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FEATURES OF THE MODERN DISTRIBUTION OF ^{137}Cs IN SOILS UNDER OVERMOISTENED GROWTH CONDITIONS OF BLACK ALDER FORESTS IN ZHYTOMYR POLISSIA, UKRAINE

Research on the modern distribution of ^{137}Cs in soils of different forest site types in black alder (*Alnus glutinosa* (L.) Gaerth.) stands was conducted. In forest litter, there is not a high percentage of its total activity in soil: in moist fairly fertile site type (C_3) – 13.4 %, damp fairly fertile site type (C_4) – 16.3 %, and wet fairly fertile site type (C_5) – 3.8 %. The mineral part of the soil in moist and damp fairly fertile site type is characterized by decreased density of radioactive contamination of soil layers with depth. In wet fairly fertile site type, this indicator increases to a depth of 6 - 8 cm and decreases with further deepening. A 10-cm layer of moist fairly fertile site type (C_3) contains 61.8 % of the total radionuclide activity in soil, damp fairly fertile site type (C_4) – 68.1%, and wet fairly fertile site type (C_5) – 70.1 %, correspondingly; a 20-cm layer has 75.4, 78.3, 91.9 % and a 30-cm layer – 80.9, 82.2, 96.0 % of the total radionuclide activity.

Keywords: Alnus glutinosa (L.) Gaerth., stands, overmoistened mineral soils, soil bulk density, radionuclides, activity concentration, vertical distribution.

1. Introduction

In the forests of Zhytomyr Polissia of Ukraine, the forest floor is quite diverse, and it is determined by a wide range of factors. The region is located within the lowland of the Prypiat River basin (northern and western parts) and the plain in the Dnipro River basin (central, southern, and eastern parts). Both these territories are characterized by the presence of significant areas of bogs of various types, wetlands, and overmoistened territories [1, 2]. The part of eutrophic bogs is about 90 % of the total number of bogs in Polissia of Ukraine [3]. Natural and artificial forests of black alder (*Alnus glutinosa* (L.) Gaertn), which have different productivity depending on the growth conditions, are widespread on the peat soils of eutrophic and meso-eutrophic bogs, as well as on overmoistened fertile and relatively fertile mineral soils. In addition, black alder stands to grow in different hydrological conditions: long-term surface waterlogging, periodic flooding, with close groundwater level to the soil surface, et cetera [4]. The alder forests of Ukrainian Polissia mostly grow on peaty soils; however, according to I. M. Grygora's data [4], in Zhytomyr Polissia of Ukraine, a significant area of alder forests grows on mineral soils.

In its case, a wide range of edaphic and hydrological conditions affects the redistribution of radionuclides in the soil and, subsequently, the intensity of their accumulation in numerous components of biocenoses. It should also be noted that under conditions of constant and long-term flowing moistening, black alder trees create specific elevations around the trunks, which consist of alder roots, organic plant residues, and soil. These elevations are also characterized by specific processes of soil formation, which affect the migration of radionuclides in the soil and the radionuclide transfer into plants that grow on it. Thus, black alder stands to grow in different types and subtypes of soils under different moisture conditions [5], manifesting in the different redistribution of ^{137}Cs in the soil and also in the components of forest phytocenoses.

Research on soil radioactive contamination of forest ecosystems and the distribution of radionuclides began in forests of Ukrainian Polissia in the first years after the accident at the Chornobyl Nuclear Power Plant. It was mainly carried out in automorphic conditions and much less in semi-hydromorphic and hydromorphic ones. The latter is probably explained by the technical difficulties in sampling for the measurement of radioactive contamination density of different soil layers. However, the researchers found a significant difference in the rates of ^{137}Cs redistribution in forest soils in different moisture conditions [6]. They stated an increased intensity of radionuclide transfer to forest plants in conditions of higher moistening (research conducted in 1994 - 1997). These conclusions were similar to those obtained by scientists in 1998 when studying ^{137}Cs accumulation by plants on agricultural lands in automorphic and semi-hydromorphic conditions [7]. The study of ^{137}Cs distribution in different soils (peaty-bog, soddy-podzolic gley sandy-loam, soddy-meadow sandy gley, sandy-dust surface peaty) of superaquatic landscapes of the Prypiat and the Uzh rivers floodplains allowed the researchers to conclude that 15 years after the Chornobyl accident, about 80 % of the radionuclide activity was in the upper 5-cm soil layer [8]. Later (2017) researchers who studied the regularities of radioactive contamination of fodder plants in peaty-bog soils in the western part of Polissia established that 60 - 80 % of ^{137}Cs activity is in the upper 6-cm soil layer and in these conditions, the radionuclide is characterized by high biological availability [9].

The researchers studied the components of above-ground phytomass in alder forests of association *Alnetum* (*glutinosae*) – *ruboso* (*idaei*+*nessensi*) – *variaherbosu*m) and ^{137}Cs distribution in this biogeocenosis [10]. They found that ten years after the accident at the Chornobyl NPP the largest part of ^{137}Cs total activity was observed in the soil, including forest litter – 3.3 %, and the mineral soil – 87.2 % (86.1 % of which was in the upper 10-cm layer). In 2006, scientists studied ^{137}Cs content in the components of black alder stands of association *Alnus glutinosa* + (*Betula pendula*) + *Thelypteris palustris*), which grew in damp fairly fertile site type (C_4) [11]. Research showed that forest litter contained 20.8 % of the total radionuclide activity in the soil. Its content gradually decreased to the depth of 10 - 15 cm, then it increased to the depth of 25 - 35 cm, and after that, the indicator fell again. Scientists showed a significant migration capacity of ^{137}Cs in soils of meso-eutrophic bogs. The data (2008) for meso-eutrophic and eutrophic alder bogs of Ukrainian Polissia are also given: forest litter contained 3.9 % of ^{137}Cs total activity in soil damp fairly fertile site type (C_4) and 3.6 % – in wet fairly fertile site type (C_5) [12].

In Rivne Nature Reserve, 25 years after the Chornobyl accident, there was conducted research on different types of bogs where stands of diverse species composition grew, including black alder on peaty bog soils of meso-eutrophic alder bogs [13]. Researchers noted significant values of ^{137}Cs activity concentration in the layer of the decomposed part of the forest litter, and the maximum value was detected in the peat layer of 0 - 5 cm with a further gradual decrease with the depth.

Even a few studies conducted in black alder stands on bogs and overmoistened areas indicated a particular difference in the results obtained, probably because of differences in ecological conditions where the studies were conducted. In the remote period since the accident at the Chornobyl NPP, such territories remained as critical ecosystems characterized by increased migration ability of ^{137}Cs, which is explained by the variety of hydrological regimes, physical and chemical processes occurring between the absorbing complex of soil and soil solution, as well as soil properties and features of the botanical composition of peat. Given this, conducting research in these ecological conditions will broaden our understanding of the long-term dynamics of radionuclide redistribution in the soils of alder biogeocenoses.

2. Objects and methodology

To determine the area of black alder stands in the studied region, establish their distribution by forest site types, and justify the research objects the relational database “Forest Fund of Ukraine” was used as of January 1, 2017. The research was conducted during 2022 - 2023 on experimental plots (EP) located in Zhytomyr Region on the territory of Luhyny Forestry and Bovsunivskyi Forestry of the “Luhyny Forestry” branch of the State Enterprise “Forests of Ukraine” (Table 1). Experimental plots are located in areas that have similar conditions in soil fertility (fairly fertile site type) but essentially differ in soil moisture – moist fairly fertile site type (C_3) (EP-6), damp fairly fertile site type (C_4) (EP-8) and wet fairly fertile site type (C_5) (EP-12). The density of ^{137}Cs soil contamination on EP-6 was 392 ± 37.3 kBq·m^{-2}, on EP-8 – 217 ± 21.0 kBq·m^{-2} and on EP-12 – 270 ± 32.8 kBq·m^{-2}.

Experimental plots were laid out according to the standard methods [14]. Within each experimental plot three soil profiles were excavated, providing descriptions of the horizons. The depth ($D(t)$, cm) of each horizon was measured, and soil samples were taken by a special sampler: 25 × 20 × 2 cm (1 dm^3). Samples were dried, mixed, and analyzed using SEG-001 “AKP-S” spectroanalyzer with a scintillation detector BDEG-20R2. The average relative error of measurement of ^{137}Cs activity concentration was less than 15 % (confidence level – 0.95). In the process of preparing soil samples, the bulk density (BD, kg·dm^{-3}) is determined. Statistical processing of obtained results was carried out using generally accepted methods in the Excel program.

Table 1. **Characteristics of experimental plots in the "Luhyny Forestry" branch of the State Enterprise "Forests of Ukraine"**

Index of experimental plot	Forest site type	Location / Geographic coordinates	Soil	Moisture regime	Phytocenosis
EP-6	Moist fairly fertile site type (C_3)	Bovsunivske Forestry, quarter No. 34, elementary forest stand No. 37 / 51°06'54.0"N 28°29'23.8"E	The rich variant of soddy-slightly podzolic	Highly flowing, does not flood. Average annual groundwater level – on the depth 100 - 110 cm	*Pineto-Querceto-Alnetum* (*glutinosae*)-*franguloso-ruboso* (*idaei*)-*majanthemosum*
EP-8	Damp fairly fertile site type (C_4)	Luhyny Forestry, quarter No. 85, elementary forest stand No. 26 / 51°07'18.4"N 28°25'19.2"E	Soddy highly podzolic, superficially peaty, gley	Moderately flowing, periodically flooded in spring. The groundwater level on a depth of 5 - 10 cm	*Betuleto* (*pendulae*)-*Alnetum* (*glutinosae*)-*caricetum* (*acutiformis*)
EP-12	Wet fairly fertile site type (C_5)	Luhyny Forestry, quarter No. 85, elementary forest stand No. 29 / 51°07'21.8"N 28°25'37.6"E	Soddy highly podzolic, ferruginous-illuvial-humified	Stagnant, periodically flooded. The water level is highly variable during the year – from the soil surface to a depth of 30 - 40 cm	*Betuleto* (*pendulae*)-*Alnetum* (*glutinosae*)-*cariceto-scirpetum* (*sylvaticus*)

3. Results and discussion

The area of black alder stands within Zhytomyr Polissia is 38,5 thous. ha. The analysis of forest management materials made it possible to establish that stands predominantly composed of black alder belong to the most widespread in the studied region and are found in 18 forest site types. This is due to the fact that in the last 50 - 60 years stands predominantly consisting of black alder, have been established in some areas with poor (infertile pine site type – A) and relatively poor (fairly infertile pine site type – B) trophotopes to improve soils and growth conditions. However, most black alder stands are concentrated in conditions of fairly fertile site type (C) – 76.9 % of the total area (Fig. 1).

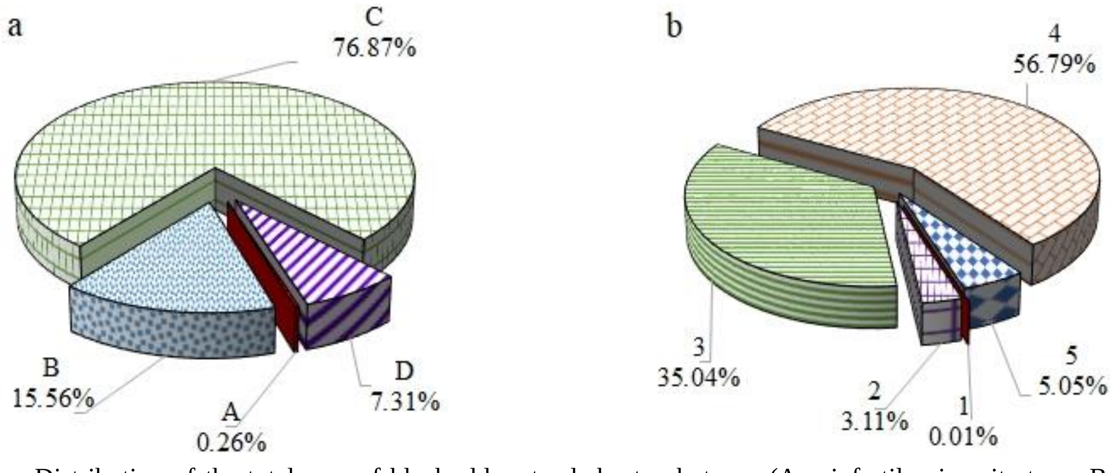

Fig. 1. *a* – Distribution of the total area of black alder stands by trophotopes (A – infertile pine site type, B – fairly infertile pine site type, C – fairly fertile site type, D – fertile site type); *b* – hygrotopes (*1* – dry site type, *2* – fresh site type, *3* – moist site type, *4* – damp site type, *5* – wet site type) in the forests of Zhytomyr Polissia. (See color Figure on the journal website.)

The value of ^{137}Cs activity concentration in different forest litter layers in all studied forest site types increased from its non-decomposed part to the decomposed one: in moist fairly fertile site type (C_3) – by 10.8 times (from 1085 ± 59.3 to 11695 ± ± 432.0 Bq·kg^{-1}), in damp fairly fertile site type (C_4) – by 2.6 times (from 2200 ± 79.4 to 5797 ± ± 104.1 Bq·kg^{-1}) and in wet fairly fertile site type (C_5) – by 2.0 times (from 4768 ± 37.3 to 9716 ± ± 62.3 Bq·kg^{-1}) (Table 2).

Table 2. **Average values of ^{137}Cs activity concentration in different soil layers on experimental plots**

Soil layer, depth	^{137}Cs activity concentration, Bq·kg^{-1}		
	EP-6 (C_3)	EP-8 (C_4)	EP-12 (C_5)
Forest litter			
Undecomposed	1085 ± 59.3	2200 ± 79.4	4768± 37.3
Semi-decomposed	2668 ± 174.5	2653 ± 58.7	9127± 156.2
Decomposed	11695 ± 432.0	5797 ± 104.1	9716± 62.3
Soil layers, cm			
0 - 2	9655 ± 167.4	10353 ± 123.0	12089± 298.2
2 - 4	5410 ± 54.9	7010 ± 58.8	17924± 537.5
4 - 6	2820 ± 93.1	2710 ± 66.4	21960± 91.6
6 - 8	1825 ± 20.8	1264 ± 29.2	11767± 247.1
8 - 10	1103 ± 38.6	811 ± 46.7	7519± 107.2
10 - 12	769 ± 22.6	574 ± 6.1	4267± 44.7
12 - 14	501 ± 17.3	301 ± 9.6	2650± 100.4
14 - 16	375 ± 6.7	262 ± 13.1	1767± 49.3
16 - 18	299 ± 8.5	188 ± 4.9	1390± 72.7
18 - 20	213 ± 3.8	174 ± 6.4	999± 65.0
20 - 22	177 ± 7.5	114 ± 3.1	438± 32.2
22 - 24	161 ± 3.8	96 ± 3.5	283± 3.8
24 - 26	160 ± 9.0	86 ± 3.1	196± 12.2
26 - 28	154 ± 10.6	73 ± 2.3	98± 4.6
28 - 30	133 ± 2.5	52 ± 2.6	93± 4.2
30 - 32	119 ± 3.8	30 ± 3.0	40± 2.0
32 - 34	120 ± 3.1	21 ± 1.0	19± 1.2
34 - 36	98 ± 3.5	13 ± 1.5	18± 1.5
36 - 38	110 ± 2.0	11 ± 1.5	15± 1.5
38 - 40	98 ± 3.1	6 ± 0.6	12± 1.5
40 - 42	84 ± 2.0	6 ± 1.0	10± 2.0
42 - 44	66 ± 4.0	6 ± 1.2	8 ± 0.6
44 - 46	55 ± 1.5	5 ± 1.2	7 ± 1.0
46 - 48	32 ± 2.0	5 ± 1.0	4 ± 1.2
48 - 50	18 ± 3.1	4 ± 1.0	3 ± 1.5

Data from Table 2 clearly testifies that there is a decrease in the mentioned ratio with an increase in the moisture soil conditions. This tendency can be explained by the gradual fixation of ^{137}Cs on clay particles in the upper soil layers in moist fairly fertile site type (C_3) and also by the sharp increase of soil bulk density in the soil of this site type compared with others.

However, significant values of ^{137}Cs activity concentration were observed in forest litter of all studied forest site types. This fact indicates that intensive migration from soil to components of phytocenoses and return to soil continues within the small biological cycle of chemical elements in forest ecosystems. The most precise reflection of this is a high radionuclide content in the layer of annual, undecomposed forest litter.

In the mineral part of the soil in moist (C_3) and damp (C_4) fairly fertile site types a gradual decrease of ^{137}Cs activity concentration was observed with depth (Fig. 2). It should be noted that the rate of decline of this parameter in the upper part of the mineral soil was much higher than in the lower part. Thus, within the upper 10-cm layer the decrease reached 8.8 times in moist fairly fertile site type (C_3) and 12.8 times in damp fairly fertile site type (C_4), and within the next 10 cm (10-20 cm) – 3.6 and 3.3 times, respectively. This can be explained by the gradual fixation of the radionuclide in the upper soil layers and the increase of soil bulk density with depth.

In the wet fairly fertile site type (C_5) there was a somewhat different trend in the soil layers: ^{137}Cs activity concentration increased from the surface to the layer at a depth of 4 - 6 cm and decreased further down the profile. It can be explained by a lower intensity of mineralization of organic residuals in a wet fairly fertile site type (C_5) with a stagnant type of soil moisture regime. The distribution of ^{137}Cs in the mineral part of the soil is approximated by the equations: in moist fairly fertile site type (C_3) – $BD = 3301.4^{-0.20D(t)}$ ($R^2 = 0.80$), in damp fairly fertile site type (C_4) – $BD = 4747.4e^{-0.31D(t)}$ ($R^2 = 0.89$), in wet fairly fertile site type (C_5) – $BD = 37701e^{-0.39D(t)}$ ($R^2 = 0.70$).

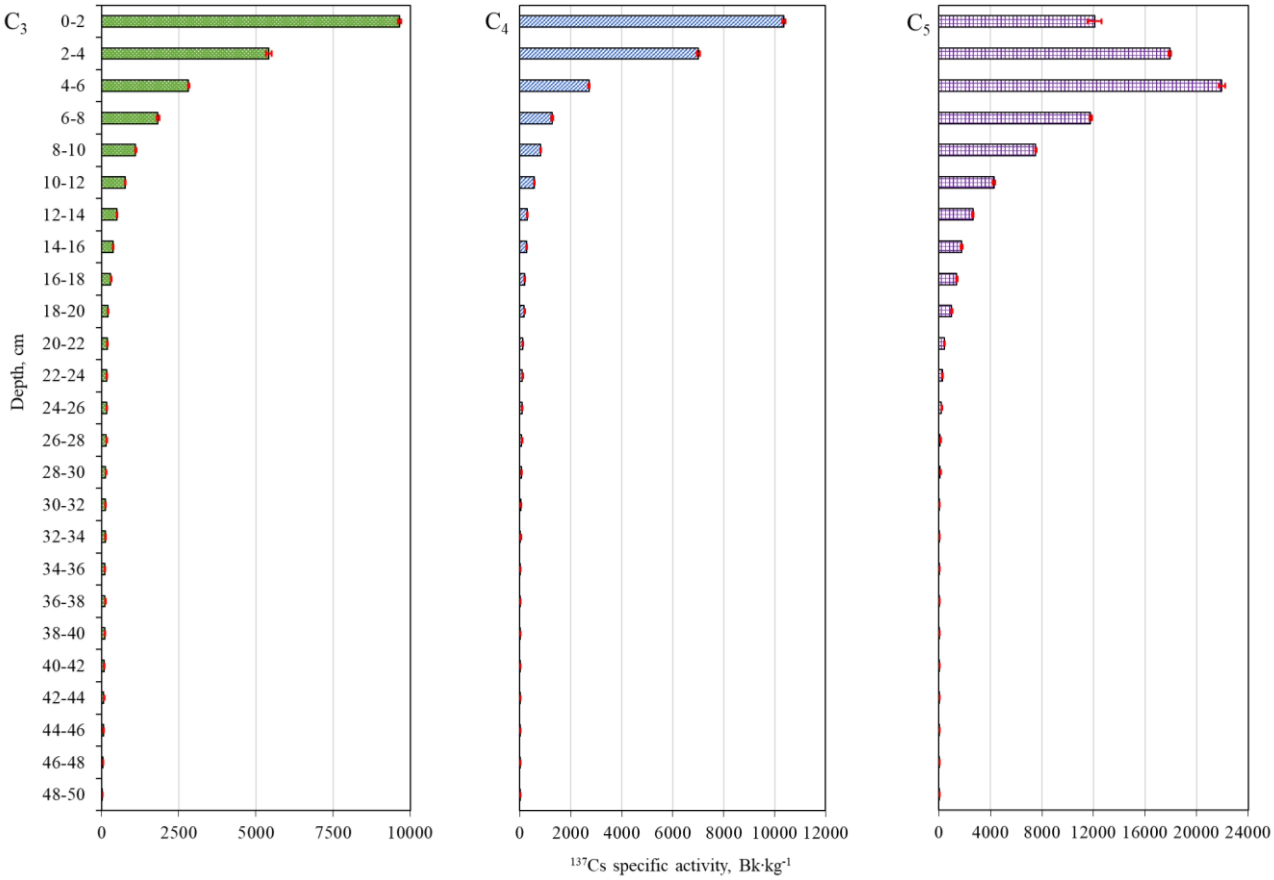

Fig. 2. Distribution of ^{137}Cs activity concentration in the mineral part of soil on experimental plots in different forest site types: C_3 – moist fairly fertile site types, C_4 – damp fairly fertile site types, C_5 – wet fairly fertile site types. (See color Figure on the journal website.)

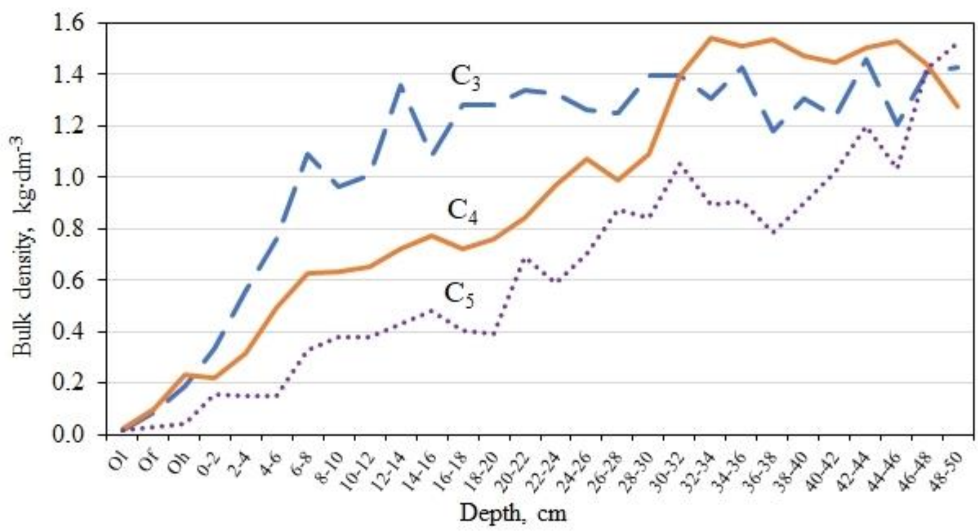

Fig. 3. Vertical distribution of soil bulk density in different forest site types: C_3 – moist fairly fertile site types, C_4 – damp fairly fertile site types, C_5 – wet fairly fertile site types. (See color Figure on the journal website.)

It is known that different layers of forest soils have different bulk densities which, in turn, depend on the mineralogical, granulometric compositions, organic matter content in the soil, and also soil processes such as eluvial and illuvial. These processes lead to the destruction of primary and secondary minerals of clay particles and the transition of them from the upper soil layers to the lower ones. Among the latter are colloid and clay particles, as well as oxides of iron, manganese, aluminium, et cetera, as a reflection of the illuvial process. Differences in soil bulk density between various soil layers on experimental plots are presented in Fig. 3.

The obtained data show an increase in the bulk density of soil layers in the mineral part and surface peaty part with depth in studied forest site types. In moist fairly fertile site type (C_3) a sharp increase of bulk density was observed in the mineral part of the soil from 0 - 2 cm to a layer of 20 - 22 cm – by 4.0 times (from 0.336 to 1.342 kg·dm^{-3}). Subsequently, this indicator fluctuated across layers within minimal ranges. In moister conditions of damp fairly fertile site type (C_4), a significant increase in bulk density was observed to a depth of 30 - 32 cm – by 6.4 times (from 0.218 to 1.398 kg·dm^{-3}). Similar to the previous forest site type, slight fluctuations of the indicator values were observed in deeper layers. In wet fairly fertile site type (C_5) the mentioned sharp increase of soil layer bulk density can be traced to a depth of 46 - 48 cm – by 9.1 times (from 0.156 to 1.424 kg·dm^{-3}).

The density of ^{137}Cs radioactive contamination of soil layers rather than radionuclide activity concentration is an indicator that demonstrates the vertical distribution of radionuclides in the soil more correctly because of significant differences in the soil bulk density. This indicator showed similar distribution regularities to that of activity concentration (Table 3). Despite relatively high values of ^{137}Cs activity concentration in forest litter, a small percentage of its total activity in soil is found: in moist fairly fertile site type (C_3) – 13.4 %, damp fairly fertile site type (C_4) – 16.3 %, and wet fairly fertile site type (C_5) – 3.8 %. In all studied forest site types, the total activity values in forest litter decrease from the upper layers to the lower ones. It can be explained by the increase in the degree of decomposition and bulk density with depth.

Table 3. **Density of ^{137}Cs contamination of forest litter and 2-cm layers of soil on experimental plots**

Soil layer, depth	EP-6 (C_3)		EP-8 (C_4)		EP-12 (C_5)	
	Bq·dm^{-3}	%%	Bq·dm^{-3}	%%	Bq·dm^{-3}	%%
Forest litter						
Undecomposed	17	0.09	57	0.55	86	0.41
Semi-decomposed	240	1.29	271	2.60	274	1.31
Decomposed	2222	11.98	1368	13.11	428	2.05
Soil layers, cm						
0 - 2	3244	17.49	2257	21.62	1886	9.03
2 - 4	3030	16.34	2201	21.08	2724	13.05
4 - 6	2138	11.53	1344	12.87	3294	15.77
6 - 8	1989	10.72	796	7.63	3883	18.60
8 - 10	1063	5.73	513	4.92	2842	13.61
10 - 12	774	4.17	373	3.57	1613	7.73
12 - 14	679	3.66	217	2.08	1145	5.48
14 - 16	408	2.20	203	1.95	845	4.05
16 - 18	384	2.07	136	1.30	564	2.70
18 - 20	273	1.47	132	1.26	392	1.88
20 - 22	237	1.28	96	0.92	301	1.44
22 - 24	214	1.15	93	0.89	167	0.80
24 - 26	202	1.09	92	0.88	138	0.66
26 - 28	193	1.04	72	0.69	86	0.41
28 - 30	185	1.00	57	0.55	78	0.37
30 - 32	166	0.89	42	0.40	42	0.20
32 - 34	157	0.85	32	0.31	17	0.08
34 - 36	140	0.75	20	0.19	16	0.08
36 - 38	130	0.70	17	0.16	12	0.06
38 - 40	128	0.69	9	0.09	11	0.05
40 - 42	104	0.56	9	0.09	10	0.05
42 - 44	96	0.52	9	0.09	10	0.05
44 - 46	66	0.36	8	0.08	7	0.03
46 - 48	45	0.24	7	0.07	6	0.03
48 - 50	26	0.14	5	0.05	5	0.02
In total:	18550	100	10436	100	20882	100

Data from Table 3 show that on all experimental plots, the largest part of ^{137}Cs total activity was observed in the upper layers of the mineral part of the soil. Thus, a 10-cm layer of moist fairly fertile site type (C_3) (EP-6) contained 61.8 %, damp fairly fertile site type (C_4) (EP-8) – 68.1 %, and wet fairly fertile site type (C_5) (EP-12) – 70.1 % of the total radionuclide activity in the soil; a 20-cm layer retained 75.4, 78.3 and 91.9 %, respectively; and 30-cm layer – 80.9, 82.2 and 95.9 %, respectively.

4. Conclusions

In forest ecosystems of black alder with over-moistened soil conditions, the intensive biological cycling of ^{137}Cs continues. This is evidenced by significant values of the radionuclide-specific activity in forest litter of all investigated forest site types. In less moist growth conditions (moist and damp fairly fertile site type (C_3 and C_4) there is a gradual decrease in the density of radioactive contamination in the mineral part of soil with depth. In conditions of constant waterlogging (wet fairly fertile site type (C_5) the density of radioactive contamination in the soil layer increases to a depth of 6-8 cm and further decreases with depth. A 10-cm layer of moist fairly fertile site type (C_3) (EP-6) contained 61.8 %, damp fairly fertile site type (C_4) (EP-8) – 68.1 %, and wet fairly fertile site type (C_5) (EP-12) – 70.1% of the total radionuclide activity in the soil; a 20-cm layer retained 75.4, 78.3 and 91.9 %, respectively; and 30-cm layer – 80.9, 82.2 and 95.9 %, respectively. Since the radionuclide's entry into forest ecosystems and soil, there has been a more significant movement of the radionuclide down to a depth of 10 - 15 cm under more moist soil conditions. Below this depth, a somewhat higher fraction of its content is observed under less moistened growth conditions.

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ОСОБЛИВОСТІ СУЧАСНОГО РОЗПОДІЛУ ^{137}Cs У ГРУНТАХ ПЕРЕЗВОЛОЖЕНИХ УМОВ ЗРОСТАННЯ ЧОРНОВІЛЬХОВИХ ЛІСІВ ЖИТОМИРСЬКОГО ПОЛІССЯ УКРАЇНИ

Проведено дослідження щодо сучасного розподілу ^{137}Cs у ґрунтах різних типів лісорослинних умов у лісових насадженнях вільхи чорної (*Alnus glutinosa* (L.) Gaerth.). У лісовій підстилці міститься невисокий відсоток його сумарної активності у ґрунті: у вологих сугрудах (C_3) – 13,4 %, сирих сугрудах (C_4) – 16,3 % і мокрих сугрудах (C_5) – 3,8 %. У мінеральній частині ґрунту вологих і сирих сугрудів спостерігається зменшення щільності радіоактивного забруднення шарів ґрунту з глибиною. У мокрих сугрудах цей показник збільшується до глибини 6 - 8 см, а з подальшим заглибленням – зменшується. У 10-см шарі вологих сугрудів (C_3) міститься 61,8 %, сирих сугрудів (C_4) – 68,1 % та мокрих сугрудів (C_5) – 70,1 % сумарної активності радіонукліду в ґрунті; у 20-см шарі – 75,4, 78,3, 91,9 %; у 30-см шарі – 80,9, 82,2, 96,0 % (відповідно до типів лісорослинних умов).

Ключові слова: Alnus glutinosa (L.) Gaerth., насадження, перезволожені мінеральні ґрунти, об’ємна щільність ґрунту, радіонукліди, питома активність, вертикальний розподіл.

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