbus aucuparia L.*) and glossy buckthorn (*Frangula alnus Mill.*). The projective covering of the herb-shrub layer is 80–85 %. It is co-dominated by bilberry (*Vaccinium vitids-idaea L.),* blueberry (*Vaccinium myrtillus L.*), alpine blueberry (*Vaccinium uliginosum L.*) marsh Labrador tea (*Ledum palustre L.).* The mossy tier has a projective covering of 85–90 %. It is dominated by dicranum moss (*Dicranum polysetum Sw.*) and Schreber's big red stem moss (*Pleurozium schreberi*). Association: green-moss blueberry pine forest. The soil is sod-medium podzolic connected-sandy, on the sandy moraine. The forest litter has a capacity of about 13 cm. The mineral part of the soil clearly exhibits the following horizons: humus-eluvial – dark gray color, with a capacity of 20 cm; illuvial – dark brown color, sandy, with a capacity of 20 cm; illuvial rock – white-yellow color, with a capacity of 44 cm. The parent rock started from the depth of 84 cm. The density of the radioactive contamination of the soil was 338.3±11.9 kBq/m^2 (9.1±0.3 Ci/km^2), the maximum values reached 470.83 kBq/m^2 (12.7 Ci/km^2), and the minimum values were 170.7 kBq/m^2 (4.6 Ci/km^2).

Within each PTA, we laid out the soil profiles, based on which we selected and determined the capacities of soil horizons, described the morphological attributes of soils, took the soil samples for a spectrometric analysis. All soil profiles were laid out in typical places that were characterized by the homogeneous elements of topography, conditions of moistening, the types of plant associations, the soil-forming rocks and by the absence of impact from forestry operations in these territories. The soil profile was described according to the procedures generally accepted in soil science: the power of genetic horizons, coloration, mechanical (granulometric) composition, structure, new formations, inclusions and composition [27].

We took the samples of soil in layers with a thickness 4 cm, repeated 10 times, using a special sampler, to a depth of 88 cm. The forest litter was divided based on the degree of mineralization; the current litter, the semi-decomposed and decomposed layers. All samples were dried to the air-dry state, ground, and homogenized. We measured specific activity of ^{137}Cs in the samples using the scintillation gamma-spectrometric device GDM-20 with the multi-channel pulse analyzer AI (Sweden). 750 samples were analyzed in total, including 90 samples of the forest litter and 660 soil samples. The relative error of measuring the ^{137}Cs specific activity in the samples did not exceed 5 %. Statistical processing of the acquired data was performed applying standard methods using the software packages Microsoft Excel and Statistica 10.0.

5. Results of research into current redistribution of ^{137}Cs in forest soils

5. 1. Studying the current redistribution of ^{137}Cs between the forest litter and mineral part of the soil for different types of forest conditions

An analysis of specific activity of ^{137}Cs in the different layers of soil indicates that its maximum magnitudes are observed in the forest litter. At the same time, for all types of forest conditions there is a decrease in a given indicator from its upper part (current litter) to bottom (decomposed) (Fig. 1). In fresh forests, the specific radionuclide activity in the current litter was 7,047±160.7 Bq/kg; in the semi-decomposed layer, 11,481±179.4 Bq/kg (1.6 times more); and in the decomposed layer, 22,131±355.3 Bq/kg (3.1 times more than that in the litter, and 1.9 times larger than that in the semi-decomposed layer). Differences between the average values for ^{137}Cs specific activity in the layers of the forest litter are quite significant and reliable. This is confirmed by the results from a one-factor dispersion analysis: current litter – semi-decomposed layer: $F_{fact.}$=339>$F_{(1;19;0,95)}$=4.4; semi-decomposed layer – decomposed layer: $F_{fact.}$=716>$F_{(1;19;0,95)}$=4.4; current litter – decomposed layer: $F_{fact.}$=1,496>$F_{(1;19;0,95)}$=4.4.

In fresh subors, the magnitude of this indicator for current litter was 14,873±344 Bq/kg; for the semi-decomposed layer, 17,356±429 Bq/kg (1.2 times more); for the decomposed layer, 18,498±582 Bq/kg (1.2 times more than that in the litter, and 1.1 times larger than that in the semi-decomposed layer). Using a one-factor dispersion analysis, it was confirmed that between the specific activity of ^{137}Cs in the current litter and in the decomposed layer, as well as in the decomposed and semi-decomposed layer, there is a reliable difference between average values: $F_{fact.}$=40>F(1;19;0,95)=4.4 and $F_{fact.}$=47>F(1;19;0,95)=4.4, respectively. It was found that there is no reliable difference between the examined parameters of the current litter and the semi-decomposed layer: $F_{fact.}$=2.5<F(1;19;0,95)=4.4.

For the wet subors, specific radionuclide activity in the current litter was 10,101±213 Bq/kg; in the semi-decomposed layer, 12,312±204 Bq/kg (1.2 times more), and in the decomposed layer, 15,422±452 Bq/kg (1.5 times larger than that in the litter, and 1.3 times more than that in the semi-decomposed layer). Based on the results of a one-factor dispersion analysis, one can note that there is a reliable difference between the specific activity in the layers of the forest litter (current litter – semi-decomposed layer, semi-decomposed layer – decomposed layer, current litter – decomposed layer): $F_{fact.}$=56>F(1;19;0,95)=4.4, Ffact.=39>F(1;19;0,95)=4.4, and $F_{fact.}$=113>F(1;19;0,95)=4.4, respectively. One can note a more intensive descent of the indicator for specific activity in forests relative to subors, and in the moist hygrotrops relative to fresh (subors).

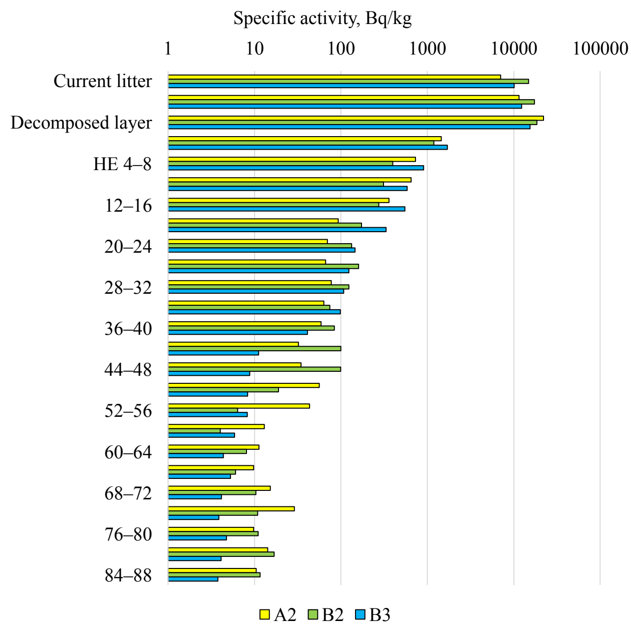

Fig. 1. Specific activity of ^{137}Cs in different layers of sod-medium podzolic soil in fresh forests and subors and moist subors, Bq /kg

One can note the largest magnitudes of the ^{137}Cs specific activity in the mineral part of the soil, in its upper part, as well as a gradual decrease in the indicator to the maternal rock, and much lower magnitudes relative to the forest litter. These patterns have been obtained for soils of all examined types of forest conditions. In fresh forests, the magnitude of the radionuclide specific activity in the upper (0–4 cm) layer was 1,450±36 Bq/kg, which is 15.3 times less than that for the decomposed part of the forest litter. In fresh subors, these magnitudes and the ratios amounted to 1,187±31 Bq/kg (15.6 times less), and in the moist subors, 1,701±91 Bq/kg (9.1 times less).

It was established for the fresh forest that the mean magnitudes of specific activity of the decomposed layer of the forest litter and a 4-centimeter layer of the humus-eluvial horizon have a reliable difference, which is confirmed by the Fisher criterion: $F_{fact.}$=3354 >$F_{(1;19;0,95)}$=4.4. We compared specific activity of 137Cs in the humus-eluvial horizon of mineral part of the soil for the following layers: 0–4 cm – 4–8 cm, and 4–8 cm – 8–12 cm; the existence of a reliable difference between the specified layers has been confirmed: $F_{fact.}$=292>$F_{(1;19;0,95)}$=4.4 and $F_{fact.}$=101>$F_{(1;19;0,95)}$=4.4, respectively.

A similar analysis was conducted based on the research, which were obtained under conditions of fresh subor. It was established that there is a reliable difference between the mean values for specific activity of ^{137}Cs in the decomposed layer of the forest litter and a 4-centimeter layer of the humus-eluvial horizon, which has been confirmed by the one-factor dispersion analysis at a 95 % confidence level: $F_{fact.}$=1,349>$F_{(1;19;0,95)}$=4.4. The reliability of difference in the mean values for specific activity of ^{137}Cs in each layer of mineral part of the soil (0–4 cm – 4–8 cm and 4–8 cm – 8–12 cm) has been also confirmed by the analysis results: $F_{theor.}$>$F_{pract.}$. ($F_{fact.}$=487>$F_{(1;19;0,95)}$=4.4 and $F_{fact.}$=18>$F_{(1;19;0,95)}$=4.4, respectively).

Similar data were acquired when comparing the specific activity of ^{137}Cs in the decomposed layer of the forest litter and in the mineral layer of 0–4 cm in the moist subor. It was established that there is a reliable difference between the mean values for these magnitudes (at a 95-% confidence level) where $F_{theor.}$>$F_{pract.}$ ($F_{fact.}$=886>$F_{(1;19;0,95)}$=4.4). Also confirmed is the existence of a reliable difference between the mean values for specific activity of ^{137}Cs in the layers of 0–4 cm – 4–8 cm: $F_{fact.}$=58>$F_{(1;19;0,95)}$=4.4, and 4–8 cm – 8–12 cm: $F_{fact.}$=17>$F_{(1;19;0,95)}$=4.4.

The more intensive reduction in the ^{137}Cs specific activity in mineral part of the soil can be observed when comparing data obtained at a depth of 0–4 cm and 84–88 cm. For the fresh forests, this decrease was 145.0 times; for the fresh subors, 98.9 times; for the wet subors, 425.0 times. There is a reliable difference between the mean values for specific activity of ^{137}Cs in the layers (0–4 cm – 20– 24 cm, and 20–24 cm – 40–44 cm), which has been confirmed by results from the one-factor dispersion analysis: fresh forests – $F_{fact.}$=1,454>$F_{(1;19;0,95)}$=4.4 and $F_{fact.}$=110>$F_{(1;19;0,95)}$=4.4, respectively; fresh subors – $F_{fact.}$=956>$F_{(1;19;0,95)}$=4.4 and $F_{fact.}$=6>$F_{(1;19;0,95)}$=4.4; moist subors – $F_{fact.}$=279>$F_{(1;19;0,95)}$=4.4 and 20–24 cm – 40–44 cm – $F_{fact.}$=38>$F_{(1;19;0,95)}$=4.4.

5. 2. Analysis of the ^{137}Cs migration in the turf-podzolic soils under different environmental conditions

Specific activity of a radionuclide in different layers of soil does not convey its actual content, because the density of the forest litter is quite small relative to mineral part of the soil while the deeper layers of the latter are denser than the upper ones. During the research, we determined the activity of ^{137}Cs in different parts (current litter, semi-decomposed and decomposed) of the forest litter and in the 4-cm layers of soil at the same areas. That made it possible to determine the vertical distribution of relative content of ^{137}Cs (%) in different layers of the sod-medium podzolic soil in fresh forests, subors, and moist subors (Fig. 2).

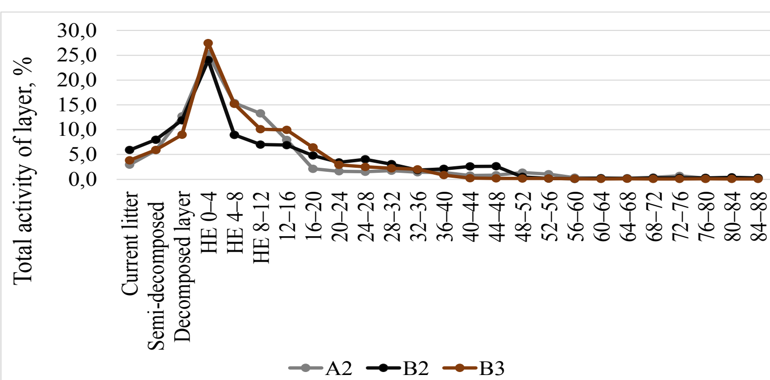

Fig. 2. Vertical distribution of relative content of 137Cs (%) in different layers of sod- podzolic soil in fresh forests, subors, moist subors

The obtained materials indicate that despite the significant level of specific activity of ^{137}Cs in the forest litter, the share of activity of the radionuclide in it is low relative to the total activity in the soil. Thus, in fresh forests, in the forest litter, the ^{137}Cs activity is only 21.5 %; in fresh subors, 25.8 %; in moist subors, 18.7 %. The lowest content of the radionuclide was found in the upper part of the forest litter (current litter): fresh forests – 2.9±0.3 %; fresh subors, 5.9±0.5 %; moist subors, 3.8±0.4 %. In the deeper layers of the forest litter the content of ^{137}Cs is larger relative to the upper ones: in fresh forests, the total radionuclide activity in the decomposed part is 4.4 times greater than that established in the current litter; in fresh subors, it is 2.0 times larger; in moist subors, 2.4 times larger.

It was established by analyzing the vertical distribution of ^{137}Cs in the layers of the forest litter (current litter – semi-decomposed layer, semi-decomposed layer – decomposed layer, current litter – decomposed layer) that the mean values for total activity differed significantly. Based on the results from a one-factor dispersion analysis in fresh forests, we established that $F_{fact.}$=255>$F_{(1;5;0,95)}$=7.7, $F_{fact.}$=116>$F_{(1;5;0,95)}$=7.7 and $F_{fact.}$=235>$F_{(1;5;0,95)}$=7.7, respectively. In fresh subors there is also a reliable difference between the mean values of activity: current litter – decomposed layer, $F_{fact.}$=281>$F_{(1;5;0,95)}$=7.7; decomposed layer – semi-decomposed layer, $F_{fact.}$=37>$F_{(1;5;0,95)}$=7.7); current litter – semi-decomposed layer, $F_{fact.}$=37>$F_{(1;5;0,95)}$=7.7). Similar patterns were established in moist subors: $F_{fact.}$==39>$F_{(1;5;0,95)}$=7.7, $F_{fact.}$=67>$F_{(1;5;0,95)}$=7.7 and $F_{fact.}$=213>>$F_{(1;5;0,95)}$=7.7 (current litter – semi-decomposed layer, semi-decomposed layer – decomposed layer, current litter – decomposed layer, respectively).

The distribution of the total ^{137}Cs activity in soil indicates the displacement of its main part to the mineral part. The share of the total radionuclide activity in the upper 0–4 cm layer exceeds the share in the decomposed part of the forest litter in fresh forests and subors by 2.0 times, and in moist subors, by 3.1 times. There is a reduction in a given indicator in proportion to deepening into the soil. Thus, in fresh forests the share of the total activity of ^{137}Cs in the layer of 0–4 cm was 25.3 %, which is 15.8 times more than that for a layer at the depth of 20–24 cm (1.6 %). A similar reduction in fresh subors equaled 7.1 times (24.0 % and 3.4 %, respectively); in moist subors – 9,5 times (27.5 % and 2.9 %). At the depth of 40–44 cm the share of the total radionuclide activity decreased: in fresh forests – to 0.76 %, in fresh subors – to 2.6 %, and in moist subors – to 0.24 %.

It should be noted that despite the penetration of ^{137}Cs to a significant depth, it is mostly concentrated in the upper part of mineral part of the soil and forest litter. In fresh forests the share of the total radionuclide activity in the soil layer of 0–12 cm is 54.0 %; in fresh subors, 40.0 %; in moist subors, 52.8 %; and together with the content of ^{137}Cs in the forest litter – 75.0 %; 65.8 %, and 71.5 % (according to the type of forest conditions).

It was established by running a one-factor dispersion analysis of average magnitudes of the total activity of the radionuclide in the decomposed layer of the forest litter and in a 4-cm layer of soil at the humus-eluvial horizon of a fresh pine forest that there is a reliable difference – $F_{fact.}$=122>$F_{(1;5;0,95)}$=7.7. In addition, with a 95 % confidence level we revealed that there is a difference between these magnitudes in the layers at a depth of 0–4 cm –

4–8 cm, and 4–8 cm – 8–12 cm ($F_{fact.}$=73>$F_{(1;5;0,95)}$=7.7 and $F_{fact.}$=8.6<$F_{(1;5;0,95)}$=7.7, respectively), as well as at a depth of 0–4 cm – 20–24 cm, and 20–24 cm – 40–44 cm ($F_{fact.}$= =605>$F_{(1;5;0,95)}$=7.7 and $F_{fact.}$=47>$F_{(1;5;0,95)}$=7.7, respectively).

Identical calculations were performed for fresh subors, which have confirmed the existence of a reliable difference at a 95 % confidence level of the total activity of ^{137}Cs in the decomposed layer of the forest litter and a 4-centimeter layer at the humus-eluvial horizon $F_{fact.}$=557>$F_{(1;5;0,95)}$=7.7; between the magnitudes obtained in the layers at a depth of 0– 4 cm – 4–8 cm, and 4–8 cm – 8–12 cm ($F_{fact.}$=760>$F_{(1;5;0,95)}$=7.7 and $F_{fact.}$=18>$F_{(1;5;0,95)}$=7.7); at a depth of 0–4 cm – 20–24 cm, and 20–24 cm – 40–44 cm ($F_{fact.}$=2,229>>$F_{(1;5;0,95)}$=7.7 and $F_{fact.}$=8.9>$F_{(1;5;0,95)}$=7.7).

Similar confirmation has been obtained when comparing the same layers of soil in moist subors: the decomposed part of the forest litter contains less ^{137}Cs than in a 0–4 cm layer of mineral part of the soil ($F_{theor.}$>$F_{pract.}$) ($F_{fact.}$=1,042>>$F_{(1;5;0,95)}$=7.7); the difference between the average values of total activity of ^{137}Cs in the layers of 0–4 cm – 4–8 cm – $F_{fact.}$=402>$F_{(1;5;0,95)}$=7.7, and 4–8 cm – 8–12 cm – $F_{fact.}$=151>$F_{(1;5;0,95)}$=7.7; in the layers of 0–4 cm – 20–24 cm, and 20–24 cm – 40–44 cm – $F_{fact.}$=1,926>>$F_{(1;5;0,95)}$=7.7 and $F_{fact.}$=121>$F_{(1;5;0,95)}$=7.7, respectively.

6. Discussion of results of the current redistribution of ^{137}Cs in forest soils

Based on the obtained results of research, one can argue about the relevance and importance of studying the current redistribution of ^{137}Cs in forest soils. We have analyzed the redistribution of ^{137}Cs in the most common types of forest conditions: fresh forests, fresh and moist subors. Radiation situation in forest ecosystems has significantly changed since the time of the accident at CHPP. This is explained by the natural radionuclide decay, its redistribution in the soil and its stabilization in the many components of forest biogeocenoses.

Papers [18, 20, 22] paid considerable attention to the radioactive contamination of forest ecosystems. Thus, it was found by their authors that in 2000, in moist forests, ^{137}Cs was concentrated mostly (69.03 %) in forest litter, and only 30.93 % – in mineral soil layers. Later research has established that over time the content of ^{137}Cs in forest soils in moist forests had changed and was 12.41 % in the forest litter and 87.59 % in mineral part of the soil. A similar distribution in moist subors was, respectively, 21.09 % and 78.91 %; in moist sudubravas – 1.7 % and 98.3 %, respectively. It is worth noting that in fresh forests the largest share of the total ^{137}Cs activity is concentrated (76.48 %) in soil, including 18.09 % in forest litter and 58.39 % in mineral soil layers. It was found that the components of the above-the-ground phytomass of coenosis retain 23.52 % of the gross stock of ^{137}Cs in a forest ecosystem [15, 21]. In addition, it was noted that over the period from 1994 to 2008 there had occurred a gradual deepening of ^{137}Cs into the lower layers of soil, that is, it migrated from the forest litter to the upper 5-cm soil layer.

In this paper, we have noted the overall pattern in the distribution of ^{137}Cs in the layers of forest litter for the examined types of forest conditions. Thus, the minimum content of ^{137}Cs is characteristic of the current litter with a gradual increase to the decomposed layer of the forest litter. In addition, one can note a more intensive descent in the indicator of specific activity in forests relative to subors, and in moist hygrotrops relative to fresh (in subors). When analyzing the distribution of ^{137}Cs in the mineral part of soil, we noted a gradual decrease in the indicators of the ^{137}Cs specific activity from the upper to the bottom part. These patterns were derived for soils of all examined types of forest conditions. The content of ^{137}Cs is mostly concentrated at the humus-eluvial horizon at a depth of sampling of 0–12 cm. The differences in the distribution of ^{137}Cs for depth can be explained by the fact that the mineral layers at different depths of the soil profile exhibit different morphological attributes (different mechanical composition of soil, which affects the vertical migration of the radionuclide), humidity and acidity of the soil, the presence of soil enzymes and living organisms, the rate of washing and the washing of radionuclides into different layers of soil. Our paper reports the following total distribution of ^{137}Cs in the turf-podzolic soils of fresh forests: 21.5 % in forest litter and 78.5 % in mineral layers; in fresh forests, 25.8 % and 74.2 %; and in moist subors, 18.7 % and 81.3 %, respectively. Thus, one could argue that the bulk of ^{137}Cs was displaced to the deeper mineral soil layers. The differences in the distribution of ^{137}Cs in turf-podzolic soils for different types of forest conditions can be explained by different trophicity and moisture content.

By examining the current redistribution of ^{137}Cs in turf-podzolic soils, and having determined that its largest amount is concentrated in a 12-cm layer of mineral part of the soil, one can predict the elevated levels of radioactive contamination of wild berries and medicinal plants (herbaceous and bush), trees and shrubs.

The benefit of this study is the new data on the content of ^{137}Cs in soils, taking into consideration current radiation situation in forest plantations. Owing to the results obtained, one can substantiate possible rehabilitation of forest areas and to justify a possibility to utilize wood and non-wood products from forestry under certain types of forest conditions. However, for a more complete assessment of the radiation situation in the forests of Ukraine, it is necessary to examine the redistribution of ^{137}Cs in all existing types of forest conditions. It is worth noting that a large area of forests still belongs to the territories where, based on the levels of the radioactive contamination, any forest managing activity is banned. These territories lack objective data on the taxa characteristics of forests, which in turn makes it difficult to conduct any research.

7. Conclusions

1. We have established, for all types of forest conditions, the maximum magnitudes of the ^{137}Cs specific activity in the forest litter, as well as a reduction in this indicator from its upper part (current litter) to the bottom (decomposed). In fresh forests, it reduces by 3.1 times; in fresh subors, 1.2 times; in moist subors, 1.5 times. The obtained materials have been confirmed by the results from a one-factor dispersion analysis at a 95 % confidence level.

2. The highest content of ^{137}Cs is observed in the upper layers of mineral part of soil. The layer of the soil with a capacity of 12 cm has concentrated: in fresh forests, 54.0 %; in fresh subors, 40.0 %; and in moist subors, 52.8 %, of the total radionuclide activity in the soil, and, together with the content of ^{137}Cs in the forest litter, 75.0 %; 65.8 %, and 71.5 % (according to the type of forest conditions).

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