UDC 574:630*18(477.42)
DOI https://doi.org/10.32782/geotech2024.38.01

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TOXICOLOGICAL STUDY OF MOSS COVER IN PINE FORESTS OF BIOGEOCHEMICAL LANDSCAPE IN BACKGROUND AREA OF UKRAINIAN POLISSIA. PART 2. RADIONUCLIDES – ^{137}Cs

Abstract. *Tasks of this study – to evaluate interspecific differences of ^{137}Cs accumulation by mosses; analyze ^{137}Cs distribution among fractions of mosses; monitor multiyear dynamics of ^{137}Cs content and values of ^{137}Cs concentration ratio in mosses in 2002–2022; calculate dependence between ^{137}Cs activity concentration in Dicranum polysetum and in the soil on the basis of statistical systematical approach; identify spatial heterogeneity of ^{137}Cs activity concentration in moss cover and in the soil and to evaluate it quantitative using fractal geometry. Study was conducted in two stages: in 2002 and 2022 at 3 experimental plots in Zhytomyr Region, Korosten district, Povchanske forest division of Branch "Lugyny Forestry" of State Enterprise "Forests of Ukraine". Vegetation was presented by pine forest of association Molinio-Pinetum Matuszkiewicz (1973) 1981, by fairly infertile pine site type (B_3). Mosses were sampled by fractions: increment of the 1st year, increment of the 2nd year, increments of earlier period and peat litter. The activity concentration of ^{137}Cs was measured using SEG-001 AKP-C-150 spectrometer analyzer with scintillation detector BDEG-20-R2. Coefficient of biological absorption (CBA) was used as an index of intensity of accumulation of ^{137}Cs in the chain "soil – moss". In 2002 according with the mean ^{137}Cs content in the increment of the 1st year (increments of 1–2 years) moss species can be placed in such order: Leucobryum glaucum > Dicranum polysetum > Polytrichum commune > Sphagnum palustre > S. capillifolium > Pleurozium schreberi, with interspecies differences of this index in 2,2 times. In 2002 and 2022 distribution of ^{137}Cs activity concentration among fractions of moss species was similar: maximum values of ^{137}Cs activity concentration were in alive, apical parts – increment of the 1st year and increments both the 1st and the 2nd years. Below this part a decrease of this index was observed in increment of the 2nd year and increments of the earlier period and peat litter. In all moss species in 2002-2022 ^{137}Cs content significantly decreased – from 2,46 times in Dicranum polysetum to 2 times in Sphagnum capillifolium. Despite a significant decrease of ^{137}Cs activity concentration in fractions of all studied moss species mean values of CBA in 2022 decreased slightly in comparison with those of 2002. In 2022 according with the mean values of CBA moss species can be placed as follows: Leucobryum glaucum (7,42 ± 0,49) > Polytrichum commune (6,72 ± 0,45) > Sphagnum palustre (6,15 ± 0,54) > Dicranum polysetum (6,11 ± 0,43) > S. capillifolium (5,99 ± 0,56) > Pleurozium schreberi (2,97 ± 0,18). Dependence of ^{137}Cs activity concentration in the soil from ^{137}Cs activity concentration in Dicranum polysetum was linear, close (r = 0,76) and reliable (p = 0,000). Spatial heterogeneity of ^{137}Cs contamination of moss cover and soil was high and had a focal character. Decreasing of mean value of ^{137}Cs activity concentration in moss cover and in the soil depending on the grid step is a confirmation of its fractal distribution. We proposed to replace full sampling matrix by Vicsek fractal matrix, with sampling only on central column and central line or on the main diagonals of full matrix, which allows to reduce total number of samples in 5 times, with relative differences of mean values of ^{137}Cs activity concentration in moss and soil in comparison with full matrix less than ±10%.*

Key words: *Ukrainian Polissia, forest biogeocenoses, soil, moss cover, fractions of mosses, ^{137}Cs activity concentration, coefficient of ^{137}Cs biological absorption, spatial heterogeneity, fractal geometry, Vicsek fractal.*

Introduction. Mosses were first proposed for the study of atmospheric deposition of pollutants in the late 1960s (Rühling & Tyler, 1968), and now special methodology of bioindication of pollution and biomonitoring has been created (Bioindicators & Biomonitors…, 2003). Due to their high surface-to-volum ratio mosses effectively absorb macro- and trace elements mainly from the wet and dry atmospheric deposition which makes them suitable test-objects for biomonitoring of atmospheric pollution, including radioactive one (Mattsson, Liden, 1975). After the Chornobyl catastrophe an interest to use of mosses for mapping and biomonitoring of radioactive depositions increased sharply. Numerical studies of Chernobyl fallouts using moss biomonitoring (bryomonitoring) technique were conducted in European countries: Norway (Steinnes and Njåstad, 1993), Sweden (Vinichuk et al., 2010), Italy (Giovani et al, 1994), Austria (Iuran et al., 2011), Poland (Dołhańczuk-Śródka et al., 2011), Serbia (Čučulović et al, 2012a; Čučulović et al, 2012b), Bosnia and Herzegovina (Adrović et al., 2017), Montenegro (Dragović et al., 2004), Turkey (Cevik & Celik, 2009), Lithuania (Jefanova et al., 2014), Ukraine (Melnyk, Kurbet, 2018a; Orlov, Dolin, 2010; Orlov, 2022), etc. For this purpose the most common and wide spread in Europe mosses were used, mainly ectohydritic ones such as *Hylocomium splendens*, *Pleurozium schreberi, Dicranum polysetum, Sphagnum* spp., and more rarely – endohydritic species such as *Polytrichum commune*, with some regional peculiarities.

Goal of study. The present study is aimed at quantitative evaluation of ^{137}Cs accumulation by the main moss species-bioindicators of radioactive contamination of background forest area of Ukrainian Polissia. The results of the study should help to interpret the data of bryomonitoring of radioactive pollution of the studied region.

Tasks of study. To evaluate interspecific differences of ^{137}Cs accumulation by various moss species; analyze ^{137}Cs distribution among fractions of mosses; monitor multiyear dynamics of ^{137}Cs content and values of ^{137}Cs concentration ratio in moss species in 2002–2022; calculate dependence between ^{137}Cs activity concentration in *Dicranum polysetum* and in the soil on the basis of statistical systematical approach; identify spatial heterogeneity of ^{137}Cs activity concentration in moss cover and in the soil and to evaluate it quantitative using fractal geometry.

Literature review. The peculiarities of ^{137}Cs accumulation in the moss cover of forests of the Ukrainian Polissia have been analyzed in (Melnyk, Kurbet, 2018a, 2018b). It was shown that in association *Dicrano-Pinetum* in fresh infertile pine site type (A_2) ^{137}Cs activity concentration in *Dicranum polysetum* Sw. ex Anon. exceeded this index of *Pleurozium schreberi* (Willd. ex Brid.) Mitt. in 1,6-1,7 times. For pine forests of association *Peucedano-Pinetum* in fresh fairly infertile pine site type (B_2) mean values of ^{137}Cs concentration ratio in the chain "soil – moss" were significantly greater in *Dicranum – polysetum* – 7,1 ± 0,2 than in *Pleurozium schreberi* – 4,2 ± 0,1 (Melnyk, Kurbet, 2018b).

Study conducted in Chornobyl Exclusion Zone in 2023 (Schmidt et al., 2023) showed that uptake of ^{137}Cs by various moss species was essentially differ. Maximum levels of ^{137}Cs activity concentration were observed in acrocarpous species (Bq·g^{-1}): *Bryum intermedium* (Brid.) Bland. – 297, *B. badium* (Brid.) Schimp. – 157 and *Dicranum polysetum* – 15,9 (Bq·g^{-1}) and minimum ones – in pleurocarpous mosses: *Pleurozium schreberi* – 3,0, *Amblystegium serpens* (Hedw.) Schimp. – 2,9 and *Brachythecium glareosum* (Bruch ex Spruce) Schimp. – 2,3.

Significant interspecific differences of ^{137}Cs accumulation by mosses were reported by researchers in Austria in vicinity of Salzburg city on peat bog (Iuran et al., 2011). In particular, it was identified that *Leucobryum glaucum* (Hedw.) Ångstr. accumulated ^{137}Cs more intense than *Sphagnum papillosum* Lindb., corresponding values of ^{137}Cs activity concentration were 14,09 kBq·kg^{-1} and 1,48 kBq·kg^{-1}.

For Serbia it was shown (Dragovich et al., 2010) that intensity of ^{137}Cs accumulation by mosses is species-specific, which, in turn, connected with interspecific differences of interception and retention of airborne radioactive particles by moss loose carpets or dense pillows (Tyler, 1990). Values of ^{137}Cs concentration ratio for moss species can be placed in such order (geometric mean ± GSD): *Hypnum cupressiforme* Hedw. (3,62 ± 3,05) > *Pleurozium schreberi* (2,00 ± 1,83) > *Hylocomium splendens* (Hedw.) Schimp. (1,80 ± 1,73) (Dragovich et al., 2010). Mentioned above values of ^{137}Cs concentration ratio were lower than those reported earlier.

Seasonal dynamics of ^{137}Cs content was studied in phytomass of *Dicranum polysetum* (Zarubina, 2023), and it was identified that, in this species clear seasonal trend was absent, however some peaks of this index were observed during the year, not associated with a specific season.

Activity concentration of ^{137}Cs was analyzed in different moss species on biogeochemical barrier in transsuperaquatic landscape of Ukrainian Polissia (Orlov, 2021). According with ^{137}Cs content in the upper, alive part moss species of this biotope can be placed in such order (Bq·kg^{-1}) (M ± m): *Sphagnum fallax* (H. Klinggr.) H. Klinggr. (2810 ± 330) > *S. capillifolium* (Ehrh.) Hedw. (2780 ± 350) > *Polytrichum commune* (1570 ± 270) > *Dicranum polysetum* (1500 ± 230) > *Pleurozium schreberi* (1064 ± 220).

In Italy, in Southern Alps on raised bog 4 years after Chornobyl disaster vertical distribution of ^{137}Cs in fractions of moss cover of *Sphagnum capillifolium* was studied (Gerdol et al., 1994). It was found that the highest ^{137}Cs content was observed in the increment of 1986 year forming, some lower of surface of alive part of moss – on the depth 4–6 cm – 2913 ± 1232 Bq·kg^{-1}, increment of 1985 year also was characterized by high ^{137}Cs activity concentration – 2853 ± 1352 Bq·kg^{-1}. Minimal ^{137}Cs activity concentration was observed in the upper, alive part of *Sphagnum* moss – increment of the first year – 2662 ± 1319 Bq·kg^{-1}. This distribution of ^{137}Cs was opposite to those obtained earlier for radiocaesium derived from the nuclear weapon tests in 1960^{s}, when values of ^{137}Cs activity concentration always were the highest in the top, alive part of *Sphagnum* spp. (Clymo, 1978; Oldfield et al., 1979).

It was shown (Holovko, 2020) that in Western Polissia of Ukraine on raised bogs maximum values of ^{137}Cs specific activity were observed in moss species of flooded hollows – *Sphagnum fallax, Aulacomnium palustre* (Hedw.) Schwägr. with ^{137}Cs concentration ratio in the chain "moss – peat" = 2,5, and minimum – in hummock's species – *Sphagnum magellanicum* Brid. s. l. and *Polytrichum strictum* Menzies ex Brid. with concentration ratio = 1,3–2,0. It was reported for montane sphagnous bog in Czech Republic that value of ^{137}Cs concentration ratio in the chain "Sphagnum moss – peat" was equaled 1,7 (Michalic et al., 2014).

For ecosystems of mezooligotrophic bogs of Ukrainian Polissia it was demonstrated that, in warm period of the year, during active vegetation season ascending flow of potassium and ^{137}Cs prevails in the thickness of sphagnous cover – from dead, lower moss parts to alive apical parts, and after the end of vegetation season – descending flow (Orlov, 2000). Distribution of ^{137}Cs activity concentration among fractions of *Sphagnum* spp. during active vegetation was similar in all studied species – ^{137}Cs activity concentration decreased in the follow order: Sphagnum alive – Sphagnum dead – peat litter in such species as *S. magellanicum*, *S. angustifolium* (C.E.O. Jensen ex Russow) C.E.O. Jensen, S. fallax, *S. cuspidatum* Ehrh. ex Hoffm. (Орлов, Долін, 2010). It indicates a release of ^{137}Cs from dead lower part of *Sphagnum* by the way of internal translocation of radionuclide to the upper alive part (Vinichuk, et al., 2011).

It was shown that close connection of ^{137}Cs activity concentration in moss cover with density of ^{137}Cs soil contamination really exists. In particular, in Norway in 1986 in *Hylocomium splendens* this dependence was linear, close (r = 0,75) and reliable (p < 0,01) (Steinnes & Njåstad, 1993); in Japan in 2014 in the zone of impact of accident on NPP Fukushima in *Hypnum plumaeforme* Wilson – it was linear, medium closeness (r = 0,55), reliable (p = 0,001) (Oguri, Deguchi, 2018); in Ukraine, in fresh infertile pine site type (A_2) – also was linear, reliable (p < 0,01), close – for *Dicranum polysetum* (r = 0,83) and for *Pleurozium schreberi* (r = 0,85) (Melnyk, Kurbet, 2018a). For the northern sector of Exclusion Zone of Chornobyl NPP it was shown (Dolgushin et al., 2020) that connection had medium closeness (r = 0,63) of ^{137}Cs activity concentration in the green part of *Pleurozium schreberi* and *Dicranum polysetum* with this index of 4–6-cm soil layer.

Study in Norway showed significant spatial heterogeneity of Chornobyl radioactive depositions on forest ecosystems on regional and local levels (Steinnes & Njåstad, 1993). In particular, in *Hylocomium splendens* ^{137}Cs activity concentration on regional level (on grid 50 x 100 km) varied in the range 2,7–62,7 kBq·kg^{-1}, and on local one (on grid 5 x 10 km) – in the range 8,5–38,8 kBq·kg^{-1}. Mosaic of radioactive contamination of forest ecosystems (Bossew et al., 1996), including their moss layer (Dolgushin et al., 2020; Fränzle, 2003) demands of systematical statistical approach to moss and soil sampling – using a grid with required step, with statistically reliable number of samples on each experimental plot.

Objects and methodology. Radioecological study of moss cover was conducted in two stages: in July of 2002 and in July of 2022 at 3 experimental plots in Zhytomyr Region, Korosten district, Povchanske forest division of Branch "Lugyny Forestry" of State Enterprise «Forests of Ukraine» (Table 1).

Vegetation was presented by pine forests of association *Molinio-Pinetum* Matuszkiewicz (1973) 1981, forest site condition – moist fairly infertile pine site type (B_3), typical for studied region. Moss layer had projective cover 75–95% and mainly consisted of *Pleurozium schreberi* (30–45%) and *Dicranum polysetum* (30–50%). Less participation took part such species as *Polytrichum commune* (3–5%), *Leucobryum glaucum* (1–3%), and in depressions – *Sphagnum capillifolium* (Ehrh.) Hedw. (1–3%) and *S. palustre* L. (1–3%).

In 2002 on each experimental plot 20 soil samples were systematically taken – by cylindrical drill, with diameter 5 cm, to the depth 10 cm. Moss were sampled in fivefold repetition by fractions: *Pleurozium schreberi* and *Dicranum polysetum* – increment of 1–2 years, increments of earlier period (Figure 1); *Polytrichum commune* – increment of the first year, increment of the second year, increments of earlier period; *Leucobryum glaucum, Sphagnum capillifolium* and *S. palustre* – increment of the first year, increment of the second year, peat litter (semi-decomposed).

Fig. 1. Scheme of sampling of moss cover from *Dicranum polysetum*
Рис. 1. Схема відбору зразків мохового покриву з *Dicranum polysetum*

Similar sampling was also carried out in 2022.

In 2002 on experimental plot in Povchanske forest division, quarter 50, elementary forest stand 20 on square

Table 1. A brief description of forest experimental plots
Таблиця 1. Коротка характеристика лісових дослідних ділянок

Forest division, quarter/ elementary forest stand	Geographical coordinates	Composition of tree canopy, stand origin	Age, years	Height, m	Dia-meter, cm	Stand density	Stand quality class
Povchanske, 50/20	51°08'13.29"N, 28°35'32.72"E	Pine – 100%, natural	66	23	28	0,70	I
Povchanske, 50/21	51°08'13.12"N, 28°35'42.41"E	Pine – 100%, forest cultures	51	16	16	0,80	II
Povchanske, 50/22	51°08'13.58"N, 28°35'48.87"E	Pine – 100%, forest cultures	51	18	22	0,80	I

1,0 ha (100 x 100 m) systematical statistical sampling of moss cover from *Dicranum polysetum* and soil under moss was conducted with grid 10 x 10 m. In total 100 moss samples and 100 soil samples were collected.

Moss and soil samples were dried during 72 h at temperature 80ºC, and then they were homogenized, subsequent sample's preparation for spectrometric analysis was carried out by standard methods. Measurement of ^{137}Cs specific activity was conducted in a Marinelli container (1000 cm^3), also smaller containers were used – with volume 135 cm^3 and 75 cm^3. The activity concentration of ^{137}Cs in the samples was measured using a SEG-001 AKP-C-150 spectrometer analyzer with scintillation detector BDEG-20-R2. The relative error of measurement of ^{137}Cs activity concentration did not exceed 15%.

Coefficient of biological absorption was used as an index of intensity accumulation of ^{137}Cs by mosses in the chain «soil – moss». It was calculated as a ratio of ^{137}Cs activity concentration in moss to radionuclide activity concentration in the soil:

$$CBA = \frac{A_{moss}}{A_{soil}}, \text{ where:}$$

CBA – coefficient of ^{137}Cs biological absorption;
A_{moss} – ^{137}Cs activity concentration in moss, Bq·kg^{-1};
A_{soil} – ^{137}Cs activity concentration in the soil, Bq·kg^{-1}.

This index is fully consistent to such index as concentration ratio, usually using in radioecology (Handbook of parameter…, 2010).

Statistical processing of obtained results was conducted by standard methods (Horkavy, 2009) in package Excel and Statistica 10.0. Evaluation of spatial heterogeneity of ^{137}Cs activity concentration in moss cover and in the soil was given using an approach, designed by I.G. Grabar (Grabar, 2023; Orlov, Grabar, 2023). Names of mosses were given by (Hodgetts et al., 2019), and forest site type – according with (Pohrebniak, 1931).

Results and discussion. For experimental plots mean values of ^{137}Cs activity concentration in the soil were calculated: in 2002 – 2850 ± 379 Bq·kg^{-1} and in 2022 – 1420 ± 243 Bq·kg^{-1} as well as mean values of density of ^{137}Cs soil contamination: in 2002 – 318,63 ± 34,18 kBq·m^{-2}, and in 2022 – 158,76 ± 20,54 kBq·m^{-2}.

The study of the values of ^{137}Cs activity concentration in fractions of moss species in 2002 and 2022 made it possible to reveal general features of radioactive contamination of moss cover in the studied area (Table 2).

In both periods an analysis of ^{137}Cs activity concentration in the upper, alive part of mosses is of great importance. In particular, in 2002 according with the mean ^{137}Cs content in increment of the 1st year (increments of 1–2 years) moss species can be placed in such order (M ± m, kBq·kg^{-1}): *Leucobryum glaucum* (21,65 ± 0,89) > *Dicranum polysetum* (21,36 ± 1,00) > *Polytrichum commune* (19,68 ± 1,48) > *Sphagnum palustre* (19,46 ± 1,51) > *S. capillifolium* (17,46 ± 1,20) > *Pleurozium schreberi* (9,91 ± 0,62). Thus in 2002 interspecies differences of the mean ^{137}Cs content in mentioned above species row reached 2,2 times.

Data of Table 2 also також testify about specific ^{137}Cs activity concentration distribution among fractions of moss cover. In particular, in 2002 mentioned above distribution in all moss species was as follows: maximum values of ^{137}Cs activity concentration were characteristic for alive, apical parts – increment of the 1st year and increments both the 1st and the 2nd years. Below in moss fractions a decrease in this index was observed in increment of the 2nd year, increments of the earlier period and peat litter. For example, in *Polytrichum commune* the mean value of ^{137}Cs activity concentration decreased in following ranged raw of fractions (M ± m, kBq·kg^{-1}): increment of the 1st year (19,68 ± 1,48) > increment of the 2nd year (15,34 ± 1,17) > increments of the earlier period (11,05 ± 1,10); in *Sphagnum palustre* corresponding values were 19,46 ± 1,51 kBq·kg^{-1}; 12,62 ± 1,46 kBq·kg^{-1} and 8,72 ± 1,05 kBq·kg^{-1}. Results of ANOVA showed that differences of mean ^{137}Cs content in fractions of moss cover were significant and reliable in all studied moss species: *Pleurozium schreberi* ($F_{fact.} = 5,70 > F_{0,95} = 5,32$; p = 0,04), *Dicranum polysetum* ($F_{fact.} = 6,15 > F_{0,95} = 5,32$; p = 0,04), *Leucobryum glaucum* ($F_{fact.} = 6,09 > F_{0,95} = 3,89$; p = 0,01), *Polytrichum commune* ($F_{fact.} = 11,69 > F_{0,95} = 3,89$; p = 0,002), *Sphagnum capillifolium* ($F_{fact.} = 5,20 > F_{0,95} = 3,89$; p = 0,02), *S. palustre* ($F_{fact.} = 16,02 > F_{0,95} = 3,89$; p = 0,000). Some differences were observed in distribution of ^{137}Cs activity concentration in fractions of *Leucobryum glaucum* and other moss species. For this species in 2002 maximum ^{137}Cs content was characteristic in the increment of the 1st year (21,65 ± 0,89 kBq·kg^{-1}), decrease of this index in the increment of the 2nd year (18,15 ± 0,77 kBq·kg^{-1}) and increase of it in peat litter semidecomposed (21,05 ± 0,58 kBq·kg^{-1}).

Comparative analysis of ^{137}Cs activity concentration in mosses after 20 years, in 2022 demonstrates an important changes (Table 2). It was identified that in all moss species values of this index significantly decreased, maximum decrease was observed in *Dicranum polysetum* – 2,46 times, and minimum one – in *Sphagnum capillifolium* – 2 times, in other studied species decrease had intermediate values. In 2022 according with the mean ^{137}Cs activity concentration in the increment of the 1st year (increments of 1–2 years) moss species formed the following row (M ± m, kBq·kg^{-1}): *Leucobryum glaucum* (10,54 ± 1,35) > *Polytrichum commune* (9,54 ± 0,99) > *Sphagnum palustre* (8,73 ± 0,83) > *Dicranum polysetum* (8,68 ± 1,07) > *Sphagnum capillifolium* (8,51 ± 0,59) > *Pleurozium schreberi* (4,22 ± 0,51). Thus, in 2022 interspecies difference of mean ^{137}Cs content in mentioned above row of species reached 2,5 times, that exceeded such index of 2002. Also it should be noted that mentioned above row of moss species in 2022 is somewhat different from those in 2002.

Data of Table 2 also testified that distribution of ^{137}Cs activity concentration among fractions of majority of moss species in 2002 and 2022 was similar: maximal values of ^{137}Cs activity concentration were observed in the increment of the 1st year (increments of 1st and the

Table 2. Activity concentration of ^{137}Cs (kBq·kg^{-1}, d.w.) in fractions of moss cover of different species in 2002 and 2022
Таблиця 2. Питома активність ^{137}Cs (кБк·кг$^{-1}$, на суху вагу) у фракціях мохового покриву різних видів у 2002 р. та 2022 р.

Moss species	Fraction of moss cover	M	m	Std	V%	P%	min.	max.
2002								
Pleurozium schreberi	Increment of 1–2 years	9,91	0,62	1,38	13,90	6,22	7,76	11,25
	Increment of earlier period	7,84	0,61	1,36	17,41	7,79	6,20	8,90
Dicranum polysetum	Increment of 1–2 years	21,36	1,00	2,22	10,42	4,66	18,58	24,31
	Increment of earlier period	17,85	1,01	2,25	12,61	5,64	15,11	20,71
Polytrichum commune	Increment of the first year	19,68	1,48	3,32	16,86	7,54	16,55	25,00
	Increment of the second year	15,34	1,17	2,62	17,09	7,64	12,93	19,53
	Increment of earlier period	11,05	1,10	2,45	22,18	9,92	9,10	15,10
Leucobryum glaucum	Increment of the first year	21,65	0,89	1,99	9,20	4,12	19,00	23,03
	Increment of the second year	18,15	0,77	1,71	9,44	4,12	16,09	20,00
	Peat litter (semidecomposed)	21,05	0,58	1,29	6,15	2,75	19,60	22,61
Sphagnum capillifolium	Increment of the first year	17,46	1,20	2,69	15,38	6,88	13,00	20,00
	Increment of the second year	15,30	1,62	3,62	23,68	10,59	10,68	20,14
	Peat litter (semidecomposed)	11,20	1,33	2,97	26,48	11,84	8,09	15,43
Sphagnum palustre	Increment of the first year	19,46	1,51	3,37	17,34	7,76	15,07	24,50
	Increment of the second year	12,62	1,46	3,27	25,95	11,61	8,55	15,92
	Peat litter (semidecomposed)	8,72	1,05	2,36	27,02	12,08	6,27	11,64
2022								
Pleurozium schreberi	Increment of 1–2 years	4,22	0,51	1,14	26,96	12,06	3,04	5,59
	Increment of earlier period	3,28	0,50	1,11	33,85	15,14	2,32	5,01
Dicranum polysetum	Increment of 1–2 years	8,68	1,07	2,40	27,69	12,38	5,80	12,20
	Increment of earlier period	6,94	0,33	0,74	10,72	4,79	5,70	7,70
Polytrichum commune	Increment of the first year	9,54	0,99	2,22	23,29	10,41	9,21	11,82
	Increment of the second year	7,55	0,58	1,30	17,26	7,72	5,62	8,73
	Increment of earlier period	5,47	0,90	2,02	36,96	16,53	3,10	8,58
Leucobryum glaucum	Increment of the first year	10,54	1,35	3,03	28,76	12,86	7,82	15,10
	Increment of the second year	9,03	1,25	2,80	31,00	13,87	6,10	12,30
	Peat litter (semidecomposed)	10,56	1,27	2,85	26,96	12,06	6,97	12,39
Sphagnum capillifolium	Increment of the first year	8,51	0,59	1,33	15,62	6,98	6,88	10,48
	Increment of the second year	6,57	0,74	1,66	25,26	11,30	4,59	8,32
	Peat litter (semidecomposed)	4,93	0,53	1,20	24,32	10,87	3,52	6,41
Sphagnum palustre	Increment of the first year	8,73	0,83	1,85	21,20	9,48	6,28	10,62
	Increment of the second year	6,18	0,72	1,60	25,95	11,61	4,18	7,79
	Peat litter (semidecomposed)	4,10	0,50	1,11	27,12	12,13	2,95	5,48

Note: *M – arithmetic mean; m – absolute error of arithmetic mean; Std – standard deviation; V% – coefficient of variation; P% – relative error of arithmetic mean.*

2nd years). Decrease of this index was noted lower in moss fractions – in the increment of the 2nd year and in increments of the earlier period and in peat litter. An exception to the regularity described above in 2022 became *Leucobryum glaucum.* Fot this species maximum ^{137}Cs content was observed in peat litter semidecomposed (10,56 ± 1,27 kBq·kg^{-1}), only slightly lower this index was in the increment of the 1st year (10,54 ± 1,27 kBq·kg^{-1}), and significantly lower – in the increment of the 2nd year (9,03 ± 1,25 kBq·kg^{-1}). However results of ANOVA indicated an absence of statistically reliable differences of ^{137}Cs content in mentioned above fractions of *Leucobryum glaucum* ($F_{fact.}$ = 1,12 < $F_{0,95}$ = 3,89).

For bryomonitoring of radioactive contamination of forest ecosystems it is important to provide the data on intensity of ^{137}Cs distribution in the chain "soil – moss" on the basis of values of coefficient of ^{137}Cs biological absorption (CBA) (Figures 2–3).

Data of Figure 2 clearly show that in 2002 the maximum values of CBA in the increment of the 1st year were observed in *Leucobryum glaucum* (7,59 ± 0,43) and *Dicranum polysetum* (7,50 ± 0,52) and minimum ones – in *Pleurozium schreberi* (3,48 ± 0,23) and *Sphagnum capillifolium* (6,13 ± 0,50). Mean values of CBA for *Dicranum polysetum* and *Pleurozium schreberi* were close to those reported earlier (Melnyk, Kurbet, 2018b).

Results of ANOVA (Table 3) also clearly showed that mean values of ^{137}Cs CBA differed reliably in *Pleurozium schreberi* and all other moss species ($F_{fact.}$ = 26,84 – 73,01 > $F_{0,95}$ = 5,32; p = 0,000 – 0,001), however, such differences were absent between the rest moss species ($F_{fact.}$ = 0,003 – 4,07 < $F_{0,95}$ = 5,32).

It should be especially emphasized that the observed high values of ^{137}Cs activity concentration in moss cover as well as values of coefficient of ^{137}Cs biological absorption are determined not by the active absorption of radionuclide from the soil during the observation period by moss species, but, on the contrary – by self-cleaning of moss cover from ^{137}Cs. As a result, part of the radionuclide activity migrates with a downflow from the moss cover into the soil. But at the same time intensive migration and redistribution of ^{137}Cs with upflow occurs in the thickness of the moss cover – from dying and died parts of mosses to alive apical ones. Last process is species-specific.

We consider it appropriate to briefly analyze sources of ^{137}Cs uptake to moss cover, and also processes providing accumulation, retention and redistribution of ^{137}Cs in the thickness of moss cover. The main sources of ^{137}Cs uptake to moss cover are follows. 1. ^{137}Cs derived from Chornobyl accidental fallouts in 1986. 2. Modern global atmospheric depositions of radionuclides, including ^{137}Cs, due to activity of nuclear facilities all over the world. According to (Report…, 2023), mean value of density of beta-active atmospheric depositions on the territory of Ukraine in 2022 amounted up to 1,6 Bq·m^{-2} per day. 3. Tree crown runoff and trunk runoff of radionuclide due to its leaching from leaves, twigs, bark, etc. 4. Resuspension which leads to surface contamination of moss cover by small soil particles containing ^{137}Cs (Garger, 1994).

In ectohydritic mosses cell walls are easily penetrable for metal ions, including ^{137}Cs, since they have neither epidermis nor cuticle and accumulate metals in a passive way acting as ion exchangers (Fränzle, 2003).

In dense pillows of ectohydritic species *Dicranum polysetum* stems are covered by dense, felt-like rhizoids, and most likely that ^{137}Cs absorption carried out by these rhizoids from solutions, entirely impregnating moss cover and often connecting with forest litter and soil. In ectohydritic moss species water moves due to capillary forces (Proctor & Tuba, 2002). Also these species have connecting elongated cells with water transport caused by surface tension (Kłos et al., 2012).

Ectohydritic moss *Pleurozium schreberi* which forms loose carpets can obtain some micronutrients from the soil

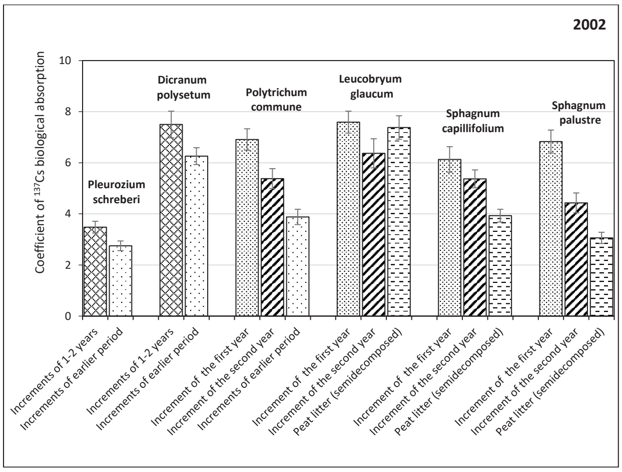

Fig. 2. Mean values of coefficient of ^{137}Cs biological absorption in moss species in 2002
Рис. 2. Середні значення коефіцієнту біологічного поглинання ^{137}Cs у видів мохів у 2002 р.

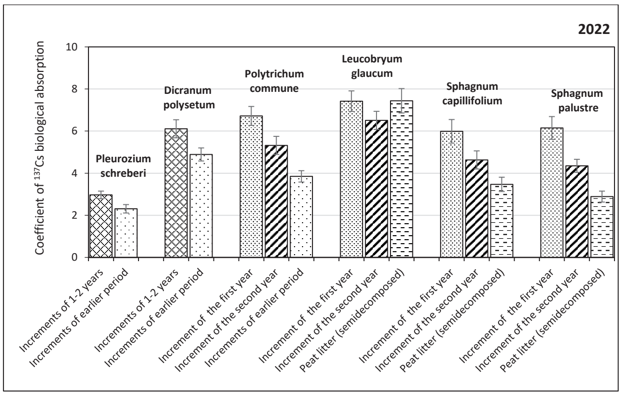

Fig. 3. Mean values of coefficient of ^{137}Cs biological absorption in moss species in 2022
Рис. 3. Середні значення коефіцієнту біологічного поглинання ^{137}Cs у видів мохів у 2022 р.

(Dołhańczuk-Śródka et al., 2011; Van Tooren et al., 1990). This species often have a little bit of soil and detrital particles nestled among the leaf bases. They could be derived from the soil and found that indeed nutrients did arrive on the plants from the soil, but in small quantities.

Table 3. Results of ANOVA of mean values of coefficient of ^{137}Cs biological absorption in moss species in 2022
Таблиця 3. Результати дисперсійного аналізу середніх значень коефіцієнта біологічного поглинання ^{137}Cs у видів мохів у 2022 р.

	Pleurozium schreberi	***Dicranum polysetum***	***Polytrichum commune***	***Leucobryum glaucum***	***Sphagnum capillifolium***
Dicranum polysetum	46,26 p = 0,000				
Polytrichum commune	59,42 p = 0,000	0,96			
Leucobryum glaucum	73,01 p = 0,000	4,07	1,10		
Sphagnum capillifolium	26,84 p = 0,001	0,03	1,04	3,73	
Sphagnum palustre	31,76 p = 0,000	0,003	0,66	3,06	0,04

Note: $F_{0,95}$ = 5,32.

For endohydric species *Polytrichum* commune (Proctor, 2000) with well-developed rhyzoids in the soil and internal water movement through the water-conduction system most likely some soil input was involved, with addition of upward water movement through external capillary action (Glime, 2017). The possibility of ^{137}Cs transfer to moss cover from forest litter through mycorrhizae probably also can take place (Ying & Liang-Dong, 2007).

In Sphagnum cover decrease of ^{137}Cs activity concentration demonstrates a release of radionuclide from dying and died fractions of moss by internal ^{137}Cs translocation upward to alive apical part – capitulum (Orlov, 2000; Vinichuk et al., 2011). This process is general for both cations – K^+ (Dainty and Richter, 1993) and $^{137}Cs^+$ (Orlov, 2000; Vinichuk et al., 2011). In Sphagnum mosses appears to be the carboxyl group of galacturonic acid in the composition of pectin, which accounts up to 30% of the dry weight of Sphagnum, that are responsible for radiological properties of these mosses (Balance et al., 2015).

Analysis of mean values of coefficient of ^{137}Cs biological absorption in mosses after 20 years, in 2022 showed important features (Figure 3). In particular, despite a significant decrease of ^{137}Cs activity concentration in fractions of all studied moss species mean values of coefficient of ^{137}Cs biological absorption decreased insignificant. For example, in *Dicranum polysetum* mean values of CBA in 2002 were equal 7,50 ± 0,52 and in 2022 – 6,11 ± 0,43; in *Polytrichum commune* – 6,91 ± 0,42 and 6,72 ± 0,45 respectively. Similar dynamics was also observed in other studied moss species. Slight decrease of coefficient of ^{137}Cs biological absorption is determined primarily by the fact that both for soil and mosses the main factor of decrease of ^{137}Cs content is physical decay, and the rest factors have a much smaller impact.

We analyzed statistical differences of mean values of CBA ^{137}Cs in fractions of studied moss species in 2022 and identified that in general they were similar to those 2002. In particular, it was shown that mean values of CBA ^{137}Cs in fractions of moss species differed significantly and reliably: *Pleurozium schreberi* ($F_{fact.} = 6{,}07 > F_{0{,}95} = 5{,}32$; $p = 0{,}04$), *Dicranum polysetum* ($F_{fact.} = 5{,}33 > F_{0{,}95} = 5{,}32$; $p = 0{,}05$), *Polytrichum commune* ($F_{fact.} = 13{,}23 > F_{0{,}95} = 3{,}89$; $p = 0{,}001$), *Sphagnum capillifolium* ($F_{fact.} = 7{,}87 > F_{0{,}95} = 3{,}89$; $p = 0{,}007$), *S. palustre* ($F_{fact.} = 17{,}54 > F_{0{,}95} = 3{,}89$; $p = 0{,}000$). The exception was *Leucobryum glaucum* in which differences in CBA between fractions were not significant ($F_{fact.} = 1{,}12 < F_{0{,}95} = 3{,}89$).

For bryomonitoring purposes of radioactive contamination by ^{137}Cs of forest biogeocenoses dependence of ^{137}Cs activity concentration in the soil from radionuclide activity concentration in moss *Dicranum polysetum* in 2002 was calculated (Figure 4).

Data of Figure 4 indicate that mentioned above dependence was linear, close ($r = 0{,}76$) and reliable ($p = 0{,}000$). These data are in the good agreement with results of other researches (Dolgushin et al., 2020; Melnyk, Kurbet, 2018a).

For bryomonitoring of radioactive contamination of forest ecosystems sampling stategy is of great importance which is caused by significant spatial heterogeneity of ^{137}Cs contamination of soil, mosses and other components of forest biogeocenosis. Therefore a general view of spatial heterogeneity of ^{137}Cs activity concentration in moss *Dicranum polysetum* and in the soil was obtained on the basis of systematical sampling on grid 10 x 10 m (Figures 5–6).

The data of Figures 5–6 clearly demonstrate a significant spatial heterogeneity of ^{137}Cs fallout in the forest ecosystem, which is naturally reflected in the spatial distribution of the activity concentration of the mentioned radionuclide both in the moss cover with *Dicranum polysetum* and in the soil. The data of Figs. 5–6 allow us to draw a general conclusion that the spatial distribution of both indexes was characterized by high spatial heterogeneity and had a focal character. The analysis

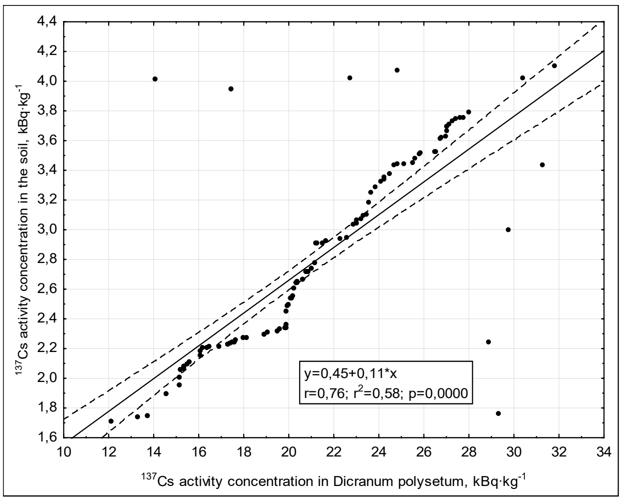

Fig. 4. Graph of dependence of ^{137}Cs activity concentration in the soil from radionuclide activity concentration in moss *Dicranum polysetum*

Рис. 4. Графік залежності питомої активності ^{137}Cs у ґрунті від концентрації радіонукліда у моху *Dicranum polysetum*

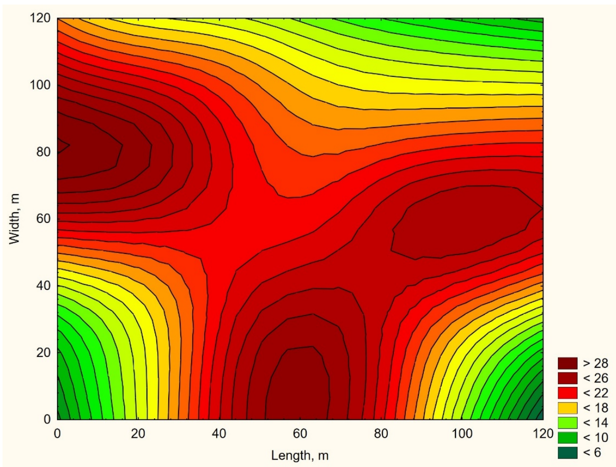

Fig. 5. Spatial heterogeneity of ^{137}Cs activity concentration (kBq·kg^{-1}) in moss *Dicranum polysetum* on the square 1 ha in 2002, based on systematical sampling (100 samples)

Рис. 5. Просторова неоднорідність питомої активності ^{137}Cs (кБк·кг$^{-1}$) у моху *Dicranum polysetum* на площі 1 га у 2002 р. на основі систематичного відбору (100 зразків) of statistical indexes shows that ^{137}Cs activity concentration in moss cover with *Dicranum polysetum* on the area of 1 ha ranged from 12,1 to 31,8 kBq·kg^{-1}, with an average value of 21,5 ± 0,46 kBq·kg^{-1}, with a coefficient of variation of 21,2%. In the soil, the minimum value of ^{137}Cs activity concentration was 1,7 kBq·kg^{-1}, maximum – 4,1 kBq·kg^{-1}, average – 2,8 ± 0,07 kBq·kg^{-1}, and coefficient of variation – 23,0%.

Not only the above statistical indexes of the studied radioecological parameters at the research site are critically important, but also their spatial distribution. Below, we make an attempt to analyze it by the methodology of fractal geometry.

The well-known postulate of B. Mandelbrot (Mandelbrot, 1982) states that almost all living and nonliving nature is filled with fractal structures. In general, we (Grabar, 2023; Grabar & Kubrak, 2023) found that random Brownian processes in the field of two or more generalized gravitational forces always generate

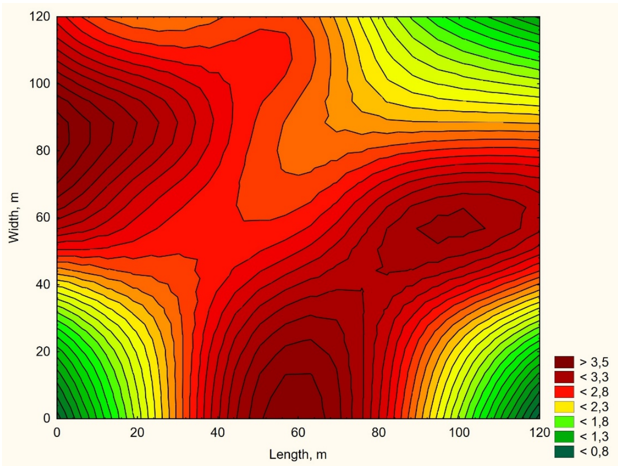

Fig. 6. Spatial heterogeneity of ^{137}Cs activity concentration (kBq·kg^{-1}) in the soil on the square 1 ha in 2002, based on systematical sampling (100 samples)
Рис. 6. Просторова неоднорідність питомої активності ^{137}Cs (кБк·кг$^{-1}$) у ґрунті на площі 1 га у 2002 р. на основі систематичного відбору (100 зразків)

fractal attractors. Formulas have been designed to quantify the fractal dimensions in engineering (porosity, aero- and hydrodynamic characteristics of synthesised fractal structures) as a function of the characteristics of the field of generalized gravity, its homogeneity, iso- or anisotropy, points of force application, etc. It has been shown that a statistical draw in the field of two or more generalized gravitational forces allows one to naturally (without artificially adding or subtracting subsets to/from the initial set) synthesize any of the known mono- or multifractals – linear, planar or volumetric, of a given fractal dimension, porosity and other useful properties (Grabar, 2023; Grabar and Kubrak, 2023). This gives us confidence in the possibility of obtaining a fractal distribution, structure or signal at the output in any natural stochastic process if the process is controlled by two or more generalized attractive forces.

In the case when the generalized forces of attraction have a homogeneous isotropic field, a monofractal structure (signal, distribution) with fractal dimension D is synthesized. If the field is isotropic and inhomogeneous, an isotropic multifractal structure (signal, distribution) is synthesized with a set of fractal dimensions D1 ... DN. If the field of generalized gravitational forces is heterogeneous and anisotropic, an anisotropic multiractal structure (signal, distribution) is synthesized with a set of fractal dimensions D1X; D1Y; D1Z ... DNX; DNY; DNZ.

The constructed tensor-matrix formalism for the synthesis of multifractals allows us to predict the size of subsets of any generation of multifractal (Grabar, 2023). We also obtained the conditions for the boundary transition to the continuum, which is considered as a particular case of a fractal distribution, structure or signal (Grabar, 2023; Grabar & Kubrak, 2023).

Figures 7–8 show in double logarithmic coordinates the dependence of the average values of ^{137}Cs activity concentration in *Dicranum polysetum* and in the soil on the grid spacing. The grid spacing was varied in the range of 10...100 m, selecting from the set of values of the baseline experiment (Tables 4 and 5), their subsets corresponding to the grid spacing of 20, 30 and 100 m (Tables 4, 4a, 4b, 4c and 5, 5a, 5b, 5c).

The decreasing of the average values of ^{137}Cs activity concentration in *Dicranum polysetum* depending on the grid spacing confirms its fractal nature.

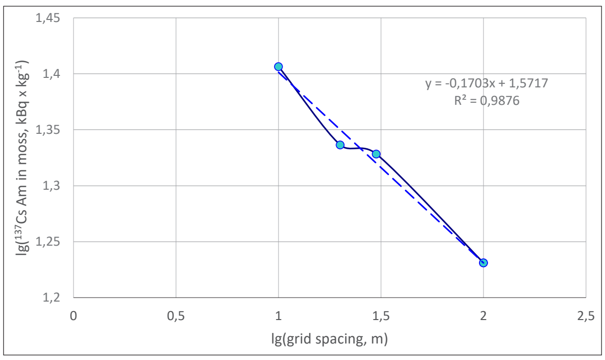

Fig. 7. Dependence of the average values of ^{137}Cs activity concentration (Am) in *Dicranum polysetum* from the grid spacing
Рис. 7. Залежність середніх значень питомої активності ^{137}Cs у *Dicranum polysetum* від кроку сітки

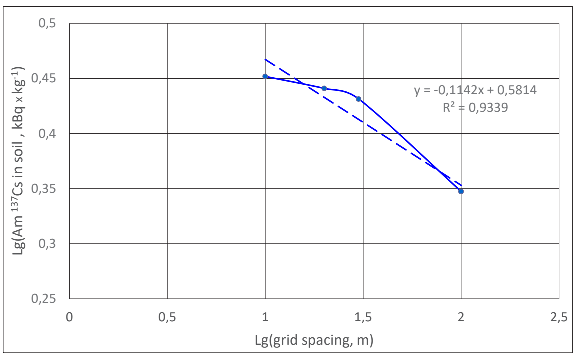

Fig. 8. Dependence of average values of ^{137}Cs activity concentration (Am) in the soil from the grid spacing
Рис. 8. Залежність середніх значень питомої активності ^{137}Cs у ґрунті від кроку сітки

Table 4. Activity concentration of ^{137}Cs in *Dicranum rolysetum*, kBq kg^{-1}, step – 10 m
Таблиця 4. Питома активність ^{137}Cs в *Dicranum polysetum*, кБк·кг$^{-1}$, крок 10 м

	1	2	3	4	5	6	7	8	9	10
1	13,7	15,1	15,5	24,7	26,8	27,1	27	23,3	16,4	16,3
2	13,3	15,1	15,3	24,5	26,7	31,3	27	23,5	16,2	16,1
3	12,1	14,6	15,2	24,2	26,5	27	27	23,5	16,1	15,6
4	15,3	14,1	15,2	24,2	24,1	23,9	23,6	23,2	23	22,8
5	20,6	20,4	20,4	20,4	20,3	19,6	23	24,8	26,5	25,8
6	22,7	22,6	22,3	21,6	20,2	19,5	20	24,8	30,4	25,8
7	29,7	29,3	28,9	21,5	20,2	19	19,9	25,1	25,5	25,6
8	27,4	31,8	28	21,3	20,1	18,9	19,9	19,9	19,9	19,8
9	27,3	27,6	27,7	21,2	20	18,1	18	17,6	17,6	17,5
10	21,2	21	20,8	20,7	20	17,4	17,4	17,3	17,3	16,9

Table 4a. Activity concentration of ^{137}Cs in *Dicranum rolysetum*, kBq kg^{-1}, step – 20 m
Таблиця 4а. Питома активність ^{137}Cs у *Dicranum rolysetum*, кБк кг$^{-1}$, крок – 20 м

	1	3	5	7	9
1	13,7	15,5	26,8	27	16,4
3	12,1	15,2	26,5	27	16,1
5	20,6	20,4	20,3	23	26,5
7	29,7	28,9	20,2	19,9	25,5
9	27,3	27,7	20	18	17,6

Table 4b. Activity concentration of ^{137}Cs in *Dicranum rolysetum*, kBq kg^{-1}, step – 30 m
Таблиця 4б. Питома активність ^{137}Cs у *Dicranum rolysetum*, кБк кг$^{-1}$, крок – 30 м

	1	4	7	10
1	13,7	24,7	27	16,3
4	15,3	24,2	23,6	22,8
7	29,7	21,5	19,9	25,6
10	21,2	20,7	17,4	16,9

Table 4c. Activity concentration of ^{137}Cs in *Dicranum rolysetum*, kBq kg^{-1}, step – 100 m
Таблиця 4с. Питома активність ^{137}Cs у *Dicranum rolysetum*, кБк кг$^{-1}$, крок – 100 м

	1	10
1	13,7	16,3
10	21,2	16,9

Table 5. Activity concentration of ^{137}Cs in the soil, kBq kg^{-1}, step – 10 m
Таблиця 5. Питома активність ^{137}Cs у грунті, кБк кг$^{-1}$, крок – 10 м

	1	2	3	4	5	6	7	8	9	10
1	1,7	2	2,1	3,4	3,6	3,7	3,7	3,1	2,2	2,2
2	1,7	2	2,1	3,4	3,6	3,4	3,7	3,1	2,2	2,2
3	1,7	1,9	2,1	3,3	3,5	3,6	3,7	3,2	2,1	2,1
4	2,1	4	2,1	2,1	3,3	3,3	3,2	3,1	3,1	3
5	2,7	2,7	2,7	2,6	2,6	2,3	3	4,1	3,5	3,5
6	4	2,9	2,9	2,9	2,6	2,3	2,5	3,4	4	3,5
7	3	1,8	2,2	2,9	2,6	2,3	2,5	3,4	3,4	3,5
8	3,7	4,1	3,8	2,9	2,5	2,3	2,5	2,4	2,3	2,3
9	3,7	3,8	3,8	2,9	2,5	2,3	2,3	2,3	2,2	2,2
10	2,8	2,7	2,7	2,7	2,5	3,9	2,2	2,2	2,2	2,2

Table 5a. Activity concentration of ^{137}Cs in the soil, kBq kg^{-1}, step – 20 m
Таблиця 5а. Питома активність ^{137}Cs у ґрунті, кБк кг$^{-1}$, крок – 20 м

	1	3	5	7	9
1	1,7	2,1	3,6	3,7	2,2
3	1,7	2,1	3,5	3,7	2,1
5	2,7	2,7	2,6	3	3,5
7	3	2,2	2,6	2,5	3,4
9	3,7	3,8	2,5	2,3	2,2

Table 5b. Activity concentration of ^{137}Cs in the soil, kBq kg^{-1}, step – 30 m
Таблиця 5б. Питома активність ^{137}Cs у ґрунті, кБк кг$^{-1}$, крок – 30 м

	1	4	7	10
1	1,7	3,4	3,7	2,2
4	2,1	2,1	3,2	3
7	3	2,9	2,5	3,5
10	2,8	2,7	2,2	2,2

Table 5c. Activity concentration of ^{137}Cs in the soil, kBq kg^{-1}, step – 100 m
Таблиця 5с. Питома активність ^{137}Cs у ґрунті, кБк кг$^{-1}$, крок – 100 м

	1	10
1	1,7	2,2
10	2,8	2,2

In Figure 9, the values of the matrices of the basic experiment (Tables 4 and 5) are expanded into a column vector and depicted graphically. The analysis of the obtained graphical images also confirms its fractal distribution.

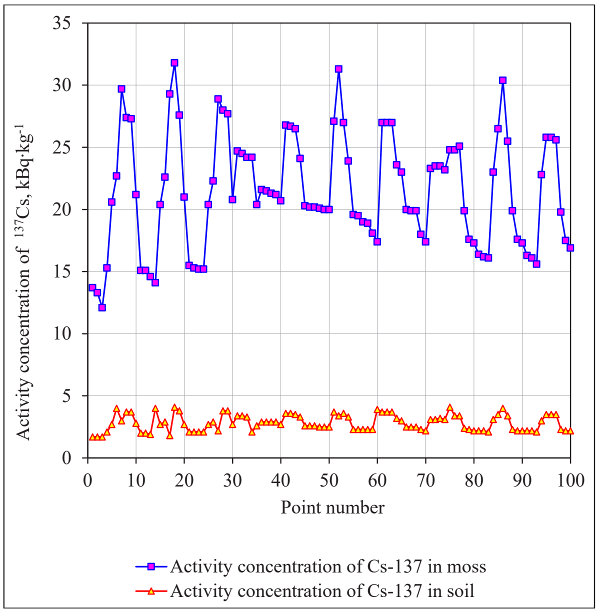

Fig. 9. Deployment of the full measurement matrix into a column vector
Рис. 9. Розгортка повної матриці вимірювань у вектор-стовбець

A full measurement/sampling matrix (100 samples) requires a lot of labour and material costs. We propose to replace the full matrix with a Vicsek matrix, when measurements are conducted only along the central column of the matrix and its central row, or along the main diagonals of the full matrix (Tables 4–5). The Vicsek fractal (Vicsek snowflake) is constructed on a square area Q by sequentially dividing it into squares and discarding the corner (cross fractal) or middle (diagonal fractal) subareas.

Replacing the full matrices with the Vicsek matrices gave the following results (Fig. 10, Table 6).

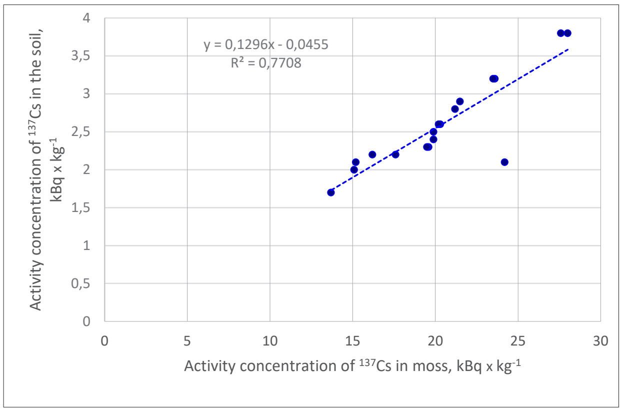

Fig. 10. Correlation between the of ^{137}Cs activity concentration in moss *Dicranum polysetum* and in the soil, built on the Vicsek fractal
Рис. 10. Кореляція між питомою активністю ^{137}Cs у моху *Dicranum polysetum* та ґрунті, побудована на фрактали Вісека

Table 6. Comparison of factual and calculated (on Vicsek matrix) values of ^{137}Cs activity concentration in *Dicranum polysetum* and in the soil, kBq·kg^{-1}
Таблиця 6. Порівняння фактичної та розрахункової (на матриці Вісека) питомої активності ^{137}Cs у *Dicranum polysetum* та у ґрунті, кБк·кг$^{-1}$

Indexes	Full matrix (100 measu-rements)	Vicsek matrix (20 measu-rements)	Relative diffe-rences, %
Average ^{137}Cs activity concentration in *Dicranum polysetum*, kBq kg^{-1}	25,5	23,4	-8,2
Average ^{137}Cs activity concentration in the soil, kBq kg^{-1}	2,83	3,06	+7,5

As can be seen from Table 3, replacing the full measurement matrix (100 measurements) with the Vicsek matrix (20 measurements) allows to optimize sampling – to reduce the number of field study (samples taken) by 5 times. At the same time, the differences between the average values of the actual and calculated of ^{137}Cs activity concentration in *Dicranum polysetum* and in the soil were less than ±10%, which is quite acceptable in environmental studies.

Conclusion. 1. In 2002 according with the mean ^{137}Cs content in increment of the 1st year (increments of 1–2 years) moss species can be placed as follows: *Leucobryum glaucum* > *Dicranum polysetum* > *Polytrichum commune* > *Sphagnum palustre* > *S. capillifolium* > *Pleurozium schreberi*. Interspecies differences of the mean ^{137}Cs content in this row reached 2,2 times.

2. In 2022 in all moss species values of ^{137}Cs activity concentration decreased, maximum decrease was observed in *Dicranum polysetum* – 2,46 times, and minimum one – in *Sphagnum capillifolium* – 2 times.

3. In 2002 and 2022 distribution of ^{137}Cs content in fractions of all moss species was similar: maximum values of ^{137}Cs activity concentration were characteristic for alive, apical parts – increment of the 1st year. Below, in moss fractions a decrease in this index was observed in the increment of the 2nd year, increments of the earlier period and in peat litter.

4. Despite a significant decrease of ^{137}Cs activity concentration in fractions of all studied moss species mean values of coefficient of ^{137}Cs biological absorption decreased insignificantly.

5. In 2022 according with the mean values of CBA moss species can be placed as follows: *Leucobryum glaucum* (7,42 ± 0,49) > *Polytrichum commune* (6,72 ± 0,45) > *Sphagnum palustre* (6,15 ± 0,54) > *Dicranum polysetum* (6,11 ± 0,43) > *S. capillifolium* (5,99 ± 0,56) > *Pleurozium schreberi* (2,97 ± 0,18).

Dependence of ^{137}Cs activity concentration in the soil from ^{137}Cs activity concentration in *Dicranum polysetum* was linear, close ($r = 0,76$) and reliable ($p = 0,000$).

Spatial heterogeneity of ^{137}Cs contamination of moss cover and soil was high and had a focal character.

Decreasing dependence of mean value of ^{137}Cs activity concentration in moss cover and in the soil from the grid step is a confirmation of its fractal distribution.

Correlation dependence between ^{137}Cs activity concentration in *Dicranum polysetum* and in the soil build on Vicsek fractal is close ($r^2 = 0,78$).

We propose replacing of full matrix with the Vicsek matrix, where the selection of sampling points is conducted only along the central column and the central row of the full matrix, or along the main diagonals of the full matrix. This allows us to optimize sampling – to reduce their number in 5 times, with the relative difference of obtained average values with the full matrix less than ±10%.

Acknowledgements. We express our sincere gratitude to Tetiana Fedoniuk, doctor of biological sciences, professor, for her help in construction of isolines and their evaluation and discussion.

Acknowledgement. This project has received funding through the MSCA4Ukraine project, which is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the MSCA4Ukraine Consortium as a whole nor any individual member institutions of the MSCA4Ukraine Consortium can be held responsible for them.

Bibliography

1. Головко, О.В. (2020), Міграція та перерозподіл ^{137}Cs в екосистемах боліт Західного Полісся України. *Автореф. дис.* … канд. сільськогосподарських наук. Спеціальність 03.00.16 – екологія. Рівне. 26 с.

2. Горкавий, В.К. (2009), *Статистика: підручник*. Київ: Аграрна освіта. 511 с.

3. Грабар, І. (2023), *Синтез мультифракталів*. Наукова монографія. Житомир: Поліський національний університет. 200 с. ISBN 978-617-8085-98–8.

4. Доповідь про стан ядерної та радіаційної безпеки в Україні у 2022 році (2023). Київ: Державна інспекція ядерного регулювання України. 88 с. Режим доступу: https://snriu.gov.ua/storage/app/sites/1/%202022.pdf.

5. Мельник, В.В., Курбет, Т.В. (2018a), Особливості накопичення цезію-137 у моховому покриві лісів Українського Полісся. *Наукові горизонти*. **2 (65)**: 51–57. http://ir.znau.edu.ua/handle/123456789/9498.

6. Мельник, В.В., Курбет, Т.В. (2018b), Радіоактивне забруднення ^{137}Cs мохово-лишайникового покриву в умовах свіжого субору. *Науковий вісник НЛТУ України*. **28 (3)**: 88–92. https://doi.org/10.15421/40280318.

7. Орлов, О.О. (2000), Роль сфагнового покриву у перерозподілі потоків калію та ^{137}Cs в екосистемах мезооліготрофних боліт. *Укр. ботан. журн.* **57 (6)**: 715–724.

8. Орлов, О.О. (2021), Закономірності міграції ^{137}Cs на геохімічних бар'єрах крайової зони мезотрофного болота в Українському Поліссі. *Геохімія техногенезу*. 6 (34): 58–70. https://doi.org/10.15407/10.15407/geotech2021.34.058.

9. Орлов, О.О., Долін, В.В. (2010), *Біогеохімія цезію-137 у лісоболотних екосистемах Українського Полісся.* Київ: Наук. думка. 198 с.

10. Погребняк, П.С. (1931), Основи типологічної класифікації та методика складати її. *Серія наук. вид. ВНДІЛГА*. Харків. **10:** 28–35.

11. Adrović, F., Damjanović, A., Adrović, J., Kamberović, J. and Hadžiselimović, N. (2017), Study of ^{137}Cs concentration activity in mosses of Bosnia and Herzegovina. *International Journal of Modern Biological Research*. **5**: 32–41.

12. Balance, S., Kristiansen, K.A., Skogaker, N.T., Tvedt, K.E., Christensen, B.E. (2012), The localisation of pectin in Sphagnum moss leaves and its role in preservation. *Carbohydrate Polymers*. **87 (2)**: 1326–1332. https://doi.org/10.1016/j.carbpol.2011.09.020.

13. *Bioindicators & Biomonitors. Principles, Concepts and Applications* (2003), Eds. B.A. Markert, A.M. Breure, H.G. Zechmeister. Amsterdam – Boston – London – New York – Oxford – Paris – San Diego – San Francisco – Singapore – Sydney – Tokyo: Elsevier Applied Science. 1017 p.

14. Bossew, P., Lettner, H., Hubmer, A.K. (1996), Spatial variability of fall-out ^{137}Cs. *Proc. of the Intern. Symp. on Radioecology 1996* "Ten years terrestrial radioecological research following the Chernobyl accident" Eds. M. Gerzabek, G. Desmet, B.J. Howard et al. Vienna. P. 179–186.

15. Cevik, U. and Celik, N. (2008), Ecological half-life of Cs-137 in mosses and lichens in the Ordu province, Turkey. *Journal of Environmental Radioactivity*. **100 (1)**: 23–28. DOI: 10.1016/j.jenvrad.2008.09.010.

16. Clymo, R.S. (1978), A model of peat bog growth. In: O.W. Heal, and D.F. Perkins (eds.), *Production Ecology of British Moors and Montane Grasslands*. Berlin: Springer Verlag. P. 187–223.

17. Čučulović, A., Čučulović, R., Sabovljević, M., Veselinović, D. (2012a), Activity concentrations of ^{137}Cs and ^{40}K in mosses from Spas in eastern Serbia. *Arch. Biol. Sci.,* **64 (3)**: 917–925. DOI: 10.2298/ABS1203917Č.

18. Čučulović, A., Popović, D., Čučulović, R. & Ajtić, J. (2012b), Natural radionuclides and ^{137}Cs in moss and lichen in Eastern Serbia. *Nuclear Technology & Radiation Protection*, 27 (1): 44–51. DOI: 10.2298/NTRP1201044.

19. Dainty, J. and Richter, C. (1993), Ion behavior in Sphagnum cell walls. *Advances in Bryology,* 5. Biology of Sphagnum. Berlin-Stuttgart: J. Cramer. P. 107–127.

20. Dolgushin, D., Korobova, E., Baranchukov, V., Dogadkin, N. (2020), Detailed study of ^{137}Cs distribution in soil-litter-moss cover within the undisturbed woodland test site in the Chernobyl abandoned zone. EGU General Assembly 2020, EGU2020-339, https://doi.org/10.5194/egusphere-egu2020-339, 2019OUT.

21. Dołhańczuk-Śródka, A., Ziembik, Z., Wacławek, M. & Hyšplerová, L. (2011), Transfer of cesium-137 from forest soil to moss Pleurozium schreberi. *Ecological Chemistry and Engineering*. **18 (4)**: 509–516.

22. Dragović, S., Mihailović, N., Gajić, B. (2010), Quantification of transfer of ^{238}U, ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in mosses of a semi-natural ecosystem. *Journal of Environmental Radioactivity*. 101: 159–164. DOI: 10.1016/j.jenvrad.2009.09.011.

23. Dragović, S., Nedić, O., Stanković, S., Bačic, G. (2004), Radiocesium accumulation in mosses from highlands of Serbia and Montenegro: chemical and physiological aspects. *Journal of Environmental Radioactivity*. 77: 381–388. DOI: 10.1016/j.jenvrad.2004.04.007.

24. Fränzle, O. (2003), Bioindicators and environmental stress assessment. In: *Bioindicators & Biomonitors. Principles, Concepts and Applications*, Eds. B.A. Markert, A.M. Breure, H.G. Zechmeister. Amsterdam – Boston – London – New York – Oxford – Paris – San Diego – San Francisco – Singapore – Sydney – Tokyo: Elsevier Applied Science. P. 41–84.

25. Garger, E.K. (1994), Air concentrations of radionuclides in the vicinity of Chernobyl and the effects of resuspension. *Journal of Aerosol Science,* **25**: 745–753.

26. Gerdol, R., Degetto, S., Mazzotta, D., Vecchiati, G. (1994). The vertical distribution of the Cs-137 derived from Chernobyl fallout in the uppermost Sphagnum layer of two peatlands in the southern Alps (Italy). *Water, Air & Soil Pollution.* **75**: 93–106.

27. Giovani, C., Nimis, P.L., Bolognini, G., Padovani, R., Usco, A. (1994), Bryophytes as indicators of radiocesium deposition in northeastern Italy. *The Science of the Total Environment*. **157**: 35–43.

28. Glime, J.M. (2017), Nutrient Relations: Requirements and Sources. Chapt. 8-1. In: J.M. Glime, *Bryophyte Ecology*. **Vol. 1. 8-1-1** Physiological Ecology. Ebook sponsored by Michigan Technological University and the International Association of Bryologists. 208 p. Last updated 3 March 2017 and available at: http://digitalcommons.mtu.edu/bryophyte-ecology/.

29. Grabar, I.G., Kubrak, Yu. O. (2023), Synthesis of multifractals by Brownian dynamics of a point in a field of N central forces. 16*th* *CHAOS Conference Proceedings, 13–16 June 2023, Heraklion, Crete, Greece,*. ISAST.

30. Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments (2010). *Technical Report Series № 472*. Vienna: International Atomic Energy Agency. 208 p. http://www-pub.iaea.org/MTCD/publications/PDF/trs472_web.pdf.

31. Hodgetts, N.G., Söderström, L., Blockeel, T.L., Caspari, S., Ignatov, M.S., Konstantinova, N.A., Lockhart, N., Papp, B., Schröck, C., Sim-Sim, M., Bell, D., Bell, N.E., Blom, H.H., Bruggeman-Nannenga, M.A., Brugués, M., Enroth, J., Flatberg, K.I., Garilleti, R., Hedenäs, L., Holyoak, D.T., Hugonnot, V., Kariyawasam, I., Köckinger, H., Kučera, J., Lara, F. & Porley, R.D. (2019), An annotated checklist of bryophytes of Europe, Macaronesia and Cyprus. *Journal of Bryology*. **42 (1)**: 1–116. DOI: 10.1080/03736687.2019.1694329.

32. Iuran, A.R., Hofmann, W., Lettner, H., Türk, R., Cosma, C. (2011), Long term study of Cs-137 concentrations in lichens and mosses. *Romanian Journal of Physics*, 56 (7–8): 983–992.

33. Jefanova, O., Marciulioniene, E.D. and Luksiene, B. (2014), The spread of ^{137}Cs in terrestrial ecosystems of the Ignalina NPP and other Lithuanian regions. *Research Journal of Chemistry and Environment.* **18 (1)**: 1–6.

34. Kłos, A., Czora, M., Rajfur, M., Wacławek, M. (2012), Mechanisms for translocation of heavy metals from soil to epigeal mosses. *Water, Air & Soil Pollution*. **223**: 1829-1836. DOI: 10.1007/s11270-011-0987-2.

35. Mandelbrot, B.B. (1982), The fractal geometry of nature. New York – Oxford: W.H. Freeman & Co. 468 p.

36. Mattsson, S., Liden, K. (1975), ^{137}Cs in carpets of the forest moss Pleurozium schreberi, 1961–1973. *Oikos*. **26**: 323–327.

37. Mihalík, J., Bartusková, M., Hölgye, Z., Jezková, T., Henych, O. (2014), Fractionation of ^{137}Cs and Pu in natural peatland. *Journal of Environmental Radioactivity*. **134**: 14–20. https://doi.org/10.1016/j.jenvrad.2014.02.015.

38. Oguri, E., Deguchi, H. (2018), Radiocesium contamination of the moss Hypnum plumaeforme caused by the Fukushima Daiichi Nuclear Power Plant accident. *Journal of Environmental Radioactivity*. **192**: 648–653. https://doi.org/10.1016/j.jenvrad.2018.02.013.

39. Oldfield, E, Appleby, P.G., Cambray, R.S., Eakins, J.D., Barber, K.E., Battarbee, R.W., Pearson, G.R., Williams, J.M. (1979), ^{210}Pb, ^{137}Cs and ^{239}Pu profiles in ombrotrophic peat. *Oikos*. **33 (1)**: 40-45. https://doi.org/10.2307/3544509.

40. Orlov, O.O., Grabar, I.G. (2023), Radioactive fallouts: fractal dimension. *Актуальні питання радіобіології – 2023*. Мат. 8-го з’їзду Радіобіологічного товариства України (м. Житомир, 21–25 серпня 2023 р.). Ред.: канд. біол. наук Н. К. Куцоконь, д-р біол. наук, проф. Н. М. Рашидов. Житомир. С. 84.

41. Orlov, O. (2022), Evaluation of mosses and lichens as test-objects of monitoring of ^{137}Cs contamination of pine forest biogeocenoses in Ukrainian Polissia. *Геохімія техногенезу*. **7 (35)**: 33–37. https://doi.org/10.32782/geotech2022.35.05.

42. Proctor, M.C. (2000), The bryophyte paradox: tolerance of desiccation, evasion of drought. *Plant Ecology*. **151**: 41–49. https://doi.org/10.1023/A:1026517920852.

43. Proctor, M.C.F. & Tuba, Z. (2002), Poikilohydry and homoihydry: anthithesis of spectrum of possibilities? *New Phytologist.* **156 (3)**: 327–349. https://doi.org/10.1046/j.1469-8137.2002.00526.x

44. Rühling, A. and Tyler, C. (1968), An ecological approach to the lead problem. *Botaniska notiser,* **122**: 321–342.

45. Schmidt, B., Kegler, F., Steinhauser, G., Chyzhevskyi, I., Dubchak, S., Ivesic, C., Koller-Peroutka, M., Laarouchi, A., Adlassnig, W. (2023), Uptake of radionuclides by Bryophytes in the Chornobyl Exclusion Zone. *Toxics*, **11 (3)**: 218. https://doi.org/10.3390/toxics11030218.

46. Steinnes, E. & Njåstad, O. (1993), Use of mosses and lichens for regional mapping of ^{137}Cs fallout from the Chernobyl accident. *Journal of Environmental Radioactivity*. **21**: 65–73.

47. Tyler, G. (1990), Bryophytes and heavy metals: a literary review. *Botanical Journal of Linnaean Society*. **104**: 231–253.

48. Van Tooren, B.F., Van Dam, D., During, H.J. (1990), The relative importance of precipitation and soil as sources of nutrients for *Calliergonella cuspidata* (Hedw.) Loeske in chalk grassland. *Functional. Ecology*. **4:** 101–107.

49. Vinichuk, M., Dahlberg, A., Rosén, K. (2011), Cesium (^{137}Cs and ^{133}Cs), potassium and rubidium in macromycete fungi and Sphagnum plants. *Radioisotopes – Application in Physical Sciences*. Ed. N. Singh. Croatia, Rijeka, InTech: 279–311.

50. Vinichuk, M., Johanson, K.J., Rydin, H. and Rosén, K. (2010), The distribution of Cs-137, K, Rb and Cs in plants in a Sphagnum-dominated peatland in eastern central Sweden. *Journal of Environmental Radioactivity*. **101 (2)**: 170–176. http://dx.doi.org/10.1016/j.jenvrad.2009.10.003.

51. Ying, Z & Liang-Dong, G. (2007), Arbuscular mycorrhizal structure and fungi associated with mosses. *Mycorrhiza*. **17**: 319–325. DOI: 10.1007/s00572-007-0107-8.

52. Zarubina, N. (2023), Circulation of ^{137}Cs in various forest plants in the Chornobyl Exclusion Zone during the year. *Ecologies*. **4 (2)**: 310–324. DOI: https://doi.org/10.3390/ecologies4020020.

References

1. Holovko, O.V. (2020), *PhD Thesis*. 26 p. (in Ukrainian).

2. Horkavy, V.K. (2009), *Statistics: textbook*. Kyiv: Agrarna osvita. 511 p. (in Ukrainian).

3. Grabar, I. (2023), *Synthesis of multifractals*. Monograph. Zhytomyr: Polissia National University. 200 p. (in Ukrainian).

4. *Report about the nuclear and radiation safety in Ukraine in 2022* (2023). 88 p. Accepted at: https://snriu.gov.ua/storage/app/sites/1/%202022.pdf (in Ukrainian).

5. Melnyk, V.V., Kurbet, T.V. (2018a), *Scientific Horizons*. **2 (65)**: 51–57 (in Ukrainian).

6. Melnyk, V.V., Kurbet, T.V. (2018б), *Scientific Bull. of NLTU of Ukraine*. **28 (3)**: 88–92 (in Ukrainian).

7. Orlov, O.O. (2000), *Ukrainian Botan. Journ.* **57(6)**: 715–724 (in Ukrainian).

8. Orlov, O.O. (2021), *Geochemistry of Technogenesis*. **6(34):** 58–70 (in Ukrainian).

9. Orlov, O.O., Dolin, V.V. (2010), *Biogeochemistry of cesium-137 in forest-bog ecosystems of Ukrainian Polissia*. Kyiv: Naukova Dumka. 198 p. (in Ukrainian).

10. Pohrebniak, P.S. (1931), *Fundamentals of typological classification and methodology of its creation*. Kharkiv, iss**. 10:** 28–35 (in Ukrainian).

11. Adrović, F., Damjanović, A., Adrović, J., Kamberović, J. and Hadžiselimović, N. (2017), *International Journal of Modern Biological Research*. 5: 32–41.

12. Balance, S., Kristiansen, K.A., Skogaker, N.T., Tvedt, K.E., Christensen, B.E. (2012), *Carbohydrate Polymers*. 87 (2): 1326–1332.

13. *Bioindicators & Biomonitors. Principles, Concepts and Applications* (2003), Eds. B.A. Markert et al. Amsterdam – Boston – London – New York – Oxford – Paris – San Diego – San Francisco – Singapore – Sydney – Tokyo: Elsevier Applied Science. 1017 p.

14. Bossew, P., Lettner, H., Hubmer, A.K. (1996), *Proc. of the Intern. Symp. on Radioecology 1996 "Ten years terrestrial radioecological research following the Chernobyl accident"* Eds. M. Gerzabek, G. Desmet, B.J. Howard et al. Vienna. P. 179–186.

15. Cevik, U. and Celik, N. (2008), *Journal of Environmental Radioactivity*. **100 (1)**: 23–28.

16. Clymo, R.S. (1978), A model of peat bog growth. In: O.W. Heal, and D.F. Perkins (eds.), *Production Ecology of British Moors and Montane Grasslands*. Berlin: Springer Verlag. P. 187–223.

17. Čučulović, A., Čučulović, R., Sabovljević, M., Veselinović, D. (2012a), *Arch. Biol. Sci.,* **64 (3)**: 917–925.

18. Čučulović, A., Popović, D., Čučulović, R. & Ajtić, J. (2012b), *Nuclear Technology & Radiation Protection*, 27 (1): 44–51.

19. Dainty, J. and Richter, C. (1993), *Advances in Bryology,* 5. Biology of Sphagnum. Berlin-Stuttgart: J. Cramer. P. 107–127.

20. Dolgushin, D., Korobova, E., Baranchukov, V., Dogadkin, N. (2020), *EGU General Assembly 2020*, EGU2020-339.

21. Dołhańczuk-Śródka, A., Ziembik, Z., Wacławek, M. & Hyšplerová, L. (2011), *Ecological Chemistry and Engineering*. **18 (4)**: 509–516.

22. Dragović, S., Mihailović, N., Gajić, B. (2010), *Journal of Environmental Radioactivity*. 101: 159–164.

23. Dragović, S., Nedić, O., Stanković, S., Bačic, G. (2004), *Journal of Environmental Radioactivity*. 77: 381–388.

24. Fränzle, O. (2003), Bioindicators and environmental stress assessment. In: *Bioindicators & Biomonitors. Principles, Concepts and Applications*, Eds. B.A. Markert, A.M. Breure, H.G. Zechmeister. Amsterdam – Boston – London – New York – Oxford – Paris – San Diego – San Francisco – Singapore – Sydney – Tokyo: Elsevier Applied Science. P. 41–84.

25. Garger, E.K. (1994), *Journal of Aerosol Science,* **25**: 745–753.

26. Gerdol, R., Degetto, S., Mazzotta, D., Vecchiati, G. (1994). *Water, Air & Soil Pollution.* **75**: 93–106.

27. Giovani, C., Nimis, P.L., Bolognini, G., Padovani, R., Usco, A. (1994), *The Science of the Total Environment*. **157**: 35–43.

28. Glime, J.M. (2017), Nutrient Relations: Requirements and Sources. Chapt. 8-1. In: Glime, J.M. *Bryophyte Ecology*. Vol. 1. 8-1-1 Physiological Ecology. Ebook sponsored by Michigan Technological University and the International Association of Bryologists. 208 p.

29. Grabar, I.G., Kubrak, Yu. O. (2023), *16th CHAOS Conference Proceedings, 13–16 June 2023, Heraklion, Crete, Greece*. ISAST.

30. *Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments* (2010). Technical Report Series № 472. Vienna: International Atomic Energy Agency. 208 p.

31. Hodgetts, N.G., Söderström, L., Blockeel, T.L., Caspari, S., Ignatov, M.S., Konstantinova, N.A., Lockhart, N., Papp, B., Schröck, C., Sim-Sim, M., Bell, D., Bell, N.E., Blom, H.H., Bruggeman-Nannenga, M.A., Brugués, M., Enroth, J., Flatberg, K.I., Garilleti, R., Hedenäs, L., Holyoak, D.T., Hugonnot, V., Kariyawasam, I., Köckinger, H., Kučera, J., Lara, F. & Porley, R.D. (2019), *Journal of Bryology*. **42 (1)**: 1–116.

32. Iuran, A.R., Hofmann, W., Lettner, H., Türk, R., Cosma, C. (2011), *Romanian Journal of Physics*, 56 (7–8): 983–992.

33. Jefanova, O., Marciulioniene, E.D. and Luksiene, B. (2014), *Research Journal of Chemistry and Environment.* **18 (1)**: 1–6.

34. Kłos, A., Czora, M., Rajfur, M., Wacławek, M. (2012). *Water, Air & Soil Pollution*. **223**: 1829–1836.

35. Mattsson, S., Liden, K. (1975), *Oikos*. **26**: 323–327.

36. Mandelbrot, B.B. (1982), *The fractal geometry of nature*. New York – Oxford: W.H. Freeman & Co.

37. Mihalík, J., Bartusková, M., Hölgye, Z., Jezková, T., Henych, O. (2014), *Journal of Environmental Radioactivity*. **134**: 14–20.

38. Oguri, E., Deguchi, H. (2018), *Journal of Environmental Radioactivity*. **192**: 648–653.

39. Oldfield, E, Appleby, P.G., Cambray, R.S., Eakins, J.D., Barber, K.E., Battarbee, R.W., Pearson, G.R., Williams, J.M. (1979), *Oikos*. **33 (1)**: 40–45.

40. Orlov, O.O., Grabar, I.G. (2023), *Actual Problems of Radiobiology – 2023.* Eds.: N.K. Kutsokon, N.M. Rashidov. Zhytomyr. P. 84.

41. Orlov, O. (2022), *Geochemistry of Technogenesis*. 7 (35): 33–37.

42. Proctor, M.C. (2000), *Plant Ecology*. **151**: 41–49.

43. Proctor, M.C.F. & Tuba, Z. (2002), *New Phytologist.* **156 (3)**: 327–349.

44. Rühling, A. and Tyler, C. (1968), *Botaniska notiser,* 122: 32l–342.

45. Schmidt, B., Kegler, F., Steinhauser, G., Chyzhevskyi, I., Dubchak, S., Ivesic, C., Koller-Peroutka, M., Laarouchi, A., Adlassnig, W. (2023), *Toxics*, 11 (3): 218.

46. Steinnes, E. & Njfistad, O. (1993), *Journal of Environmental Radioactivity*. 21: 65–73.

47. Tyler, G. (1990), *Botanical Journal of Linnaean Society*. 104: 231–253.

48. Van Tooren, B.F., Van Dam, D., During, H.J. (1990), *Functional. Ecology*. 4: 101–107.

49. Vinichuk, M., Dahlberg, A., Rosén, K. (2011), *Radioisotopes – Application in Physical Sciences*. Ed. N. Singh. Croatia, Rijeka, InTech: 279–311.

50. Vinichuk, M., Johanson, K.J., Rydin, H. and Rosén, K. (2010), *Journal of Environmental Radioactivity*. 101 (2): 170–176.

51. Ying, Z & Liang-Dong, G. (2007), *Mycorrhiza*. 17: 319–325.

52. Zarubina, N. (2023), *Ecologies*. **4 (2)**: 310–324.

ТОКСИКОЛОГІЧНЕ ДОСЛІДЖЕННЯ МОХОВОГО ПОКРИВУ У СОСНОВИХ ЛІСАХ БІОГЕОХІМІЧНОГО ЛАНДШАФТУ У ФОНОВОМУ РАЙОНІ УКРАЇНСЬКОГО ПОЛІССЯ. ЧАСТИНА 2. РАДІОНУКЛІДИ – ^{137}Cs

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Завдання досліджень – оцінити міжвидові відмінності акумуляції ^{137}Cs мохами; проаналізувати розподіл ^{137}Cs між фракціями мохів; виявити багаторічну динаміку вмісту ^{137}Cs у мохах та величини коефіцієнта біологічного поглинання ^{137}Cs мохами у 2002–2022 рр.; розрахувати залежність між питомою активністю ^{137}Cs у Dicranum polysetum та у ґрунті на основі статистичного систематичного підходу; виявити просторову неоднорідність питомої активності ^{137}Cs у моховому покриві та ґрунті й кількісно оцінити її з використанням засобів фрактальної геометрії. Дослідження проведене у 2 етапи: у 2002 р. та 2022 р. на 3 пробних площах у Житомирській обл., Коростенському р-ні, Повчанському лісництві, філії «ДП Лугинське лісове господарство» ДП «Ліси України». Рослинність була представлена сосновим лісом асоціації Molinio-Pinetum Matuszkiewicz (1973) 1981, у типі лісорослинних умов вологий субір (B_3). Зразки мохів відбирали по фракціях: приріст першого року, приріст другого року, приріст більш ранніх років та очіс. Питому активність ^{137}Cs вимірювали на спектроаналізаторі СЕГ-001 АКП-С-150 із сцинтиляційним детектором БДЕГ-20-Р2. Як показник інтенсивності акумуляції ^{137}Cs у ланці «ґрунт – мох» був використаний коефіцієнт біологічного поглинання (КБП). У 2002 р. за середніми значеннями вмісту ^{137}Cs у прирості першого року (приростах першого та другого років) види мохів можна розмістити в такому порядку: Leucobryum glaucum > Dicranum polysetum > Polytrichum commune > Sphagnum palustre > S. capillifolium > Pleurozium schreberi, з міжвидовими відмінностями цього показника у 2,2 раза. У 2002 р. та 2022 р. розподіл питомої активності ^{137}Cs між фракціями мохів був подібним: максимальні величини питомої активності ^{137}Cs були в живих, верхівкових частинах – прирості першого року (приростах першого та другого років). Нижче цієї частини спостерігалося зменшення цього показника у прирості другого року, приростах більш раннього періоду й очосі. У всіх видів мохів у 2002–2022 рр. вміст ^{137}Cs суттєво зменшився – від 2,46 раза у Dicranum polysetum до 2 разів у Sphagnum capillifolium. Незважаючи на суттєве зменшення питомої активності ^{137}Cs у фракціях усіх досліджених видів мохів, середні величини КБП у 2022 р. слабо зменшилися порівняно з такими 2002 р. У 2022 р. за середніми значеннями КБП види мохів можуть бути розміщені таким чином: Leucobryum glaucum (7,42 ± 0,49) > Polytrichum commune (6,72 ± 0,45) > Sphagnum palustre (6,15 ± 0,54) > Dicranum polysetum (6,11 ± 0,43) > S. capillifolium (5,99 ± 0,56) > Pleurozium schreberi (2,97 ± 0,18). Залежність питомої активності ^{137}Cs у ґрунті від питомої активності ^{137}Cs у Dicranum polysetum була лінійною, тісною (r = 0,76) і достовірною (p = 0,000). Просторова неоднорідність забруднення ^{137}Cs мохового покриву та ґрунту була високою та мала осередковий характер. Зменшення середніх значень питомої активності ^{137}Cs у моховому покриві та ґрунті залежно від кроку сітки є підтвердженням їх фрактального розподілу. Ми запропонували замінити повну матрицю відбору проб матрицею на фракталі Вісека, з відбором проб лише по центральному стовбцю та центральному рядку або по головних діагоналях повної матриці, що дає змогу зменшити загальну кількість зразків у 5 разів, з відносною різницею середніх значень питомої активності ^{137}Cs у моху та ґрунті порівняно з повною матрицею менше за ±10 %.

Ключові слова: *Українське Полісся, лісові біогеоценози, ґрунт, моховий покрив, фракції мохів, питома активність ^{137}Cs, коефіцієнт біологічного поглинання ^{137}Cs, просторова неоднорідність, фрактальна геометрія, фрактал Вісека.*