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CURRENT ^{137}Cs ACCUMULATION BY MUSHROOMS IN DIFFERENT SITE TYPES OF SCOTS PINE FORESTS OF UKRAINIAN POLISSIA

The study of ^{137}Cs radioactive contamination of fruiting bodies of mushrooms was carried out in September - October 2022 in 18 sampling sites laid out in the Korosten district of Zhytomyr region in 3 of the most widespread forest site types (FST): fresh infertile pine site type (A_2), fresh fairly infertile pine site type (B_2) and moist fairly infertile pine site type (B_3). It was found that the highest levels of ^{137}Cs content in investigated FST were characteristic of symbiotrophic mushroom species – *Cortinarius mucosus*, *Cortinarius caperatus*, *Sarcodon imbricatus*, *Imleria badia*, *Tricholoma equestre*, *Paxillus involutus*, *Hygrophorus hypothejus*, and the lowest – for xylotrophes-saprotrophes such as *Armillaria mellea* and *Tapinella atrotomentosa*. When analyzed, it was shown that interspecific differences of average values of ^{137}Cs aggregated transfer coefficient (*Tag*) among mushrooms in each FST varied in a wide range: they reached $1.1 \cdot 10^3$ times in FST-A_2 – from 435 in *Cortinarius mucosus* to 0.4 $m^2 \cdot kg^{-1} \cdot 10^{-3}$ in *Armillaria mellea*; 71.4 times – in FST-B_2 – from 162 in *Sarcodon imbricatus* to 2.3 $m^2 \cdot kg^{-1} \cdot 10^{-3}$ in *Armillaria mellea*; and 12 times – in FST-B_3 – from 111 in *Imleria badia* to 9.2 $m^2 \cdot kg^{-1} \cdot 10^{-3}$ in *Leccinum scabrum*. Also, it was shown that in genus *Russula* even in the same FST-B_2 among five studied species a 24-fold change in average values of ^{137}Cs *Tag* are observed – from 67 in *Russula vinosa* to 2.8 $m^2 \cdot kg^{-1} \cdot 10^{-3}$ in *Russula aeruginea*. The results of ANOVA were discussed as well as the essentiality of the difference of the average values of *Tag* in mushroom species in different FST.

Keywords: pine stand, ^{137}Cs activity concentration, density of contamination, ^{137}Cs aggregated transfer coefficient, permissible levels.

1. Introduction

Currently, despite more than 36 years since the Chornobyl disaster, radioactive contamination of macromycetes attracts the attention of researchers in Europe: Italy [1], Czech Republic [2], Slovakia [3], Poland [4, 5], Bulgaria [6], Turkey [7]. After the accident at the Fukushima Nuclear Power Plant, the radioecology of macromycetes obtained a new development in Asia – Japan [8, 9] and China [10]. The largest number of studies on both continents is devoted to edible species of mushrooms, which are characterized by significant levels of ^{137}Cs accumulation and when frequently used, can cause significant levels of internal radiation exposure in the population [2, 11]. At the same time, researchers emphasize the wide interspecies differences in ^{137}Cs accumulation by mushroom fruiting bodies of different species even in a separate forest site type (FST) [12]; by the same mushroom species in different FST, at different densities of the territory radioactive contamination [13]; and in different periods after the Chornobyl NPP accident [12, 14]. Publications devoted to ^{137}Cs accumulation by mushroom fruiting bodies in Ukraine are few in recent years; therefore, the study of the current accumulation levels of the mentioned radionuclide by mushrooms in the country is relevant.

2. An analysis of the last studies

In the post-Chornobyl period, there have been a significant number of publications devoted to the ^{137}Cs accumulation by macromycetes fruiting bodies, however, the principal purpose of this study is to analyze the publications on the investigated problem over the last five years. G. A. Grodzynska [12] listed the main factors that determine the radioactive contamination of macromycetes. The biological and ecological-biological factors are the following: species specificity of a certain radionuclide accumulation; mycosymbiotrophic interaction with woody plants (for ectomycorrhizal species); the depth of mycelium location in soil; trophic group. Environmental factors include: radioactive contamination of the atmosphere; density of contamination with certain radionuclides; soil parameters: soil bulk density, humidity, pH. G. A. Grodzynska provided numerous data showing ^{137}Cs content in different species of macromycetes, in different sampling sites, in different years but without taking into account FST. It was noted that species of the trophic group of humus saprotrophs were characterized by relatively low ^{137}Cs content in their fruiting bodies: *Agaricus* sp., *Macrolepiota procera*, *Lycoperdon* sp., as well as xylotrophs-saprotrophs and xylotrophs-parasites: *Armillaria mellea*, *Pleurotus osteatus*, *Festulina hepatica, etc.* It was demonstrated that the maximum values of ^{137}Cs activity concentration were characteristic for mycosymbiotrophic species of *Cortinariaceae* and *Boletaceae* families.

G. A. Grodzynska [15] analyzed ^{137}Cs content in dry fruiting bodies of wild mushrooms in contrasting levels of radioactive contamination of the territory of Zhytomyr Polissia. In particular, it was shown that in a zone of high levels of density of ^{137}Cs contamination of forests (up to 1480 kBq·m^{-2}) ^{137}Cs activity concentration decreased in mushrooms in the following descending order: *Imleria badia* – *Tricholoma equestre* – *Lactarius rufus* – *Sarcodon imbricatus* – *Leccinum scabrum* – *Suillus bovinus* – *Boletus edulis*, with diapason of ^{137}Cs content from 2680 to 96 kBq·kg^{-1} dry weight. In forest sites with relatively low levels of ^{137}Cs ground deposition (up to 27.8 kBq·m^{-2}) radionuclide content in mushrooms fruiting bodies decreased in such order: *Imleria badia* – *Lactarius vellereus* – *Suillus luteus*, with the range from 7.7 to 1.4 kBq·kg^{-1} dry weight.

Content of ^{137}Cs in fresh fruiting bodies of three species of mushrooms – *Boletus edulis*, *Leccinum aurantiacum*, and *Leccinum scabrum* in the Korosten and Luginy districts of Zhytomyr region was studied [16]. The highest median ^{137}Cs activity concentration was detected in *Boletus edulis* fruiting bodies – 580 Bq·kg^{-1} (range of values – 27 - 1800 Bq·kg^{-1}); the second highest level showed *Leccinum scabrum* – 290 Bq·kg^{-1} (18 - 1400 Bq·kg^{-1}). The lowest median values of mentioned radionuclide activity concentration were reported for *Leccinum aurantiacum* – 250 Bq·kg^{-1} (15 - 480 Bq·kg^{-1}). Thus, the mentioned above scientists emphasized the limitations of their own research – a lack of data on the ^{137}Cs density of contamination in the mushroom sampling sites and also a lack of data about specific FST. Therefore, these results should be considered only as a screening of mushroom radioactive contamination in studied areas.

In Bulgaria, 32 years after the Chornobyl accident, the levels of ^{137}Cs in three species of mushrooms were studied: *Hydnum repandum*, *Suillus luteus* and *Morchella esculenta* [6]. Significant interspecies differences in the content of mentioned radionuclide in their dry fruiting bodies were shown. It was found that the maximum ^{137}Cs content was observed in dry fruiting bodies of the symbiotroph *Hydnum repandum* – 110 ± 10 Bq·kg^{-1}. The content of ^{137}Cs radionuclide was half lower in fruiting bodies of the symbiotroph *Suillus luteus* – 50 ± 10 Bq·kg^{-1}, and the lowest – in fruiting bodies of the humus saprotroph *Morchella esculenta* – 6 ± 2 Bq·kg^{-1}. It should be noted that the authors did not indicate density of ^{137}Cs contamination deposition and FST in sampling sites.

In the Czech Republic, in areas with the highest levels density of contamination with ^{137}Cs (Silesia), the content of ^{137}Cs was studied separately in caps and stipes of mushroom species – *Imleria badia*, *Russula ochroleuca* and *Armillaria mellea*. However, the levels of ^{137}Cs ground deposition were not given [2]. The highest values of ^{137}Cs activity concentration were detected in dry fruiting bodies of *Imleria badia* – 11.8 kBq·kg^{-1} in caps and 10.3 kBq·kg^{-1} – in stipes. Corresponding values in *Russula ochroleuca* were 8.8 and 4.0 kBq·kg^{-1}. The smallest content of mentioned radionuclide was recorded in *Armillaria mellea* – 217 and 102 Bq·kg^{-1}, respectively.

Accumulation of ^{137}Cs by fresh fruiting bodies of *Suillus luteus* in sampling sites in the Exclusion Zone of the Chornobyl NPP and in some other areas of the Kyiv region outside the Exclusion Zone in the years 1986 - 2020 was studied [17]. The two-stage dynamics of ^{137}Cs activity concentration in fruiting bodies of studied species were demonstrated. The first stage is 1986 - 1996 (1997), in this period the annual increase of ^{137}Cs content in *Suillus luteus* was observed in sampling sites. The second stage is characterized by the decrease of ^{137}Cs activity concentration in the fruiting bodies of the mushroom. This period, according to researchers, continues until now. The duration of the effective ecological half-life period for ^{137}Cs in *Suillus luteus* fruiting bodies in the studied period was calculated. It was demonstrated that the value of this parameter depended on the predominant form of radionuclide fallout – condensation or fuel form, which prevailed at a certain distance from the destroyed power unit 4 of the Chornobyl NPP. In particular, in vicinities of the former village Yaniv (2 km from the Chornobyl NPP) effective ecological half-life for ^{137}Cs in *Suillus luteus* fruiting bodies was equal to 3.1 years; village Dytyatky (30 km from the Chornobyl NPP) – 5.4 years; village Staiky (150 km from the Chornobyl NPP) – 8.3 years; town Rzhyshchiv (160 km from the Chornobyl NPP) – 11.9 years.

From this brief review, it can be concluded that such important parameters of mushroom sampling sites as FST and values of ^{137}Cs ground deposition were absent in the majority of mentioned publications. Taking into account the above, the tasks of our research were the following: to analyze the values of ^{137}Cs activity concentration in fruiting bodies of different mushrooms species in different FST taking into account values of ^{137}Cs ground deposition; to identify and statistically evaluate differences in the intensity of ^{137}Cs accumulation (average values of ^{137}Cs aggregated transfer coefficient (*Tag*) by different species of mushrooms in studied FST.

3. Objects and methodology

The study of ^{137}Cs radioactive contamination in fruiting bodies of mushrooms was carried out in September - October 2022 in 18 temporary sample sites laid out in Zhytomyr region, Korosten district, Povchanske, Lypnytske and Luhynske forestries of the "Lugyny Forestry" branch of the State Enterprise "Forests of Ukraine", as well as in Narodytske Forestry of the Drevliansky Nature Reserve (Table 1) in three most important FST – fresh infertile pine site type (A_2), fresh fairly infertile pine site type (B_2) and moist fairly infertile pine site type (B_3). These sites share from the total pine forests area in Volyn' and Zhytomyr Polissia of Ukraine is 47.8 % [18].

Table 1. **Location and brief characteristic of sampling sites**

Forest division, quarter/elementary stand	Geographical coordinates	Composition of tree canopy / stand origin	Age, years	Stand density
Fresh infertile pine site type (A_2). Association Dicrano-Pinetum Preising et Knapp ex Oberd. 1957				
Lypnytske, 41/1	51°09'25.9"N, 28°28'28.2"E	Pine 95 %, birch 5 % / nat.	75	0.73
Povchanske, 49/18	51°08'17.2"N, 28°35'29.6"E	Pine 95 %, birch 5 % / art.	75	0.60
Povchanske, 49/20	51°08'15.6"N, 28°35'00.9"E	Pine 95 %, birch 5 % / art.	55	0.80
Povchanske, 49/22.1	51°08'15.3"N, 28°34'58.2"E	Pine 100 % / nat.	61	0.80
Povchanske, 49/34	51°08'11.8"N, 28°35'27.0"E	Pine 100 % / art.	55	0.70
Narodytske, 92/2	51°08'19.2"N, 29°05'24.3"E	Pine 70 %, birch 30 % / art.	34	0.75
Fresh fairly infertile pine site type (B_2). Association Peucedano-Pinetum Matuszkiewicz (1962) 1973				
Lugynske, 79/29	51°07'45.0"N, 28°27'05.3"E	Pine 100 % / art.	72	0.70
Lugynske, 79/30	51°07'47.3"N, 28°27'24.3"E	Pine 100 % / art.	72	0.70
Lugynske, 87/4	51°07'43.4"N, 28°27'09.1"E	Pine 100 % / art.	75	0.70
Povchanske, 50/1.1	51°08'20.5"N, 28°36'01.8"E	Pine 100 % / nat.	90	0.60
Povchanske, 50/1.2	51°08'19.0"N, 28°35'40.4"E	Pine 100 % / nat.	90	0.60
Narodytske, 56/1	51°09'23.8"N, 29°04'42.0"E	Pine 100 % / nat.	89	0.81
Moist fairly infertile pine site type (B_3). Association Molinio-Pinetum Matuszkiewicz (1973) 1981				
Lugynske, 69/21	51°08'31.7"N, 28°25'15.2"E	Pine 90 %, birch 10 % / nat.	64	0.67
Lugynske, 79/22	51°07'45.1"N, 28°27'18.4"E	Pine 80 %, birch 20 % / nat.	79	0.70
Lugynske, 79/27	51°07'48.4"N, 28°27'25.0"E	Pine 80 %, birch 20 % / art.	40	0.80
Povchanske, 49/22.2	51°08'12.9"N, 28°35'06.2"E	Pine 95 %, birch 5 % / nat.	61	0.80
Povchanske, 50/22	51°08'20.5"N, 28°36'01.8"E	Pine 95 %, birch 5 % / art.	59	0.80
Narodytske, 64/2	51°09'40.9"N, 29°07'57.6"E	Pine 80 %, birch 20 % / nat.	84	0.79

N o t e: pine – Scots pine (*Pinus sylvestris* L.); birch – silver birch (*Betula pendula* Roth); nat. – natural origin; art. – artificial origin.

The data of Table 1 show that all sample sites consist of pure stands of *Pinus sylvestris* L. with some participation of *Betula pendula* Roth in their composition – from a single tree to several units per tree stand. Half of the sampling sites are represented by Scots pine plantation up to 75 - 90 years old, and two of them are 34 and 40 years old.

The majority of sampling sites are represented by Scots pine stands with high stand density (0.70 - 0.81), which determines the formation of rich species diversity of macromycetes. FST-A_2 was presented by the association *Dicrano-Pinetum* Preising et Knapp ex Oberd. 1957 with soddy-slighty-podzolic sandy soils, where under tree canopy was presented only a layer of green mosses (*Pleurozium schreberi* (Willd. ex Brid.) Mitt., *Dicranum polysetum* Hedw.) with projective cover 90 - 95 %. FST-B_2 was presented by the association *Peucedano-Pinetum* Matuszkiewicz (1962) 1973 with soddy-slighty-podzolic sandy-loam soils, where grass – the dwarf-shrub layer was sparse (5 - 15 %) and consisted of *Peucedanum oreoselinum* (L.) Moench, *Calamagrostis arundinacea* (L.) Roth, *Convallaria majalis* L., etc. Moss layer was dense, with projective cover 85 - 95 % (*Pleurozium schreberi*, *Dicranum polysetum*). FST-B_3 was presented by the association *Molinio-Pinetum* Matuszkiewicz (1973) 1981 with soddy-medium-podzolic sandy-loam soils. Its grass – dwarf-shrub layer with projective cover of 60 - 80 % consisted of

Vaccinium myrtillus L., *Vaccinium vitis-idaea* L., *Molinia caerulea* (L.) Moench, etc., and moss layer (65 - 95 % cover) – *Pleurozium schreberi*, *Dicranum polysetum* and *Hylocomium splendens* (Hedw.) Schimp.

Fruiting bodies of each mushroom species were collected in 3 - 7 fold repetition in each sample site. In total there were studied 18 species of mushrooms. In mushroom sampling sites, an appropriate number of soil samples were taken according to [19], with a cylindrical drill (diameter 5 cm) to a depth of 20 cm at 5 points for each collected mushroom sample. The mentioned 5 individual soil samples were combined into one collecting sample, which characterized soil radioactive contamination at the place of mushroom fruiting bodies sampling. However, in contrast to the mentioned method, soil mineral layers were collected together with forest litter, since the mycelium of many mushroom species is situated in both mentioned layers, and in some species, for example, litter saprotrophs, they can be found exclusively in the forest litter.

In laboratory conditions, mushroom fruiting bodies were carefully cleaned from forest litter and soil particles, then they were cut into small parts, homogenized and placed into a measuring container: a Marinelli container (1000 cm^3), half a Marinelli container (500 cm^3) or Denta (135 cm^3). Soil samples were dried for 72 h at a temperature of 80ºC, and then they were homogenized. The activity concentration of ^{137}Cs in samples was measured using a SEG-001 AKP-C-150 spectroanalyzer with a BDEG-20-R2 scintillation detector. The relative error of measurement of ^{137}Cs activity concentration did not exceed 15 %.

The indicator of ^{137}Cs accumulation intensity by mushroom fruiting bodies was the *Tag* of the mentioned radionuclide in the chain "soil – mushroom fruiting bodies", which was defined as the ratio of ^{137}Cs activity concentration in mushroom fruiting bodies of a certain species (Bq·kg^{-1}) to the ^{137}Cs ground deposition (kBq·m^{-2}). *Tag* had the generally accepted dimension unit – m^2·kg^{-1}·10^{-3} [20]. Statistical processing of the obtained results was carried out according to [21] using the Excel package.

The FST were defined according to the edaphic grid of Alekseev - Pogrebnyak [22], and associations of forest vegetation – by the methodology of floristic classification [23, 24]. The names of vegetation syntaxons are given according to [25]. The names of all mushroom species are aligned according to the modern nomenclature of Index Fungorum [26].

4. Results and discussion

The study of the values of ^{137}Cs activity concentration in fresh fruiting bodies of mushrooms and their comparison with the corresponding values of ^{137}Cs ground deposition with mentioned radionuclide made it possible to reveal the general picture of mushroom radioactive contamination in the studied area (Table 2). Analysis of data showed that the maximum average values of ^{137}Cs content in fruiting bodies in sample sites FST-A$_2$ were observed in *Cortinarius mucosus* – 117.9 kBq·kg^{-1}, *Tricholoma equestre* – 76.4 kBq·kg^{-1}, *Hygrophorus hypothejus* – 70.4 kBq·kg^{-1}. In this FST the minimum average values of ^{137}Cs content were typical for the fruiting bodies of *Armillaria mellea* – 0.12 kBq·kg^{-1}, *Tapinella atrotomentosa* – 0.70 kBq·kg^{-1}, *Boletus edulis* – 2.24 kBq·kg^{-1}. In general, it should be noted that the majority of mushroom species in FST-A$_2$ were selected at fairly significant levels of soil radioactive contamination – from 142.3 to 410 kBq·m^{-2}, so the content of ^{137}Cs in fruiting bodies of most species was significant and exceeded the level expected for ^{137}Cs radioactive waste – 10 kBq·kg^{-1} [27].

Table 2. **Statistic indexes of ^{137}Cs activity concentration in fresh mushroom fruiting bodies and density of contamination in sampling sites**

№	Forest division, quarter/elementary stand	Species of mushroom	Radioecological indexes	Statistics		
				M ± m	V	P
Fresh infertile pine site type (A$_2$)						
1	Povchanske, 49/20	*Suillus luteus* (L.) Roussel	Am ^{137}Cs, f.w.	12.4 ± 0.7	10.2	5.9
			As ^{137}Cs	249 ± 2	1.1	0.6
2	Povchanske, 49/22	*Suillus variegatus* (Sw.) Richon & Roze	Am ^{137}Cs, f.w.	28 ± 3	15.2	8.8
			As ^{137}Cs	190 ± 7	5.9	3.4
3	Povchanske, 49/20	*Leccinum scabrum* (Bull.) Gray	Am ^{137}Cs, f.w.	1.7 ± 0.1	11.5	6.6
			As ^{137}Cs	279 ± 7	4.5	2.6
4	Povchanske, 49/20	*Imleria badia* (Fr.) Vizzini	Am ^{137}Cs, f.w.	16 ± 2	19.7	11.4
			As ^{137}Cs	260 ± 35	23.1	13.3
5	Povchanske, 49/20	*Tricholoma equestre* (L.) P. Kumm	Am ^{137}Cs, f.w.	76 ± 18	40.3	23.3
			As ^{137}Cs	291 ± 5	3.1	1.8
6	Povchanske, 49/20	*Tricholoma portentosum* (Fr.) Quél	Am ^{137}Cs, f.w.	10 ± 3	64.8	29
			As ^{137}Cs	218 ± 36	37.2	16.6

Continuation of Table 2

№	Forest division, quarter/elementary stand	Species of mushroom	Radioecological indexes	Statistics		
				M ± m	V	P
7	Povchanske, 49/20	*Tricholoma imbricatum* (Fr.) P. Kumm	Am ^{137}Cs, f.w.	8.5 ± 0.3	5.9	3.4
			As ^{137}Cs	142 ± 14	16.7	9.7
8	Povchanske, 49/20	*Sarcodon imbricatus* (L.) P. Karst	Am ^{137}Cs, f.w.	50 ± 4	15.1	8.7
			As ^{137}Cs	245 ± 14	9.7	5.6
9	Povchanske, 49/20	*Hydnum repandum* L.	Am ^{137}Cs, f.w.	11.3 ± 0.7	11.1	6.4
			As ^{137}Cs	290 ± 15	8.9	5.2
10	Povchanske, 49/22	*Lactarius rufus* (Scop.) Fr.	Am ^{137}Cs, f.w.	22 ± 4	41.0	18.4
			As ^{137}Cs	220 ± 34	34.9	15.7
11	Povchanske, 94/2	*Lactarius deliciosus* (L.) Gray	Am ^{137}Cs, f.w.	44 ± 1	5.1	3.0
			As ^{137}Cs	402 ± 26	11.2	6.5
12	Povchanske, 49/20	*Cortinarius mucosus* (Bull.) J. Kickx f.	Am ^{137}Cs, f.w.	117 ± 14	20.5	11.8
			As ^{137}Cs	270 ± 23	14.5	8.4
13	Povchanske, 49/22	*Paxillus involutus* (Batsch) Fr.	Am ^{137}Cs, f.w.	23 ± 9	65.2	37.7
			As ^{137}Cs	193 ± 57	50.9	29.4
14	Lypnytske, 41/1	*Tapinella atrotomentosa* (Batsch) Šutara	Am ^{137}Cs, f.w.	0.7 ± 0.1	11.5	6.6
			As ^{137}Cs	14.3 ± 0.2	2.8	1.6
15	Povchanske, 49/20	*Russula aeruginea* Lindblad ex Fr.	Am ^{137}Cs, f.w.	3.0 ± 0.2	11.3	6.5
			As ^{137}Cs	191 ± 6	5.1	2.9
16	Povchanske, 49/18	*Armillaria mellea* (Vahl.) P. Kumm	Am ^{137}Cs, f.w.	0.12 ± 0.01	15.5	8.9
			As ^{137}Cs	323 ± 40	21.2	12.3
17	Povchanske, 49/20	*Hygrophorus hypothejus* (Fr.) Fr.	Am ^{137}Cs, f.w.	70 ± 2	4.9	2.8
			As ^{137}Cs	182 ± 13	12.5	7.2
18	Narodytske, 94/2	*Boletus edulis* Bull.	Am ^{137}Cs, f.w.	2.2 ± 0.4	52.8	18.7
			As ^{137}Cs	263 ± 47	51.1	18.1
Fresh fairly infertile pine site type (B_2)						
1	Povchanske, 50/1	*Imleria badia* (Fr.) Vizzini	Am ^{137}Cs, f.w.	10.0 ± 1.3	33.0	13.5
			As ^{137}Cs	193 ± 15	18.7	7.7
2	Povchanske, 50/1	*Armillaria mellea* (Vahl.) P. Kumm	Am ^{137}Cs, f.w.	0.47 ± 0.13	48.4	27.9
			As ^{137}Cs	203 ± 15	13.0	7.5
3	Povchanske, 50/1	*Tricholoma portentosum* (Fr.) Quél	Am ^{137}Cs, f.w.	10.4 ± 0.4	6.5	3.7
			As ^{137}Cs	225 ± 32	24.3	14.0
4	Povchanske, 50/1	*Paxillus involutus* (Batsch) Fr.	Am ^{137}Cs, f.w.	13 ± 3	43.7	25.2
			As ^{137}Cs	143 ± 23	27.5	15.9
5	Povchanske, 50/1	*Lactarius rufus* (Scop.) Fr.	Am ^{137}Cs, f.w.	6.5 ± 0.5	13.0	7.5
			As ^{137}Cs	109 ± 13	20.9	12.1
6	Povchanske, 50/1	*Russula vinosa* Lindblad	Am ^{137}Cs, f.w.	10.3 ± 0.5	9.1	5.3
			As ^{137}Cs	154 ± 11	12.4	7.1
7	Povchanske, 50/1	*Russula xerampelina* (Schaeff.) Fr.	Am ^{137}Cs, f.w.	2.0 ± 0.1	9.6	5.6
			As ^{137}Cs	196 ± 6	5.1	2.9
8	Povchanske, 50/1	*Russula paludosa* Britzelm	Am ^{137}Cs, f.w.	4.4 ± 0.2	9.7	5.6
			As ^{137}Cs	299 ± 26	15.2	8.8
9	Povchanske, 50/1	*Sarcodon imbricatus* (L.) P. Karst	Am ^{137}Cs, f.w.	32 ± 2	12.1	7.0
			As ^{137}Cs	197 ± 11	9.3	5.4
10	Lugynske, 79/29	*Cantharellus cibarius* Fr.	Am ^{137}Cs, f.w.	2.4 ± 0.1	8.2	4.7
			As ^{137}Cs	398 ± 35	15.1	8.7
11	Lugynske, 87/42	*Leccinum scabrum* (Bull.) Gray	Am ^{137}Cs, f.w.	0.53 ± 0.03	9.2	5.3
			As ^{137}Cs	90 ± 14	26.2	15.1
12	Lugynske, 79/29	*Russula aeruginea* Lindblad ex Fr.	Am ^{137}Cs, f.w.	0.83 ± 0.05	10.2	5.9
			As ^{137}Cs	314 ± 62	34.1	19.7
13	Narodytske, 56/1	*Boletus edulis* Bull.	Am ^{137}Cs, f.w.	2.8 ± 0.1	12.0	4.5
			As ^{137}Cs	368 ± 45	32.2	12.2
14	Narodytske, 56/1	Cortinarius caperatus (Pers.) P. Karst.	Am ^{137}Cs, f.w.	40 ± 5	27.6	12.4
			As ^{137}Cs	410 ± 30	16.5	7.4

Continuation of Table 2

№	Forest division, quarter/elementary stand	Species of mushroom	Radioecological indexes	Statistics		
				M ± m	V	P
Moist fairly infertile pine site type (B_3)						
1	Povchanske, 50/23	*Imleria badia* (Fr.) Vizzini	Am ^{137}Cs, f.w.	19 ± 4	39.3	19.7
			As ^{137}Cs	168 ± 6	7.6	3.8
2	Povchanske, 50/23	*Boletus subtomentosus* L.	Am ^{137}Cs, f.w.	1.9 ± 0.5	42.7	24.6
			As ^{137}Cs	135 ± 27	34.6	19.9
3	Lugynske, 69/12	*Tapinella atrotomentosa* (Batsch) Šutara	Am ^{137}Cs, f.w.	1.3 ± 0.4	46.1	26.6
			As ^{137}Cs	28 ± 3	21.1	12.2
4	Narodytske, 64/2	*Paxillus involutus* (Batsch) Fr.	Am ^{137}Cs, f.w.	35 ± 6	27.8	16.1
			As ^{137}Cs	344 ± 35	17.4	10.0
5	Lugynske, 79/22	*Lactarius rufus* (Scop.) Fr.	Am ^{137}Cs, f.w.	20 ± 4	36.7	21.2
			As ^{137}Cs	189 ± 46	42.4	24.5
6	Lugynske, 79/27	*Russula paludosa* Britzelm	Am ^{137}Cs, f.w.	2.8 ± 0.2	15.1	8.7
			As ^{137}Cs	146 ± 8	8.9	5.2
7	Lugynske, 79/27	*Boletus edulis* Bull.	Am ^{137}Cs, f.w.	1.5 ± 0.2	20.4	11.8
			As ^{137}Cs	143 ± 12	14.9	8.6
8	Narodytske, 64/2	*Cortinarius caperatus* (Pers.) P. Karst	Am ^{137}Cs, f.w.	30 ± 1	6.0	3.0
			As ^{137}Cs	287 ± 28	19.4	9.7
9	Narodytske, 64/2	*Cantharellus cibarius* Fr.	Am ^{137}Cs, f.w.	2.7 ± 0.4	26.7	13.3
			As ^{137}Cs	276 ± 10	6.9	3.5
10	Narodytske, 64/2	*Leccinum scabrum* (Bull.) Gray	Am ^{137}Cs, f.w.	2.6 ± 0.7	44.4	25.7
			As ^{137}Cs	287 ± 10	6.0	3.5

Note: Am ^{137}Cs – ^{137}Cs activity concentration in fresh fruiting bodies of mushrooms, kBq·kg^{-1}; As ^{137}Cs – density of contamination, kBq·m^{-2}; f. w. – fresh weight. Statistics: M – arithmetic mean, m – error of arithmetic mean; V – coefficient of variation, %; P – relative error of arithmetic mean, %.

In FST-A_2, the excess of the mentioned level was observed in 67 % of the analyzed species, with the maximum excess in *Cortinarius mucosus* – 11.8 times and the minimum – in *Hydnum repandum* – 1.12 times. The results of the analysis also showed that the values of ^{137}Cs activity concentration in fresh mushrooms fruiting bodies in FST-A_2 for most species exceeded the permissible level recommended by IAEA [11] – 1.0 kBq·kg^{-1}, such as *Leccinum scabrum* – 1.7 times, *Cortinarius mucosus* – 117.8 times. The exceptions are *Armillaria mellea* and *Tapinella atrotomentosa*.

In FST-B_2, the highest values of ^{137}Cs activity concentration were observed for *Cortinarius caperatus* – 40.1 kBq·kg^{-1}, *Sarcodon imbricatus* – 31.8 kBq·kg^{-1} and *Paxillus involutus* – 13.1 kBq·kg^{-1}. The lowest values of this parameter were in *Armillaria mellea* – 0.47 kBq·kg^{-1}, *Leccinum scabrum* – 0.50 kBq·kg^{-1}, and *Russula aeruginea* – 0.83 kBq·kg^{-1}. In general, in FST-B_2, an excess of [27] level was observed in 36 % of the analyzed species, with the maximum excess in *Cortinarius caperatus* – 4.0 times and the minimum – in *Paxillus involutus* – 1.3 times. It was also found that the values of ^{137}Cs activity concentration in fresh mushroom fruiting bodies of the majority species in FST-B_2, with the exception of *Armillaria mellea*, *Leccinum scabrum* and *Russula aeruginea*, exceeded the ^{137}Cs permissible level recommended by the IAEA [11]: from 2.0 times in *Russula xerampelina* up to 40.1 times in *Cortinarius caperatus*.

In FST-B_3, the maximum values of ^{137}Cs average content in fresh fruiting bodies were detected in *Paxillus involutus* – 34.8 kBq·kg^{-1}, *Cortinarius caperatus* – 29.7 kBq·kg^{-1}, *Lactarius rufus* – 20.0 kBq·kg^{-1}, and minimal – in *Tapinella atrotomentosa* – 1.34 kBq·kg^{-1}, *Boletus edulis* – 1.53 kBq·kg^{-1} and *Boletus subtomentosus* – 1.86 kBq·kg^{-1}. In FST-B_3, an excess of the level [27] was observed in 40 % of the analyzed species, with the maximum values in *Paxillus involutus* – 3.5 times and the minimum – in *Imleria badia* – 1.9 times. It was also found that the values of ^{137}Cs activity concentration in fresh mushrooms fruiting bodies for all species exceeded the permissible level of ^{137}Cs content recommended by the IAEA [11] – from 1.3 times in *Tapinella atrotomentosa* to 34.8 times in *Paxillus involutus*.

Thus, it was found that the maximum levels of ^{137}Cs content in studied FST were characteristic of symbiotrophic species such as *Cortinarius mucosus, C. caperatus, Sarcodon imbricatus, Imleria badia, Tricholoma equestre, Paxillus involutus, Hygrophorus hypothejus*. This conclusion correlates well with the data of other researchers, who, in particular, had reported data about the intensive accumulation of ^{137}Cs by symbiotrophic species of the *Cortinariaceae* family [28, 29], *Imleria badia* [30 - 32], *Paxillus involutus* [12, 33]. We also confirmed the results of research [34] that *Tricholoma equesre* accumulates ^{137}Cs much more intensively than *Tricholoma portentosum.* The minimum ^{137}Cs content was measured in xylotrophs-saprotrophs – *Armillaria mellea* and *Tapinella atrotomentosa*.

The calculated average values of ^{137}Cs *Tag* in the chain "soil – fresh mushrooms fruiting bodies", summarized according to FST, are of great scientific and practical importance (Figs. 1 - 3).

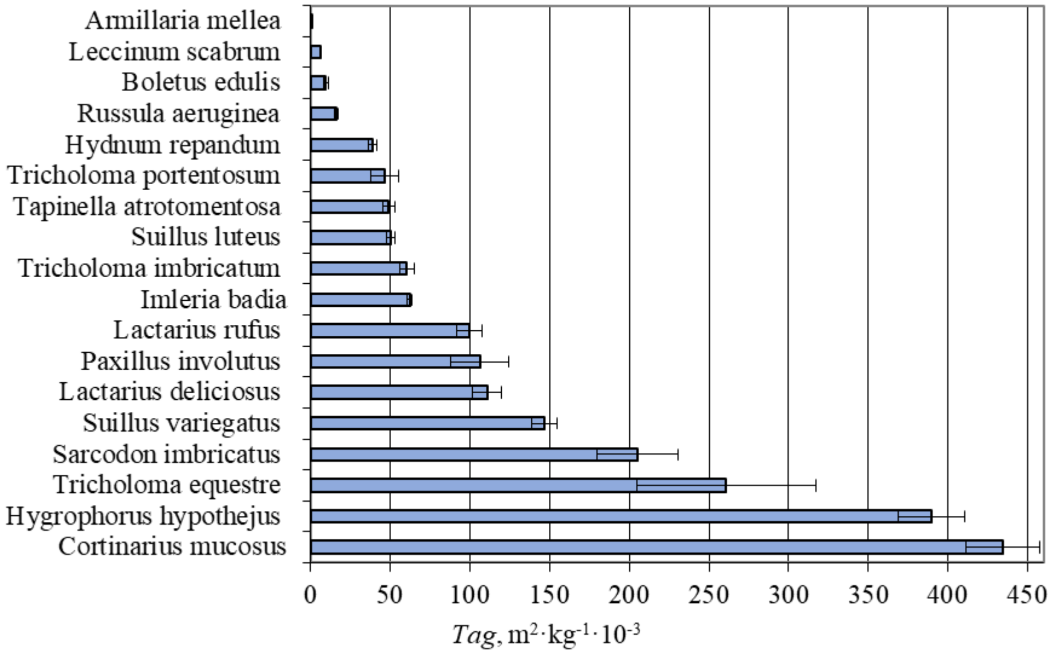


Fig. 1. Average values of *Tag* of ^{137}Cs in the chain "soil – fresh fruiting bodies of mushrooms" in FST-A_2.
(See color Figure on the journal website.)

Researchers have previously provided data that even in one ecotope, the interspecies difference in ^{137}Cs *Tag* values can reach 10^4 times [35]. In general, it was found that in FST-A_2 the increased intensity of ^{137}Cs accumulation was typical for species that can be placed in the following descending order: *Cortinarius mucosus* > *Hygrophorus hypothejus* > *Tricholoma equestre* > *Sarcodon imbricatus*, with a diapason of average values of ^{137}Cs *Tag* 434.5 ± 23.3 – 205.4 ± 25.5 $m^2 \cdot kg^{-1} \cdot 10^{-3}$. The minimum average *Tag* values were obtained for *Armillaria mellea, Leccinum scabrum,* and *Boletus edulis* with a range of 0.4 ± 0.1 – 9.5 ± 1.4 $m^2 \cdot kg^{-1} \cdot 10^{-3}$.

In FST-B_2 the interspecies difference in the average values of ^{137}Cs *Tag* was equal to 71.4 times, with the maximum value in *Sarcodon imbricatus* – 161.5 ± 10.4 $m^2 \cdot kg^{-1} \cdot 10^{-3}$ and the minimum one in *Armillaria mellea* – 2.3 ± 0.5 $m^2 \cdot kg^{-1} \cdot 10^{-3}$ (Fig. 2).

According to the intensity of ^{137}Cs accumulation in fruiting bodies, the first five species are as follows: *Sarcodon imbricatus* > *Cortinarius caperatus* > *Paxillus involutus* > *Russula vinosa* > *Lactarius rufus*. Interesting data were obtained as a result of average values analysis of ^{137}Cs *Tag* in various species of the genus *Russula*. It was found that according to the average *Tag* values, they can be placed in the following ranked order: *Russula vinosa* (67.0 ± 3.9 $m^2 \cdot kg^{-1} \cdot 10^{-3}$) > *Russula paludosa* (14.7 ± 1.1 $m^2 \cdot kg^{-1} \cdot 10^{-3}$) > *Russula xerampelina* (10.4 ± 0.9 $m^2 \cdot kg^{-1} \cdot 10^{-3}$) > *Russula aeruginea* (2.8 ± 0.4 $m^2 \cdot kg^{-1} \cdot 10^{-3}$). Thus, a 24-fold difference in the average values of ^{137}Cs *Tag* is observed in the genus *Russula*.

In FST-B_3, the interspecies difference in the average values of ^{137}Cs *Tag* in mushrooms exceeded a mathematical order (Fig. 3).

The maximum value of the mentioned parameter was calculated for *Imleria badia* – 111 ± ± 18 $m^2 \cdot kg^{-1} \cdot 10^{-3}$, and the minimum one – for *Leccinum scabrum* – 9.2 ± 2.6 $m^2 \cdot kg^{-1} \cdot 10^{-3}$. The intensity of ^{137}Cs accumulation in the first four species by the *Tag* value in FST-B_3 decreased in the following order: *Imleria badia* > *Lactarius rufus* > *Cortinarius caperatus* > *Paxillus involutus.* This order correlates well with the data of other researchers [12, 29, 31, 32], who also concluded that the mentioned mushroom species demonstrate intensive accumulation of ^{137}Cs.

The obtained average values of ^{137}Cs *Tag* in the chain "soil – fresh mushrooms fruiting bodies" in different FST make it possible to calculate the normalizing radionuclide content in mushrooms at ^{137}Cs ground deposition in 37 $kBq \cdot m^{-2}$. In FST-A_2,

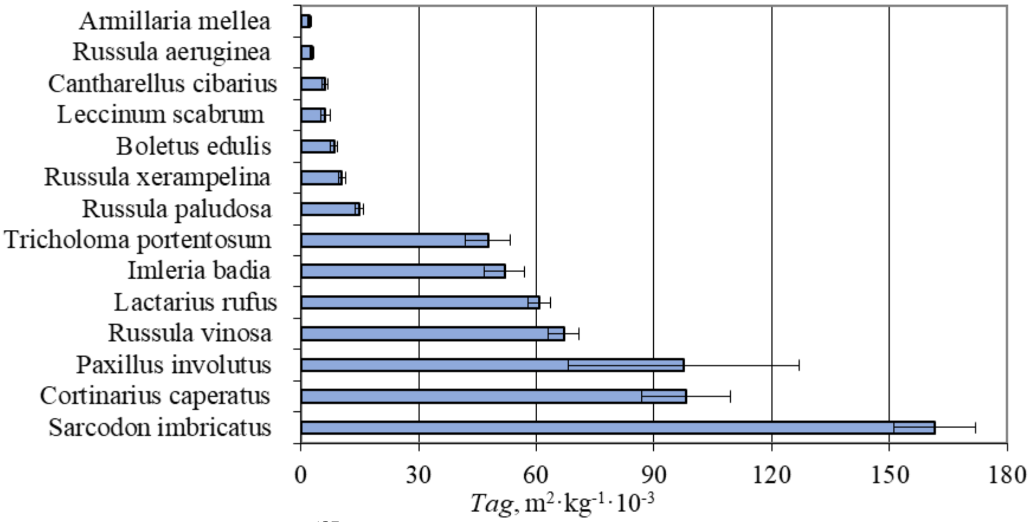


Fig. 2. Average values of *Tag* of ^{137}Cs in the chain "soil – fresh fruiting bodies of mushrooms" in FST-B_2. (See color Figure on the journal website.)

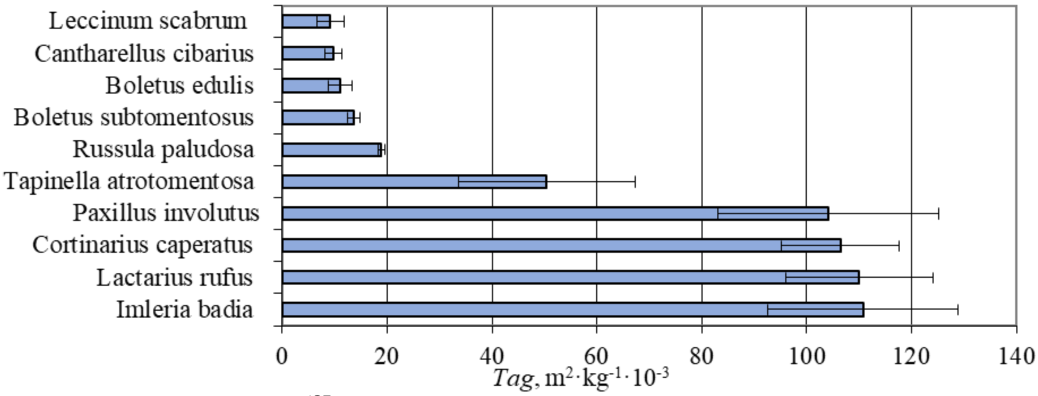
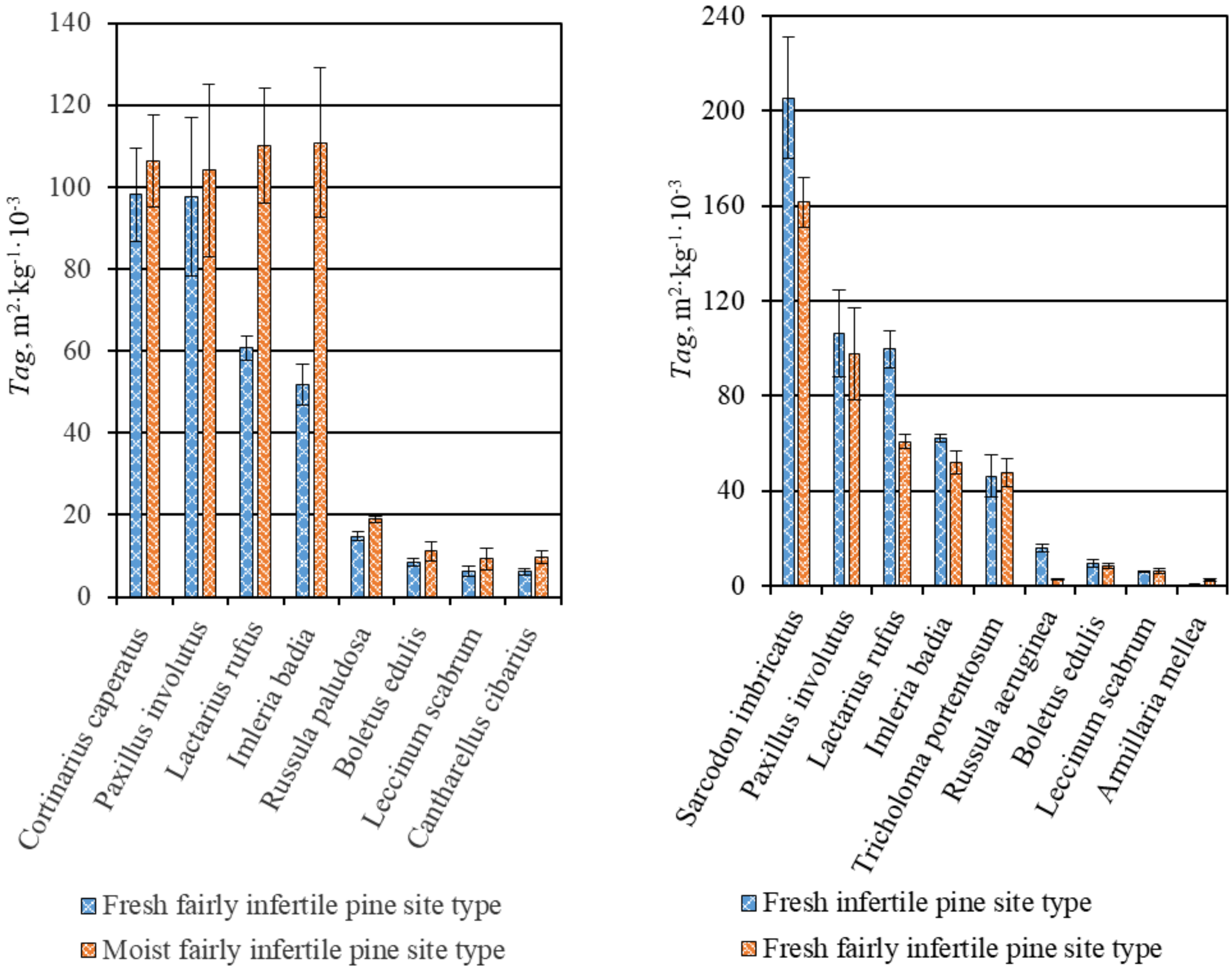


Fig. 3. Average values of *Tag* of ^{137}Cs in the chain "soil – fresh fruiting bodies of mushrooms" in FST-B_3. (See color Figure on the journal website.)

the content of ^{137}Cs in fresh fruiting bodies at the mentioned density of contamination did not exceed the maximum permissible level of 500 $Bq{\cdot}kg^{-1}$ [36] only in 3 species of mushrooms: *Boletus edulis*, *Leccinum scabrum*, and *Armillaria mellea*; in the other species, ^{137}Cs content significantly exceeded permissible level – from 16.1 in *Cortinarius mucosus* to 0.6 $kBq{\cdot}kg^{-1}$ in *Russula aeruginea*. In FST-B_2, it was detected that 8 of 14 species of mushrooms were ^{137}Cs accumulators, the mentioned radionuclide content in its fruiting bodies exceeded the maximum permissible level [36] at ^{137}Cs ground deposition in 37 $kBq{\cdot}m^{-2}$, from 6.0 in *Sarcodon imbricatus* to 0.54 $kBq{\cdot}kg^{-1}$ in *Russula paludosa*. In FST-B_3, 6 of 10 species of mushrooms accumulate ^{137}Cs most intensively; their ^{137}Cs content exceeded the maximum permissible level at ^{137}Cs ground deposition in ^{137}Cs 37 $kBq{\cdot}m^{-2}$ from 4.1 in *Imleria badia* up to 0.7 $kBq{\cdot}kg^{-1}$ in *Russula paludosa*.

A part of the studied mushroom species was sampled in several FST. A comparison of the average values of ^{137}Cs *Tag* in the chain "soil – fresh mushrooms fruiting bodies" in different FST is of practical importance. The data of Fig. 4 demonstrate the general regularity identified earlier [13] – when the fertility of soil increases, the values of ^{137}Cs *Tag* in mushrooms, as a rule, decrease, and when the soil moisture increases, the values of *Tag* increase. For example, in *Sarcodon imbricatus* in FST-A_2, the average ^{137}Cs *Tag* values were equal to $205 \pm 26\ m^2{\cdot}kg^{-1}{\cdot}10^{-3}$, in FST-$B_2$ – $162 \pm 10\ m^2{\cdot}kg^{-1}{\cdot}10^{-3}$; in *Paxillus involutus* FST-A_2 – $106 \pm 18\ m^2{\cdot}kg^{-1}{\cdot}10^{-3}$, FST-$B_2$ – $98 \pm 18\ m^2{\cdot}kg^{-1}{\cdot}10^{-3}$; FST-$B_3$ – $104 \pm 21\ m^2{\cdot}kg^{-1}{\cdot}10^{-3}$. A similar regularity was also typical for the rest of the mushroom species shown in Fig. 4.

It is important to assess the statistical significance of the detected differences in the mean values of ^{137}Cs *Tag* in studied mushroom species in different FST. The results of ANOVA (dispersion analysis) demonstrated the absence of statistical differences of ^{137}Cs *Tag* average values at a 95 % confidence interval between forest sites types A_2 and B_2 in such species as *Sarcodon imbricatus* ($F_{fact.} = 2.55 < F_{0.95} = 7.71$; $n = 6$), *Tapinella atrotomentosa* ($F_{fact.} = 0.01 < F_{0.95} = 7.71$; $n = 6$), *Tricholoma portentosum* ($F_{fact.} = 0.01 < F_{0.95} = 5.99$; $n = 8$), *Cortinarius caperatus* ($F_{fact.} = 0.27 < F_{0.95} = 5.59$; $n = 9$). There is no statistically significant difference in the average values of ^{137}Cs *Tag* at the 95 %



a *b*

Fig. 4. Differences of mean values of *Tag* of ^{137}Cs in mushroom species in conditions of different trophotops – A_2-B_2 (*a*) and different hygrotops – B_2-B_3 (*b*). (See color Figure on the journal website.)

confidence interval in all dispersion pairs of forest sites types (A_2-B_2, B_2-B_3, A_2-B_3) for such species as *Paxillus involutus* ($F_{fact.}$ = 0.01-0.06 < $F_{0.95}$ = 7.71; n = 6), *Boletus edulis* ($F_{fact.}$ = 0.35-2.45 < $F_{0.95}$ = 4.67-5.32; n = 9), *Leccinum scabrum* ($F_{fact.}$ = 0.01-1.42 < $F_{0.95}$ = 7.71; n = 6). On the other hand, an essential difference in the average values of ^{137}Cs *Tag* at a significance level of 5 % was found in *Lactarius rufus* in pairs A_2-B_2 ($F_{fact.}$ = 13.54 > $F_{0.95}$ = 5.99; p = 0.01; n = 8) and B_2-B_3 ($F_{fact.}$ = 11.83 > > $F_{0.95}$ = 7.71; p = 0.03; n = 6); *Imleria badia* in the pair B_2-B_3 ($F_{fact.}$ = 11.26 > $F_{0.95}$ = 5.59; p = 0.01; n = 9); *Russula aeruginea* in the pair A_2-B_2 ($F_{fact.}$ = 80.16 > $F_{0.95}$ = 7.71; p = 0.001; n = 6); *Armillaria mellea* in the pair A_2-B_2 ($F_{fact.}$ = 15.65 > $F_{0.95}$ = 7.71; p = 0.02; n = 6); *Russula paludosa* in the pair of forest sites types B_2-B_3 ($F_{fact.}$ = 10.89 > $F_{0.95}$ = 7.71; p = 0.03; n = 6).

The absence of a statistically significant difference in the average values of ^{137}Cs *Tag* in a number of FST dispersion pairs in many mushroom species probably is explained by a wide variation of *Tag* values in each mushroom species within each of the studied FST. This, in turn, is probably due to the depth variation of the main part of active mushroom mycelium location in the soil as well as the presence of microniches in each forest biotope [37] which differ in the soil agrochemical parameters and also – ^{137}Cs bioavailability for mushrooms.

5. Conclusions

1. The majority of mushroom samples in the studied FST were collected at significant levels of ^{137}Cs ground deposition with the range of 109 ± 13 – 410 ± 30 kBq·m^{-2}. Therefore, the activity concentration of ^{137}Cs in fresh fruiting bodies of most species was significant and exceeded the OSPU-2005 level for ^{137}Cs radioactive waste and the limit level of ^{137}Cs content recommended by IAEA-1994.

2. It was found that in the studied FST, the maximum ^{137}Cs content was detected in such symbiotrophic species as *Cortinarius mucosus, C. caperatus*, *Sarcodon imbricatus*, *Imleria badia*, *Tricholoma equestre*, *Paxillus involutus*, *Hygrophorus hypothejus*, and the minimum content – in xylotrophs-

saprotrophs such as *Armillaria mellea* and *Tapinella atrotomentosa*.

3. In FST-A_2, the interspecies difference in the average values of ^{137}Cs *Tag* was equal $1.1 \cdot 10^3$ times, in FST-B_2, – 71.4 times, in FST-B_3 they exceeded a mathematical order.

4. It was confirmed that with the increase in soil fertility the values of ^{137}Cs *Tag* in mushrooms decrease, and the increase in soil moisture causes the increase of ^{137}Cs *Tag* values.

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СУЧАСНЕ НАКОПИЧЕННЯ ^{137}Cs ГРИБАМИ У РІЗНИХ ТИПАХ ЛІСОРОСЛИННИХ УМОВ СОСНОВИХ ЛІСІВ УКРАЇНСЬКОГО ПОЛІССЯ

Вивчення радіоактивного забруднення ^{137}Cs плодових тіл грибів проведено у вересні - жовтні 2022 р. на 18 тимчасових пробних площах, закладених у Коростенському районі Житомирської області, у 3 найбільш поширених у регіоні типах лісорослинних умов (ТЛУ) – свіжий бір (A_2), свіжий та вологий субір (B_2 та B_3). Установлено, що у досліджених ТЛУ найвищі рівні вмісту ^{137}Cs були характерними для симбіотрофних видів – *Cortinarius mucosus*, *Cortinarius caperatus*, *Sarcodon imbricatus*, *Imleria badia*, *Tricholoma equestre*, *Paxillus involutus*, *Hygrophorus hypothejus*, а найнижчі – для ксилотрофів-сапротрофів, таких, як *Armillaria mellea* та *Tapinella atrotomentosa.* Продемонстровано, що міжвидові відмінності середніх значень коефіцієнтів переходу ^{137}Cs у кожному ТЛУ широко варіювали: вони сягали $1,1 \cdot 10^3$ разів у свіжому борі (A_2) – від 435 у *Cortinarius mucosus* до 0,4 $м^2 \cdot кг^{-1} \cdot 10^{-3}$ у *Armillaria mellea*; 71,4 раза – у свіжому суборі (B_2) – від 162 у *Sarcodon imbricatus* до 2,3 $м^2 \cdot кг^{-1} \cdot 10^{-3}$ у *Armillaria mellea*; 12 разів – у вологому суборі (B_3) – від 111 у *Imleria badia* до 9,2 $м^2 \cdot кг^{-1} \cdot 10^{-3}$ у *Leccinum scabrum*. Також показано, що у роді *Russula* у свіжому суборі (B_2) серед п'яти досліджених видів спостерігалася 24-кратна різниця середніх значень коефіцієнта переходу ^{137}Cs – від 67 у *Russula vinosa* до 2,8 $м^2 \cdot кг^{-1} \cdot 10^{-3}$ у *Russula aeruginea*. Обговорено результати дисперсійного аналізу – суттєвості різниці середніх значень коефіцієнту переходу у грибів у різних ТЛУ.

Ключові слова: сосновий деревостан, питома активність ^{137}Cs, щільність радіоактивного забруднення ґрунту, коефіцієнт переходу, допустимі рівні.

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