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Original article

Contamination of wild mushrooms with ^{137}Cs after the Chernobyl nuclear power plant catastrophe in the Vyshhorod District of the Kyiv region of Ukraine

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ABSTRACT

Throughout the period 1990–2021, the activity of radiocaesium was measured using gamma spectrometry (using a HPGe detector) in sporocarps of 101 species of wild mushrooms and soil samples from localities in the Vyshhorod district of the Kyiv region, outside the Chernobyl exclusion zone. Especially high levels of radiocaesium activity were noted in the case of mycosymbiotrophs from the familie Cortinariaceae, Bankeraceae (*S. imbricatus),* Tricholomataceae *(T. equestre, T. fulvum, A. clavipes),* Russulaceae (*Lactarius* spp*.),* Boletaceae *(I. badia, Suillus* spp.), and Paxillaceae (*P. involutus*). According to the value of the calculated potential annual effective dose (contribution of ^{137}Cs only) for the period 2020–2021, the most popular edible species of mushrooms of the residents of Ukrainian Polissya can be presented in the following sequence: *B. edulis* < *C. cibarius* < *Xerocomu* spp. < *C. caperatus* < *T. equestre* < *Suillus* spp. (up to 0.054 mSv) < *I. badia* (up to 0.070 mSv*),* which indicates a relatively low dose as a result of consuming wild mushrooms. However, considering that half of the mushroom samples exceed the permissible levels adopted in Ukraine (2500 Bq/kg dry mass), the extremely high level of variability of radioecological data and the heterogeneity of radioactive contamination of these territories, during mass gathering and harvesting of wild mushrooms, even in territories with pollution < 37 kBq/m^2, mandatory radiation control is recommended.

KEY WORDS: radiocaesium, bioaccumulation, fungi, effective dose, bioindication

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1. Introduction

Powerful releases of radiocaesium (^{137}Cs and ^{134}Cs), like other radionuclides, accompanied by their active emission from the destroyed reactor for 10 days into the environment occurred as a result of the accident at the Chernobyl nuclear power plant (NPP) in April 26, 1986. This huge technological disaster, in addition to severe socio-economic and medical consequences, necessitated long-term radioecological monitoring and raised the question of bio-accumulation of radionuclides, their transfer into the food chain and of food safety in general. A significant part of the population, especially those in rural areas, which belongs to the category of increased risk due to living in the territory polluted by more than 37 kBq/m^2, and now, already more than 38 years after the Chernobyl NPP disaster, is under the constant and significant influence of radiation. Despite the natural process of decay of radioactive materials, the main dose-forming elements of the Chernobyl fallout – ^{137}Cs and ^{90}Sr, continue to pose a danger to people's health. Today, the main danger to people's health is internal radiation due to, in particular, the consumption of radioactively contaminated wild mushrooms, berries and game (20 YEARS…, 2006; THIRTY-FIVE YEARS …, 2021).

The use of mushrooms for culinary and medicinal purposes in the centuries-old traditions of the population, especially those living in the north of the country, in the Polissya zone, is very important. Mushroom dishes not only represent a significant regular part of the diet, for the rural, and also the urban population, and practically replaces protein-containing products (meat, fish, eggs, milk and its derivatives) that are prohibited during strict Orthodox fasts. In addition, the sale of wild mushrooms provides an additional income for the rural population.

At the same time, the forest ecosystems of 18 regions of Ukraine, which are the main source of wild mushrooms, with an area of more than 3.5 million hectares, were affected by the Chernobyl incident fallout, which is 39% of the total forest area of the country (KRASNOV ET AL., 2007). The aim of this study was to estimate the levels of radiocaesium contamination of wild mushrooms and its potential danger to the population of the Vyshhorod district (in the Kyiv region) many years after the Chernobyl disaster.

2. Materials and methods

In 1990–2021 fruiting bodies of wild mushrooms and average soil samples were collected at 14 locations in the Vyshhorod district of the Kyiv region of Ukraine, outside the exclusion zone (Fig. 1, Table 1). Soil samples were taken from 0–5 cm of the upper soil layer and from 4 extreme points along the diagonal and one in the centre for each locality (the "envelope" method). Sometimes, when there was an abundance of fruiting bodies in one location, their own average soil sample was taken for each sampling site and group of mushroom samples. The location was approximately 25 x 25 m in size. In one location there were from one to five sampling sites, in each case we collect an average soil sample.

Fig. 1.Maps of the Kyiv region and Vyshhorod district

Table 1. List of sampling sites and their coordinates in Vyshhorod district of Kyiv region

Location	Latitude	Longitude	Altitude (m a.s.l.)
Near the village of Abramivka	50°44'19.42"N	30°05'31.87"E	152
Near the settlement of Dymer	50°48'00.66"N	30°17'35.97"E	109
Near the village of Hotyanivka	50°37'11.29"N	30°33'27.08"E	100
Near the village of Katyuzhanka	50°47'44.44"N	30°06'18.67"E	151
Near the village of Lebedivka	50°40'19.48"N	30°34'26.49"E	108
Near the village of Lyutizh	50°40'25.33"N	30°22'07.28"E	151
Near the village of Novosilky	50°38'01.85"N	30°37'37.59"E	119
Near the village of Pirnove	50°45'17.77"N	30°39'22.43"E	112
Near the village of Rovzhy	50°50'51.78"N	30°36'12.86"E	108
Near the village of RudniaTals'ka	50°51'27.56"N	29°58'57.91"E	129
Near the village of Sukholuchchya	50°56'31.19"N	30°25'27.47"E	108
Near the village of Suvydy	50°51'58.42"N	30°45'48.89"E	117
Near the city of Vyshhorod (Vodogin)	50°34'15.75"N	30°27'40.30"E	178
Near the villages of Vyshcha Dubechnya	50°43'45.85"N	30°38'35.07"E	106

Mushrooms (2–15 complete fruiting bodies per species, mass of mushroom sample was in the range from 1 up to 10 g). Each average soil sample contained 5 subsamples (mass of an average soil sample was in the range of 15 up to 60 g). Mushroom samples were carefully cleaned from plant and soil debris, dried at 60℃, ground to a fine dispersion, dried again at 80℃ for 24 hours, then placed in polyethylene bags with a ziplock. The same procedure was used for the soil samples. We used γ-spectrometry (Ge-detector Canberra GLX 4019, Mirion Technology, Atlanta, USA) to determine ^{137}Cs–activity in fruiting bodies of 101 species (Table 2). The currently valid names of mushrooms including author names are listed according to the Index Fungorum (www.indexfungorum.org), and the edibility of the species is indicated according to the World of Mushrooms of Ukraine (http://gribi.net.ua).

Table 2. List of the studied species (edibility of mushrooms species are given according to http://gribi.net.ua)

	Species, Author	Edibility
1	*Agaricus sylvaticus* Schaeff.	Edible
2	*Amanita citrina* Pers.	Poisonous
3	*Amanita fulva* Fr.	Edible
4	*Amanita muscaria* (L.) Lam.	Poisonous
5	*Amanita panterina* (DC.) Krombh.	Poisonous
6	*Amanita phalloides* (Vaill. ex. Fr.) Link	Poisonous
7	*Amanita rubescens* Pers.	Edible
8	*Amanita vaginata* (Bull.) Lam.	Edible
9	*Ampulloclitocybe clavipes* (Pers.) Redhead, Lutzoni, Moncalvo & Vilgalys	Edible
10	*Apioperdon pyriforme* (Schaef.) Vizzini	Edible
11	*Armillaria mellea* (Vahl) P. Kumm.	Edible
12	*Aspropaxillus giganteus* (Sowerby) Kühner & Maire	Edible
13	*Boletus edulis* Bull.	Edible
14	*Cantharellus cibarius* Fr.	Edible
15	*Cerioporus squamosus* (Huds.) Quél.	Edible
16	*Chlorophyllum rhacodes* (Vittad.) Vellinga	Edible
17	*Clitocybe infundibuliformis* (Schaeff.)Quél.	Edible
18	*Clitocybe nebularis* (Batsch) P. Kumm.	Edible
19	*Clitocybe rivulosa* (Pers.) P. Kumm.	Poisonous
20	*Coltricia perennis* (L.) Murrill	Inedible
21	*Cortinarius caerulescens* (Schaeff.) Fr.	Edible
22	*Cortinarius caperatus* (Pers.) Fr.	Edible
23	*Cortinarius duracinus Fr.*	Inedible
24	*Cortinarius olivaceofuscus* Kühner	Edibility unknown
25	*Cortinarius praestans* (Cordier) Gillet	Edible
26	*Cortinarius semisanguineus* (Fr.) Gillet	Poisonous
27	*Cortinarius subferrugineus* (Batsch) Fr.	Inedible
28	*Cortinarius trivialis* J.E. Lange	Inedible
29	*Cortinarius venetus* (Fr.) Fr.	Inedible
30	*Cystoderma amianthinum* (Scop.) Fayod	Conditionally edible
31	*Fistulina hepatica* (Schaeff.) With.	Edible
32	*Fomitopsis betulina* (Bull.) B.K. Cui, M.L. Han & Y.C. Dai	Inedible
33	*Gomphidius glutinosus* (Schaeff.) Fr.	Edible
34	*Gymnopilus junonius* (Fr.) P.D. Orton	Inedible
35	*Hortiboletus rubellus* (Krombh.) Simonini, Vizzini & Gelardi	Edible
36	*Hygrophoropsis aurantiaca* (Wulfen) Maire	Inedible
37	*Hygrophorus eburneus* (Bull.)Fr.	Edible
38	*Hypholoma capnoides* (Fr.) P.Kumm.	Edible
39	*Hypholoma fasciculare* (Huds.) P. Kumm.	Poisonous
40	*Hypholoma lateritium* (Schaeff.) P. Kumm.	Inedible
41	*Imleria badia* (Fr.) Vizzini	Edible
42	*Kuehneromyces mutabilis* (Schaeff.) Singer & A.H. Sm.	Edible
43	*Laccaria laccata* (Scop) Cooke	Edible
44	*Laccaria proxima* (Boud.) Pat.	Edible

45	*Lactarius deliciosus* (L.) Gray	Edible
46	*Lactarius helvus* (Fr.) Fr.	Inedible
47	*Lactarius rufus* (Scop.) Fr.	Conditionally edible
48	*Lactarius turpis* (Weinm.) Fr.	Conditionally edible
49	*Lactifluus piperatus* (L.) Russel	Conditionally edible
50	*Lactifluus vellereus* (Fr.) Kuntze	Conditionally edible
51	*Leccinum aurantiacum* (Bull.) Gray	Edible
52	*Leccinum scabrum* (Bull.) Gray	Edible
53	*Leucocybe connata* (Schumach.) Vizzini, P. Alvarado, G. Moreno & Consiglio	Edible
54	*Lycoperdon perlatum* Pers.	Edible
55	*Macrolepiota procera* (Scop.) Singer	Edible
56	*Mutinus caninus* (Schaeff.) Fr.	Inedible
57	*Neolentinus lepideus* (Fr.) Redhead & Ginns	Edible
58	*Paralepista flaccida* (Soerby) Vizzini	Poisonous
59	*Paxillus involutus* (Batsch) Fr.	Poisonous
60	*Phlegmacium glaucopus* (Schaeff.) Wünsche	Edible
61	*Pholiota squarrosa* (Vahl.) P. Kumm.	Conditionally edible
62	*Pluteus cervinus* (Schaeff.) P. Kumm.	Edible
63	*Psathyrella cotonea* (Quél.) Konrad & Maubl.	Inedible
64	*Ramaria aurea* (Schaeff.) Quél.	Conditionally edible
65	*Ramaria flava* (Schaeff.) Quél.	Inedible
66	*Ramaria stricta* (Pers.) Quél.	Inedible
67	*Rhodocollybia butyraceae* (Bull.) Lennox	Edible
68	*Rhodocollybia maculata* (Alb. & Schwein.) Singer	Inedible
69	*Rhodocollybia prolixa* (Fr.) Antonin & Noordel.	Edible
70	*Russula adusta* (Pers.) Fr.	Conditionally edible
71	*Russula aeruginea* Lindblad ex Fr.	Edible
72	*Russula amethystina* Quél.	Edible
73	*Russula cyanoxantha* (Schaeff.) Fr.	Edible
74	*Russula emetica* (Schaeff.) Pers.	Inedible
75	*Russula foetens* Pers.	Conditionally edible
76	*Russula integra* (L.) Fr.	Edible
77	*Russula vesca* Fr.	Edible
78	*Russula vinosa* Lindblad	Edible
79	*Russula ochroleuca* Fr.	Edible
80	*Russula queletii* Fr.	Inedible
81	*Russula xerampelina* (Schaeff.) Fr.	Edible
82	*Sarcodon imbricatus* (L.) P. Karst.	Edible
83	*Scleroderma verrucosum* (Bull.) Pers.	Poisonous
84	*Sparassis crispa* (Wulfen) Fr.	Edible
85	*Stropharia aeruginosa* (Curtis) Quél.	Edible
86	*Suillellus luridus (*Schaeff.*) Murrill*	Conditionally edible
87	*Suillus bovinus* (L.) Roussel	Edible
88	*Suillus granulatus* (L.) Roussel	Edible
89	*Suillus grevillei* (Klotzsch) Singer	Edible
90	*Suillus luteus* (L.) Roussel	Edible
91	*Tapinella atrotomentosa* (Batsch) Šutara	Conditionally edible
92	*Trametes versicolor* (L.) Lloyd	Inedible
93	*Tricholoma equestre* (L.) P. Kumm.	Edible
94	*Tricholoma fulvum* (DC.) Bigeard & H. Guill.	Edible
95	*Tricholoma portentosum* (Fr.) Quél.	Edible
96	*Tricholoma saponaceum* (Fr.) P. Kumm.	Inedible
97	*Tricholoma terreum* (Schaeff.) P. Kumm.	Edible
98	*Tricholomopsis rutilans* (Schaeff.) Singer	Conditionally edible
99	*Tylopilus felleus* (Bull.) P. Karst.	Inedible
100	*Xerocomellus chrysenteron* (Bull.) Šutara	Edible
101	*Xerocomus subtomentosus* (L.) Quél.	Edible

Every sample was analyzed during 6–36 h (the sample measurement time depended on its activity; with weak activity, the measurement time increases). The measurement error (CV, %) of ^{137}Cs was usually less than 10% and processed with the use of Win spectrum program (https://winspectrum.software.informer.com/).

To assess the activity of radionuclide accumulation by fruiting bodies, we calculated the bioconcentration factor (BCF), which is equal to the ratio of the activity of the radionuclide in the mushroom sample to its activity in the soil of the relevant habitat (Falandysz & Borovička, 2013). For estimation of the potential risk to human health, the possible average dose of internal irradiation was calculated according to the formula:

$$H_{int} = c \times d_{int} \times e \times k$$

Where

H_{int} – dose of internal irradiation; c – specific activity of ^{137}Cs in Bq/kg of crude weight, d_{int} – the dose conversion coefficient for adult intake (age 20 and older, 1.3 x 10^{-5} mSv/Bq for ^{137}Cs); e – estimated volume of annual consumption of mushrooms, kg (5 kg per person per year); k – coefficient of culinary processing (0.5) (Shabaleva et al., 2014; Orita et al., 2018; Grodzinskaya et al., 2022).

3. Results and discussion

Predictive estimation of the uptake of radiocaesium by living organisms in Ukraine is complicated due to the mosaic and extremely heterogeneous nature of contamination (20 years..., 2006). Some mushroom species are characterized by the phenomenon of accumulation and even hyper-accumulation of radiocaesium (Grodzinskaya et al., 2003; 2013). This feature not only allows them to be used for bioindication of radioactive contamination of the territory, but also to assess the potential danger of consuming these and other species of culinary – medicinal mushrooms in this territory (Haselwandter et al., 1988; Fraiture et al., 1990; Grodzinskaya et al., 2011, 2019; Kalač, 2012; Caridi et al., 2017). Radioecological monitoring of Ukrainian mushrooms has shown that some samples from the Chernobyl exclusion zone and from locations adjacent to it remained highly contaminated throughout the post-accident period, in some cases reaching 10^5–10^7 Bq/kg dry mass (Grodzinskaya et al., 1995, 2003, 2013). Analysis of the literature and author's data enabled the grouping of complex factors to determine the degree of radioactive contamination of mushrooms: atmospheric pollution, dust transfer, meteorological factors (precipitation, wind direction), soil radionuclide contamination gradient, pH, humidity, physical and chemical composition of soil, soil type, the time since accident, microclimatic conditions, landscape features (Kalač, 2012; Grodzynska, 2017; Gabriel et al., 2023). In addition to these factors, biological factors are also extremely important – depth of mycelium in the soil layer (Kalač, 2001), differences in accumulation between above-ground parts of fruiting bodies (Heinrich, 1992), mycosymbiotrophic interaction (Steiner et al., 2002), species specificity of accumulation (Haselwandter & Berreck, 1994, Falandysz & Borovička, 2013), ecological confinement of species (Wasser & Grodzinskaya, 1993; Yoshida & Muramatsu, 1994), stage of development of the fruiting bodies (Baeza et al., 2006).

In the first post-Chernobyl period, the maximum activity of radiocaesium was found in the fruiting bodies of mycorrhizal species – *L. helvus* – up to 150,689, *I. badia* – 65,183, *P. involutus* – 40,799, *B. edulis* – 27,994, and *X. chrysenteron* – 20,054 Bq/kg dry mass, respectively, and bioconcentration factors (BCFs) reached two orders of magnitude (Table 3) (Wasser & Grodzinskaya, 1993; Wasser, ed., 2012). It should be noted that during this period ^{137}Cs ($T_{1/2}$-30.07 years), ^{134}Cs ($T_{1/2}$-2.06 years) were also found in samples, but since 1998, ^{134}Cs has no longer been detected in the fruiting bodies of mushrooms. Minimum levels of BCFs (<1) were recorded mainly in xylotrophs, humus saprotrophs and litter saprotrophs – *F. betulina, H. lateritium, L. perlatum, C. perennis*, and *M. procera*, the only exception is xylotroph *T. atrotomentosa*, which demonstrates both high accumulation levels of radiocaesium – up to 89,095 Bq/kg dm, and high BCF (up to 215.56). It should be noted that in Ukraine the maximum permissible levels (PL) for dry mushrooms are 2,500 Bq/kg dry mass (Permissible levels, 1997). In the period 1990–1996, 59.57% of mushroom samples from these sampling sites in the Vyshhorod district exceeded this level.

Table 3. Activity of radiocaesium (^{134}Cs and ^{137}Cs) in fruiting bodies of Wild mushrooms from the Vyshhorod district in 1990–1996

Year, sampling site, species	^{134}Cs (604 KeV, 795 KeV)	BCF, ^{134}Cs	^{137}Cs	BCF, ^{137}Cs
1990				
NEAR THE VILLAGE OF LEBEDIVKA				
Cantharellus cibarius	549+561	1.97, 1.25	4,196	4.88
Cantharellus cibarius	251+249	0.90, 0.55	2,078	2.42
Fomitopsis betulina	BDL		152	0.18
Soil	279+450		859	
NEAR THE VILLAGE OF PIRNOVE				
Leccinum scabrum	2,416+2,689		18,541	
Ramaria aurea	299+215		1,887	
1991				
NEAR THE CITY OF VYSHHOROD				
Ramaria stricta	135+213	7.11, 9.68	1,867	7.91
Soil	19+22		236	
NEAR THE VILLAGE OF KATYUZHANKA				
Xerocomellus chrysenteron	970+989	1.29, 1.16	11,133	1.42
Soil	754+853		7,831	
NEAR THE VILLAGE OF LYUTIZH				
Amanita pantherina	361+348	3.05, 1.77	3,162	1.69
Amanita rubescens	520+426	3.1,2.16	5,677	3.03
Clitocybe infundibuliformis	284+312	1.69, 1.58	3,397	1.81
Coltricia perennis	BDL		1,099	0.59
Lycoperdon perlatum	87+141	0.52, 0.72	1,107	0.59
Ramaria stricta	102+139	0.61, 0.71	1,368	0.73
Russula foetens	420+497	2.5,2.52	5,397	2.88
Russula integra	108+117	0.54, 0.59	1,276	0.68
Russula vinosa	256+254	1.52, 1.29	3,199	1.71
Scleroderma verrucosum	860+1011	5.12, 5.13	15,190	8.11
Suillus luteus	902+1142	5.37,5.8	5,677	3.03
Tapinella atrotomentosa	353+356	2.1,1.81	3,868	2.07
Tricholomopsis rutilans	978+1248	5.82, 6.34	11,598	6.19
Xerocomellus chrysenteron	1465+2027	8.72,10.29	20,054	10.71
Soil*	168+197		1,873	
1992				
NEAR THE VILLAGE OF LEBEDIVKA				
Mutinus caninus	92	1.56	310	1.38
Soil	59		225	
NEAR THE CITY OF VYSHHOROD, VODOGIN				
Boletus edulis	86	4.53	841	5.01
Soil	19		168	
1993				
NEAR THE CITY OF VYSHHOROD, VODOGIN				
Hypholoma fasciculare	BDL		376	2.09
Soil	17.9		180	
1996				
NEAR THE VILLAGE OF LYUTIZH				
Hypholoma lateritium	1.7	0.4	651	0.66
Lactarius helvus	47.7	11.09	150,689	153.45
Macrolepiota procera	BDL		833	0.85
Paxillus involutus	24.7	5.74	40,799	41.55
Soil	4.3		982	
Boletus edulis	16	6.4	27,994	173.88
Clitocybe nebularis	BDL		565	3.51
Lactarius helvus	114	45.6	137,634	854,87
Lycoperdon perlatum	BDL		566	3.52
Soil	2.5		161	

In 1998, the highest levels of radiocaesium activity were found in *C. praestans* – 210,210 Bq/kg dm (BCF – 16.3) (exceeding the permissible level reached 84–fold!), *P. involutus* – 126,525 (BCF – 9.81), *L. rufus* – 117,200 (BCF – 9.09), *S. luridus* – 108,757 Bq/kg dm (BCF – 8.43). In general, in 1998, 73.91% of mushroom samples exceeded the PL (Table 4).

In 1999, the highest levels of ^{137}Cs–activity were found in *L. helvus* – 127,770 (BCF – 101.4), *I. badia* – 77,120 (BCF – 94.05), *C. praestans* – 65.442 (BCF – 186.98), *X. chrysenteron* – 41,510 (BCF – 118.6), and *P. involutus* – 41,380 (BCF – 79.58). It should be noted not only significant differences in the levels of contamination of fruiting bodies of the same species collected in different localities, but also in one locality (for example, near the village of Lyutizh) – in *X. chrysenteron* the differences reached 461–fold, in the case of *I. badia* – about 29–fold. 55.10% of mushroom samples exceeded the PL.

In 2000, an excess of PL was recorded in 61.67% of mushroom samples. The highest levels of ^{137}Cs–activity were recorded in *L. rufus* – 146,000 (BCF – 41.48), *I. badia* – 97,700 (BCF – 27.76), and *P. involutus* – 96,000 Bq/kg dm (BCF – 27.27). In some species (*L. perlatum, F. betulina*), radiocaesium activity was below the detection limit (BDL).

In 2001, the highest levels of ^{137}Cs–activity were found in *L. rufus* – 143,213 (BCF – 57.86), *S. luteus* – 81,260 (BCF – 73.61), *P. involutus* – 58,664 (BCF – 53.14), *I. badia* – 57,032 Bq/kg dm (BCF – 27.18). Also, significant differences in the levels of contamination in the same species were noted at the same sampling site near the village of Katyuzhanka: in *A. muscaria, P. involutus* and *X. chrysenteron* samples were more than 63, 12 and 5–fold different, respectively. At the sampling site near the village of Lyuthizh, for *A. pantherina, A. citrina*, and *I. badia* these differences were more than 15, 6, and 3–fold different, respectively. That year the excess of Permissible Levels was found in 48% mushroom samples.

In 2002, the highest activities of ^{137}Cs were found in *P. involutus* (up to 40,005 Bq/kg dm, BCF – 13.84), *C. venetus* – 21,116 (BCF – 12.56), *T. equestre* – 19,732 (BCF – 19.06), and *I. badia* – 18,448 Bq/kg dm (BCF – 11.07). Differences in the levels of contamination of the same species, within the same sampling site, were reached in *S. aeruginosa* – 20.9, in *I. badia* – 5.5, and *X. chrysenteron* 5.3–fold (near the village of Katyuzhanka). The activity of ^{137}Cs in 50% of mushroom samples exceeded the PL.

In 2004, the most abundant radiocaesium contamination was found in *C. praestans* – 269,692 (BCF – 226.44), *A. clavipes* – up to 49,581 (BCF – 41.63), *L. rufus* – 35,694 (BCF – 29.97), and *P. involutus* – 32,851 Bq/kg dm (BCF – 27.58). It can be noted that along with the species of *Lactarius* genus (*L. helvus, L. rufus*), *Cortinarius* spp. also exhibits hyper-accumulating properties in relation to radiocaesium. Other authors also reported increased levels of radiocaesium in representatives of Cortinariaceae (Haselwandter et al., 1988; Klán et al., 1988; Yoshida & Muramatsu, 1994; Grodzinskaya et al., 2003, 2011, 2023; Zalewska et al., 2016; Gabriel et al., 2023). In particular, Falandysz et al. (2019) attribute the capacity of *C. caperatus* to be an effective bioconcentrator of ^{137}Cs from contaminated soil substrata to the phenomenon of gradual leaching of ^{137}Cs into the lower layers of surface soils and the ability of mycelium of this species to penetrate to relatively greater depths, which may be the cause of persistent high activity values. In 2004, 60% of mushroom samples exceeded the PL.

In 2005, the highest radiocaesium levels were found in *L. rufus* – 122,424 Bq/kg dm (BCF – 93.38), *I. badia* – 31,410 (BCF – 23.98), and *A. clavipes* – 28,105 (BCF –14.51). In general, 61.9% of mushroom samples were in excess of PL in this year. High levels of radiocaesium contamination during all periods of investigations were found in *I. badia* (Boletaceae). This species, being an active accumulator of ^{137}Cs and other radionuclides, is at the same time quite common and massively harvested not only in Ukraine, but also in some European countries, which explains the increased interest in it (Mietelski et al., 1994; Grodzinskaya et al., 2003; Malinowska et al., 2006; Harkut et al., 2021; Ernst et al., 2022; Ronda et al., 2022).

In 2006, 60.9% of samples exceeded the PL. The highest levels of radiocaesium were detected in *L. helvus* – 152,312 (BCF – 96.46), *R. emetica* – 65,993 (BCF – 41.79), *L. rufus* – 49,036 (BCF – 31.06), and *R. ochroleuca* – 18,717 Bq/kg dm (BCF – 11.85). An unusually high level of radiocaesium was measured in the *M. procera* sample – 12,000 Bq/kg dm, the fruiting bodies of which were collected directly next to the roadway.

In 2007, the highest levels of radiocaesium were found in *P. involutus* – up to 71,086 Bq/kg dm (BCF – 76.11), *L. rufus* – 38,858 (BCF – 41.60), and in *I. badia* – 19,843 (BCF – 21.25). It was noted that 72.22% of the mushroom samples exceeded PL.

In 2008, only 35.29% of the mushroom samples exceeded the PL. The highest levels of radiocaesium activity were recorded in *L. rufus* – 59,193 (BCF – 55.84), *L. piperatus* – 49,118 (BCF – 46.34), *T. equestre* – 46,309 (BCF – 44.69), and *P. involutus* – 44,154 Bq/kg dm (BCF – 41.65).

In 2010, there was an obvious decrease in radiocaesium accumulation levels, the highest activity values were found in *T. portentosum* – 5,660 Bq/kg dm and *T. equestre* – 5,587 Bq/kg dm. It should be noted that, as observed in previous years, the increased levels in *A. clavipes* (Tricholomataceae) may obviously indicate a high accumulating capacity in some representatives of this family to radiocaesium.

As an exception, in 2010 we determined the levels of radiocaesium contamination in different parts of the fruiting body of *B. edulis*. A comparison of the data obtained showed that the cap accumulated approximately 2–fold more radiocaesium than the stipe and cuticle of the cap (Table 4). In this year an excess of PL was recorded in 42.86% of mushroom samples.

In 2013, the highest levels of ^{137}Cs were found in the fruiting bodies of *C. semisanguineus* – 95,623 (BCF – 41.04), *L. rufus* – 63,938 (BCF – 27.44), and *T. fulvum* – 37,732 Bq/kg dm (BCF – 16.19).

Considering that these samples were collected in one locality (near the village of Rudnya Talska) and 80% of the samples exceeded the PL, this may indicate the need for additional radioecological monitoring of forest products in this area.

There also remains a danger from the consumption of mushrooms collected near the village of Katyuzhanka, where, in 2018, 66.67% of mushroom samples exceeded the PL, and the maximum levels of radiocaesium activity were recorded in *C. caperatus* – 26,378 (BCF – 28.73) and *S. granulatus* – 12,864 Bq/kg dm (BCF – 14.01).

In 2020, the highest levels of radiocaesium were found in *T. fulvum* – 40,800 (BCF – 37.85), *C. olivaceofuscus* – 36,418 (BCF – 46.69), *C. duracinus* – 31,526 (BCF – 68.68), and *C. subferrugineus* – 27,934 Bq/kg dm (BCF – 188.68). Permitted limits were exceeded in 49.28% of mushroom samples. As in previous years, significant differences remain in the ^{137}Cs–activity in mushrooms of the same species collected in the same location (differences reached 14.3–fold in *C. olivaceofuscus* and 7,2–fold in *C. praestans*) and even from the same sampling site (in *R. cyanoxantha* – 29.3–fold) (samples collected near the village of Sukholuchchya).

In 2021, the highest levels of radiocaesium were found in *C. subferrugineus* – 86,729 (BCF – 172.08), *S. imbricatus* – 64,737 (BCF – 44.65), – 26,946 (BCF – 53.46), *C. olivaceofuscus* – 24,655 (BCF – 17.0), *I. badia* – 21,439 (BCF – 14.79). Our previous studies have show high ^{137}Cs–activity in the mycorrhizal species *S. imbricatus* (up to 464,800 Bq/kg dm) from Drevlyanskyi Nature Reserve, a territory adjacent to the Chernobyl zone, as well as in other locations (Grodzinskaya et al., 2022, 2023). Half of the mushroom from the sampling localities exceeded the PL in radiocaesium activity.

Data presented here and our previous data demonstrate significant differences in the levels of contamination of macromycetes, observed in the same species not only from different localities, but also within the same one (Grodzynska, 2017; Grodzinskaya et al., 2022; Gabriel et al., 2023). Obviously, this phenomenon is associated with the extremely heterogeneous character of soil contamination (which apparently persists throughout the post-Chernobyl period), and microclimatic conditions.

At the same time, in the process of long-term monitoring, significant changes in the BCF levels for each species were also recorded (Fig. 2). In addition to biological features (in particular, the depth of the mycelium in the soil layers), these changes can also be related to the specific radioecological situation at the collection point and to complex of reasons. To establish the reliable dynamics of the BCF change of each species during the post-accident period, additional research is needed.

To assess the overall bioaccumulation capacity of macromycetes, the geometric mean values of BCF of various species from the studied localities of the Vyshhorod district were calculated (Table 5).

For valuable culinary-medicinal species, with a fairly large scatter of BCF values for all years, geometric mean BCF values were established, which make it possibile to assess the potential danger from their consumption. Thus, the geometric mean value of BCF for *B. edulis* is 3.49 (with a spread of BCF values from 1.01 up to 173.88), *I. badia* – 10.51 (from 0.85 up to 157.83), *S. luteus* – 15.02 (from 3.03 up to 73.61), *L. scabrum* – 6.76 (from 0.14 up to 34.10), *X. chrysenteron* – 4.02 (from 0.19 up to 118.6), *C. cibarius* – 2.76 (from 0.84 up to 14.15), *C. caperatus* – 25.22 (from 7.41 up to 57.76), and *T. equestre* (from 3.22 up to 43.69).

Table 4. Activity of ^{137}Cs (Bq/kg dm) in fruiting bodies of wild mushrooms from the Vyshhorod district between 1998–2021

Year, sampling site	^{137}Cs	BCF	Year, sampling site	^{137}Cs	BCF
1998			**2004 continued**		
NEAR THE VILLAGE OF KATYUZHANKA			*Tricholoma equestre*	9,053	7.6
Armillaria mellea	11,268	0.89	Soil	1,191	
Boletus edulis	13,697	1.08	*Gomphidius glutinosus*	8,998	10.16
Imleria badia	29,944	2.37	*Gymnopilus junonius*	1,315	1.48
Leccinum scabrum	1,714	0,14	*Hypholoma fasciculare*	1,099	1.24
Xerocomellus chrysenteron	21,323	1.69	*Imleria badia*	10,380	11.72
Soil	12,644		*Laccaria laccata*	13,831	15.61
NEAR THE VILLAGE OF LYUTIZH			*Laccaria proxima*	908	1.02
Amanita citrina	9,602	8.45	*Lycoperdon perlatum*	372	0.42
Amanita muscaria	1,578	1.39	*Macrolepiota procera*	152	0.17
Amanita phalloides	80,564	70.98	*Pluteus cervinus*	1,158	1.31
Amanita rubescens	1,756	1.55	*Tapinella atrotomentosa*	21,189	23.92
Apioperdon pyriforme	BDL		*Xerocomellus chrysenteron*	2,996	3.38
Fomitopsis betulina	BDL		*Xerocomellus chrysenteron*	10,889	12.29
Lactarius deliciosus	23,499	20,67	Soil	886	
Lactarius turpis	21,746	19.16	**2005**		
Lycoperdon perlatum	645	0.57	NEAR THE VILLAGE OF LEBEDIVKA		
Macrolepiota procera	582	0.51	*Amanita muscaria*	2,987	1.49
Paxillus involutus	39,489	34.8	*Lactarius turpis*	3,766	1.88
Russula cyanoxantha	9,479	8.35	*Trametes versicolor*	336	0.17
Russula xerampelina	17,978	15.84	Soil	1,999	
Soil	1,135		*Fomitopsis betulina*	570	5.0
Clitocybe infundibuliformis	24,852	2.42	Substrate	114	
Imleria badia	37,305	3.63	*Fomitopsis betulina*	352	1.68
Lactarius rufus	26,028	2,53	Substrate	210	
Lycoperdon perlatum	14	0.001	NEAR THE VILLAGE OF PIRNOVE		
Xerocomellus chrysenteron	13,396	1.3	*Amanita fulva*	5,938	3.07
Soil	10,275		*Amanita muscaria*	3,976	2.05
Boletus edulis	5,425	1.53	*Ampulloclitocybe clavipes*	28,105	14.51
Imleria badia	50,185	14.12	*Hygrophorus eburneus*	5,024	2.59
Lactarius rufus	31,706	8.92	*Imleria badia*	10,424	5.38
Paxillus involutus	35,943	10.11	*Russula aeruginea*	2,080	1.07
Pholiota squarrosa	1,537	0.43	*Russula foetens*	14,625	7.55
Ramaria flava	194	0.05	*Russula xerampelina*	1,800	0.93
Russula xerampelina	25,676	7.22	Soil	1,937	
Soil	3,554		NEAR THE VILLAGE OF SUVYDY		
NEAR THE VILLAGE OF NOVOSILKY			*Amanita citrina*	7,295	5.56
Cantharellus cibarius	12,213	1.09	*Cortinarius praestans*	11,758	8.97
Cerioporus squamosus	BDL		*Imleria badia*	31,410	23.98
Paralepista flaccida	1,172	0.10	*Lactarius rufus*	122,424	93.38
Soil	11,241		*Russula adusta*	21,161	16.14
Amanita citrina	104,794	8.13	*Russula foetens*	1,205	0.92
Amanita muscaria	9,081	0.7	*Russula xerampelina*	1,694	1.29
Amanita rubescens	20,042	1.6	Soil	1,311	
Boletus edulis	17,555	1.4	*Fistulina hepatica*	1,882	2.64
Cortinarius caperatus	210,210	16.3	Substrate	712	
Lactarius helvus	12,273	0.95	**2006**		
Lactarius rufus	117,200	9.09	NEAR THE VILLAGE OF KATYUZHANKA		
Lactarius turpis	36,430	2.83	*Amanita citrina*	9,879	6.26
Lycoperdon perlatum	2,679	0.21	*Amanita muscaria*	754	0.48
Paxillus involutus	126,525	9.81	*Amanita muscaria*	2,119	1.34
Suillellus luridus	108,757	8.43	*Amanita rubescens*	2,352	1.49
Tapinella atrotomentosa	33,170	2.57	*Cortinarius trivialis*	7,932	5.02
Russula xerampelina	37,864	2.94	*Fomitopsis betulina*	529	0.34
Soil	12,894		*Hypholoma fasciculare*	7,850	4.97
1999			*Lactarius helvus*	152,312	96.46
NEAR THE VILLAGE OF KATYUZHANKA			*Lactarius rufus*	49,036	31.06

Amanita muscaria	1,250	0.99
Lactarius helvus	127,770	101.4
Lactarius rufus	24,500	19.44
Lactarius turpis	24,980	19.83
Leccinum scabrum	40,660	32.27
Macrolepiota procera	100	0.08
Russula adusta	2,260	1.79
Russula cyanoxantha	250	0.20
Russula emetica	3,550	2.82
Xerocomellus chrysenteron	6,730	5.34
Soil	1,260	
NEAR THE VILLAGE OF LEBEDIVKA		
Imleria badia	77,120	94.05
Paxillus involutus	5,016	6.12
Suillus luteus	13,650	16.65
Soil	820	
Amanita pantherina	3,030	0.46
Soil	6,650	
Amanita muscaria	4,790	4.24
Soil	1,130	
Lactarius turpis	14,150	42.88
Soil	330	
NEAR THE VILLAGE OF LYUTIZH		
Amanita muscaria	980	2.80
Amanita pantherina	120	0.34
Amanita rubescens	800	2.29
Cortinarius praestans	65,442	186.98
Imleria badia	24,780	70.8
Lactarius rufus	2,110	6.03
Macrolepiota procera	280	0.8
Paxillus involutus	30,340	86.69
Xerocomellus chrysenteron	41,510	118.6
Soil	350	
Chlorophyllum rhacodes	7,690	6.57
Soil	1,170	
Amanita rubescens	5,050	10.75
Imleria badia	990	2.11
Lactarius helvus	4,570	9.72
Xerocomellus chrysenteron	90	0.19
Soil	470	
Amanita muscaria	890	1.71
Amanita pantherina	1,660	3.19
Imleria badia	28,470	54.75
Lactarius helvus	5,430	10.44
Macrolepiota procera	581	1.12
Paxillus involutus	41,380	79.58
Xerocomellus chrysenteron	4,870	9.37
Soil	520	
NEAR THE VILLAGE OF NOVOSILKY		
Boletus edulis	1,010	1.4
Cantharellus cibarius	1,690	2.35
Cortinarius caperatus	36,670	50.93
Hortiboletus rubellus	140	0.19
Lactarius helvus	2,490	3.46
Leccinum scabrum	13,430	18.65
Lycoperdon perlatum	900	1.25
Russula ochroleuca	990	1.38
Tapinella atrotomentosa	38,370	53.29
Xerocomellus chrysenteron	4,170	5.79
Xerocomus subtomentosus	1,490	2.07
Soil	720	
Leccinum scabrum	10,650	6.74
Russula aeruginea	11,055	7.0
Russula emetica	65,993	41.79
Russula ochroleuca	18,717	11.85
Russula xerampelina	2,702	1.7
Tylopilus felleus	15,317	9.7
Xerocomus subtomentosus	9,016	5.71
Xerocomus subtomentosus	7,680	4.86
Soil	1,579	
NEAR THE VILLAGE OF LEBEDIVKA		
Chlorophyllum rhacodes	86	0.05
Macrolepiota procera (at the road side)	16,820	9.34
Paxillus involutus	2,147	1.19
Soil	1,800	
NEAR THE VILLAGE OF ROVZHY		
Chlorophyllum rhacodes	94	0.11
Soil	890	
2007		
NEAR THE VILLAGE OF ABRAMIVKA		
Amanita muscaria	9,486	10.16
Armillaria mellea	377	0.4
Fomitopsis betulina	521	0.56
Hypholoma fasciculare	569	0.61
Imleria badia	9,060	9.7
Paxillus involutus	16,275	17.43
Paxillus involutus	71,086	76.11
Soil	934	
Imleria badia	19,843	21.25
Lactarius rufus	38,858	41.60
Paxillus involutus	41,419	44.35
Russula ochroleuca	8,856	9.48
Soil	1,194	
NEAR THE CITY OF DYMER		
Chlorophyllum rhacodes	1,047	0,86
Clitocybe nebularis	774	0.64
Paxillus involutus	51,151	45.43
Soil	1,214	
NEAR THE VILLAGE OF KATYUZHANKA		
Leccinum scabrum	6,615	3.89
Paxillus involutus	9,658	5.68
Russula ochroleuca	5,082	2.99
Xerocomellus chrysenteron	8,819	5.19
Soil	1,699	
2008		
NEAR THE SETTLEMENT OF DYMER		
Armillaria mellea	391	0.45
Boletus edulis	2,291	2.66
Xerocomellus chrysenteron	1,061	1.23
Soil	860	
Amanita citrina	222	0.21
Amanita muscaria	2,269	2.19
Armillaria mellea	665	0.64
Clitocybe nebularis	174	0.17
Fomitopsis betulina	1,206	1.16
Hygrophoropsis aurantiaca	1,676	1.62
Neolentinus lepideus	1,182	1.14
Paxillus involutus	13,730	13.25
Suillus granulatus	748	0.72
Soil	1,036	
Amanita fulva	153	0.09
Clitocybe nebularis	4,588	2.8

NEAR THE VILLAGE OF V. DUBECHNYA		
Amanita muscaria	1,050	4.38
Soil	240	
2000		
NEAR THE VILLAGE OF HOTYANIVKA		
Imleria badia	4,780	6.42
Lycoperdon perlatum	BDL	
Macrolepiota procera	720	0.97
Soil	744	
NEAR THE VILLAGE OF KATYUZHANKA		
Amanita citrina	2,980	1.58
Amanita muscaria	2,340	1.28
Amanita pantherina	2,860	1.56
Fomitopsis betulina	BDL	
Imleria badia	70,600	38.58
Leccinum scabrum	62,400	34.1
Paxillus involutus	1,470	0.8
Russula aeruginea	743	0.41
Russula ochroleuca	5,460	2.98
Suillus bovinus	9,269	5.07
Soil	1,830	
Amanita citrina	1,500	2.06
Armillaria mellea	7,370	10.12
Boletus edulis	7,020	9.64
Imleria badia	11,300	15.52
Lactarius rufus	28,900	39.7
Lycoperdon perlatum	397	0.55
Russula cyanoxantha	2,790	3.83
Suillus luteus	29,100	39.97
Soil	728	
NEAR THE VILLAGE OF LYUTIZH		
Amanita muscaria	3,630	8.64
Amanita pantherina	4,370	10.4
Amanita rubescens	192	0.46
Clitocybe infundibuliformis	90	0.21
Coltricia perennis	BDL	
Imleria badia	25,900	61.7
Paxillus involutus	45,700	108.81
Russula aeruginea	2,930	6.98
Suillus luteus	11,100	26.43
Soil	420	
Imleria badia	23,000	6.08
Imleria badia	32,600	8.62
Lycopedron perlatum	BDL	
Paxillus involutus	93,800	24.81
Russula xerampelina	2,920	0.77
Suillus luteus	31,300	8.28
Soil	3,780	
Aspropaxillus giganteus	1,420	0.4
Clitocybe infundibuliformis	2,490	0.71
Clitocybe nebularis	1,339	0.38
Imleria badia	97,700	27.76
Lactarius rufus	146,000	41.48
Lycoperdon perlatum	BDL	
Macrolepiota procera	2,800	0.8
Paxillus involutus	96,000	27.27
Suillus luteus	11,900	3.38
Tricholomopsis rutilans	47,600	13.52
Soil	3,520	
Amanita citrina	11,000	16.74
Amanita pantherina	2,780	4.23
Aspropaxillus giganteus	1,870	2.85
Clitocybe rivulosa	239	0.15
Hypholoma fasciculare	764	0.47
Imleria badia	2,242	1.37
Imleria badia	1,540	0.94
Stropharia aeruginosa	420	0.26
Soil	1,638	
NEAR THE VILLAGE OF LYUTIZH		
Imleria badia	6,890	7.14
Macrolepiota procera	BDL	
Soil	1,638	
NEAR THE VILLAGE OF SUKHOLUCHCHYA		
Amanita muscaria	1,758	1.66
Boletus edulis	2,584	2.44
Cortinarius trivialis	10,102	9.53
Imleria badia	25,774	24.32
Laccaria laccata	789	0.74
Lactarius rufus	59,193	55.84
Lactifluus piperatus	49,118	46.34
Paxillus involutus	44,154	41.65
Russula aeruginea	746	0.7
Russula xerampelina	15,264	14.4
Sarcodon imbricatus	36,865	34.78
Tricholoma equestre	46,309	43.69
Tricholoma portentosum	3,007	2.84
Soil	1,060	
2010		
NEAR THE SETTLEMENT OF DYMER		
Armillariella mellea	140	
NEAR THE VILLAGE OF KATYUZHANKA		
Boletus edulis	2,604	3.03
Soil	860	
Boletus edulis (cuticula)	3,257	3.57
Boletus edulis (cap)	6,429	7.05
Boletus edulis (stipe)	3,196	3.50
Soil	912	
NEAR THE VILLAGE OF LYUTIZH		
Cortinarius olivaceofuscus	2,020	2.20
Hygrophoropsis aurantiaca	694	0.76
Macrolepiota procera	430	0.47
Tricholoma equestre	5,587	5.09
Tricholoma portentosum	5,660	6.17
Soil	918	
2013		
NEAR THE VILLAGE OF RUDNIA TALS'KA		
Amanita muscaria	861	0.37
Boletus edulis	9,564	4.10
Cortinarius semisanguineus	95,623	41.04
Imleria badia	10,947	4.70
Lactarius rufus	63,938	27.44
Russula aeruginea	9,882	4.24
Russula amethystina	7,224	3.10
Suillus grevillei	19,169	8.23
Tricholoma fulvum	37,732	16.19
Tricholoma terreum	3,013	1.29
Soil	2,330	
2018		
NEAR THE VILLAGE OF KATYUZHANKA		
Cortinarius caperatus	26,378	28.73
Hypholoma fasciculare	2,409	2.62
Imleria badia	6,230	6.79
Macrolepiota procera	416	0.45
Paxillus involutus	5,136	5.59

Clitocybe nebularis	2,850	4.34
Cortinarius subferrugineus	64,700	98.48
Cystoderma amianthinum	BDL	
Hypholoma capnoides	1,340	2.04
Imleria badia	10,500	15.98
Lycoperdon perlatum	BDL	
Macrolepiota procera	2,230	3.39
Paxillus involutus	6,210	9.45
Stropharia aeruginosa	776	1.18
Tricholoma terreum	1,780	2.71
Soil	657	
NEAR THE VILLAGE OF RUDNIA TALS'KA		
Imleria badia	86,300	40.86
Soil	2,112	
2001		
NEAR THE VILLAGE OF KATYUZHANKA		
Amanita citrina	1,363	2.13
Amanita muscaria	656	1.03
Amanita pantherina	1,449	2.27
Amanita rubescens	40	0.06
Armillaria mellea	1,070	1.67
Fomitopsis betulina	146	0.23
Imleria badia	544	0.85
Kuehneromyces mutabilis	1,446	2.26
Lactarius turpis	6,314	9.88
Lactifluus vellereus	469	0.73
Leccinum aurantiacum	339	0.53
Lycoperdon perlatum	236	0.37
Paxillus involutus	4,882	7.64
Russula adusta	2,030	3.18
Russula foetens	1,241	1.94
Russula xerampelina	354	0.55
Xerocomellus chrysenteron	2,007	3.14
Soil	639	
Amanita muscaria	41,467	37.56
Ampulloclitocybe clavipes	14,273	12.93
Chlorophyllum rhacodes	876	0.79
Clitocybe infundibuliformis	474	0.43
Fistulina hepatica	2,421	2.19
Hypholoma fasciculare	4,699	4.26
Leccinum scabrum	15,294	13.85
Paxillus involutus	58,664	53.14
Suillus luteus	81,260	73.61
Tricholomopsis rutilans	7,354	6.66
Xerocomellus chrysenteron	10,466	9.48
Soil	1,104	
NEAR THE VILLAGE OF LYUTIZH		
Amanita citrina	8,189	3.31
Amanita muscaria	4,710	1.9
Amanita pantherina	12,504	5.05
Ampulloclitocybe clavipes	38,109	15.4
Armillaria mellea	902	0.36
Lactarius rufus	143,213	57.86
Russula aeruginea	22,343	9.03
Soil	2,475	
Ampulloclitocybe clavipes	31,407	10.76
Sparassis crispa	478	0.16
Soil	2,920	
Ampulloclitocybe clavipes	37,930	18.08
Cantharellus cibarius	5,760	2.46
Clitocybe infundibuliformis	791	0.38
Hypholoma fasciculare	26,041	12.41
Suillus granulatus	12,864	14.01
Soil	918	
2020		
NEAR THE VILLAGE OF KATYUZHANKA		
Amanita citrina	634	1.38
Amanita muscaria	193	0.42
Amanita phalloides	411	0.90
Cortinarius duracinus	31,526	68.68
Hortiboletus rubellus	1,141	2.49
Hypholoma fasciculare	1,983	4.32
Imleria badia	3,297	7.18
Lactarius rufus	5,319	11.59
Macrolepiota procera	1,122	2.44
Paxillus involutus	5,637	12.28
Sparassis crispa	835	1.82
Suillus granulatus	6,673	14.54
Soil	459	
NEAR THE VILLAGE OF LYUTIZH		
Amanita citrina	1,360	9.19
Amanita muscaria	1,097	7.41
Amanita rubescens	983	6.64
Coltricia perennis	342	2.31
Cortinarius duracinus	3,804	25.70
Cortinarius subferrugineus	27,924	188.68
Imleria badia	14,217	96.06
Soil	148	
NEAR THE VILLAGE OF SUKHOLUCHCHYA		
Amanita muscaria	4,207	3.90
Amanita pantherina	239	0.22
Cantarellus cibarius	1,541	1.43
Cantarellus cibarius	907	0.84
Clitocybe infundibuliformis	477	0.44
Cortinarius caperatus	7,983	7.41
Cortinarius olivaceofuscus	2,554	2.37
Cortinarius praestans	2,601	2.41
Hygrophoropsis aurantiaca	189	0.18
Paxillus involutus	5,098	4.73
Phlegmacium glaucopus	2,601	2.41
Pluteus cervinus	697	0.65
Tricholoma equestre	3,466	3.22
Tricholoma fulvum	40,800	37.85
Xerocomus subtomentosus	934	0.87
Soil	1,078	
Amanita citrina	1,550	2.50
Amanita fulva	1,290	2.08
Amanita muscaria	956	1.54
Amanita rubescens	2,688	4.34
Boletus edulis	890	1.44
Fomitopsis betulina	305	0.49
Hygrophoropsis aurantiaca	479	0.77
Hypholoma fasciculare	2,262	3.65
Imleria badia	2,668	4.31
Paxillus involutus	1,813	2.93
Russula cyanoxantha	1,679	2.71
Russula cyanoxantha	256	0.41
Russula queletii	2,940	4.75
Russula xerampelina	5,550	8.97
Stropharia aeruginosa	1,581	2.55
Suillus bovinus	7,366	11.90
Suillus luteus	3,509	5.67
Tricholoma equestre	13,512	21.83
Tricholoma saponaceum	6,705	10.83

Imleria badia	57,032	27.18
Lactarius rufus	122,524	58.4
Ramaria aurea	2,007	0.96
Soil	2,098	
Amanita citrina	1,229	0.86
Amanita pantherina	830	0.58
Imleria badia	18,883	13.20
Russula xerampelina	3,957	2.77
Soil	1,430	
NEAR THE VILLAGE OF ROVZHY		
Amanita muscaria	509	0.73
Paxillus involutus	1,610	2.3
Soil	700	
2002		
NEAR THE VILLAGE OF KATYUZHANKA		
Armillaria mellea	480	0.17
Hygrophoropsis aurantiaca	3,758	1.3
Imleria badia	3,347	1.16
Paxillus involutus	40,005	13.84
Soil	2,890	
Armillaria mellea	1,205	1.16
Cantharellus cibarius	6,708	6.48
Ampulloclitocybe clavipes	12,642	12.21
Rhodocollybia butyraceae	3,474	3.36
Stropharia aeruginosa	16,451	15.89
Tricholoma equestre	19,732	19.06
Xerocomellus chrysenteron	3,411	3.3
Soil	1,035	
Hypholoma capnoides	435	0.26
Hypholoma fasciculare	698	0.42
Imleria badia	18,448	11.07
Macrolepiota procera	191	0.11
Russula vesca	161	0.1
Stropharia aeruginosa	6,264	3.76
Soil		
Clitocybe nebularis	154	0.11
Cortinarius caerulescens	16,957	12.26
Hygrophoropsis aurantiaca	2,155	1.56
Hypholoma capnoides	1,096	0.79
Laccaria laccata	1,119	0.81
Lycoperdon perlatum	BDL	
Xerocomellus chrysenteron	1,908	1.34
Soil	1,383	
Chlorophyllum rhacodes	354	0.17
Clitocybe nebularis	376	0.18
Cortinarius venetus	26,116	12.56
Hypholoma fasciculare	739	0.36
Imleria badia	10,624	5.11
Macrolepiota procera	161	0.08
Paxillus involutus	35,316	16.99
Rhodocollybia maculata	4,533	2.18
Stropharia aeruginosa	789	0.38
Xerocomellus chrysenteron	10,031	4.82
Soil	2,079	
2003		
NEAR THE VILLAGE OF RUDNIA TALS'KA		
Cantharellus cibarius	39,051	14.15
Soil	2,759	
2004		
NEAR THE VILLAGE OF HOTYANIVKA		
Suillus bovinus	19,322	27.71
Tricholomopsis rutilans	481	0.78
Soil	619	
Amanita muscaria	2,573	3.30
Cortinarius olivaceofuscus	36,418	46.69
Cortinarius praestans	18,753	24.04
Cortinarius trivialis	1,733	2.22
Hygrophoropsis aurantiaca	189	0.24
Hypholoma fasciculare	1,047	1.34
Imleria badia	3,830	4.91
Lactarius rufus	13,628	17.47
Lactarius turpis	1,818	2.33
Paxillus involutus	8,177	10.48
Phlegmacium glaucopus	3,733	4.79
Russula cyanoxantha	6,645	8.52
Russula cyanoxantha	227	0.29
Russula ochroleuca	687	0.88
Suillus bovinus	10,308	13.22
Suillus luteus	16,620	21.31
Trametes versicolor	324	0.42
Soil	780	
2021		
NEAR THE VILLAGE OF HOTYANIVKA		
Amanita citrina	1,103	5.25
Amanita muscaria	1,694	8.07
Amanita vaginata	2,631	12.53
Boletus edulis	1,263	6.01
Cantharellus cibarius	539	2.57
Coltricia perennis	98	0.47
Cortinarius caperatus	12,130	57.76
Hypholoma fasciculare	1,453	6.92
Imleria badia	6,752	32.15
Lactarius helvus	1,346	6.41
Lactarius rufus	7,506	35.74
Leccinum scabrum	879	4.19
Lycoperdon perlatum	104	0.5
Paxillus involutus	6,117	29.13
Russula ochroleuca	592	2.82
Suillellus luridus	6,068	28.9
Suillus bovinus	2,175	10.36
Suillus luteus	9,232	43.96
Xerocomellus chrysenteron	971	4.62
Soil	210	
NEAR THE VILLAGE OF SUKHOLUCHCHYA		
Amanita citrina	3,116	2.15
Amanita muscaria	4,032	2.78
Boletus edulis	1,468	1.01
Cantharellus cibarius	1,261	0.87
Cortinarius olivaceofuscus	24,655	17.0
Cortinarius trivialis	16,670	11.5
Imleria badia	21,439	14.79
Lactarius rufus	12,892	8.89
Macrolepiota procera	845	0.06
Paxillus involutus	8,326	5.74
Russula aeruginea	10,452	7.21
Russula xerampelina	5,145	3.55
Sarcodon imbricatus	64,737	44.65
Suillus bovinus	14,098	9.72
Tricholoma equestre	9,316	6.42
Xerocomellus chrysenteron	8,213	5.66
Soil	1,450	
NEAR THE VILLAGE OF LYUTIZH		

Soil	890		*Agaricus sylvaticus*	212	0.42
NEAR THE VILLAGE OF KATYUZHANKA			*Amanita citrina*	909	1.8
Armillaria mellea	538	0.96	*Amanita muscaria*	1,848	3.67
Hypholoma lateritium	532	0.95	*Armillaria mellea*	179	0.36
Imleria badia	3,475	6.2	*Cantharellus cibarius*	2,119	4.2
Macrolepiota procera	370	0.66	*Clitocybe nebularis*	1,193	2.37
Paxillus involutus	2,352	4.2	*Coltricia perennis*	203	0.4
Soil	560		*Cortinarius praestans*	9,104	18.06
NEAR THE VILLAGE OF LYUTIZH			*Cortinarius subferrugineus*	86,729	172.08
Amanita citrina	6,690	5.62	*Fomitopsis betulina*	105	0.2
Ampulloclitocybe clavipes	49,581	41.63	*Hortiboletus rubellus*	1,839	3.65
Ampulloclitocybe clavipes	39,904	33.5	*Hypholoma capnoides*	412	0.82
Canthartellus cibarius	8,251	6.93	*Hypholoma fasciculare*	1,997	3.96
Cortinarius praestans	269,692	226.44	*Imleria badia*	6,793	13.34
Cystoderma amianthinum	706	0.59	*Imleria badia*	3,016	5.98
Hypholoma fasciculare	4,424	3.71	*Lactarius helvus*	3,613	7.17
Imleria badia	5,380	4.52	*Lactarius rufus*	26,946	53.46
Lactarius rufus	35,694	29.97	*Lycoperdon perlatum*	68	0.13
Leucocybe connata	8,211	6.89	*Paxillus involutus*	17,948	35.61
Lycopedron perlatum	BDL		*Russula xerampelina*	1,560	3.1
Paxillus involutus	32,851	27.58	*Tapinella atrotomentosa*	746	1.48
Psathyrella cotonea	533	0.45	*Tricholoma equestre*	7,324	14.53
Rhodocollybia prolixa	2,284	1.92	*Tylopilus felleus*	4,006	7.95
Russula xerampelina	6,702	5.63	*Xerocomellus chrysenteron*	2,611	5.18
Tapinella atrotomentosa	15,269	12.82	Soil	504	

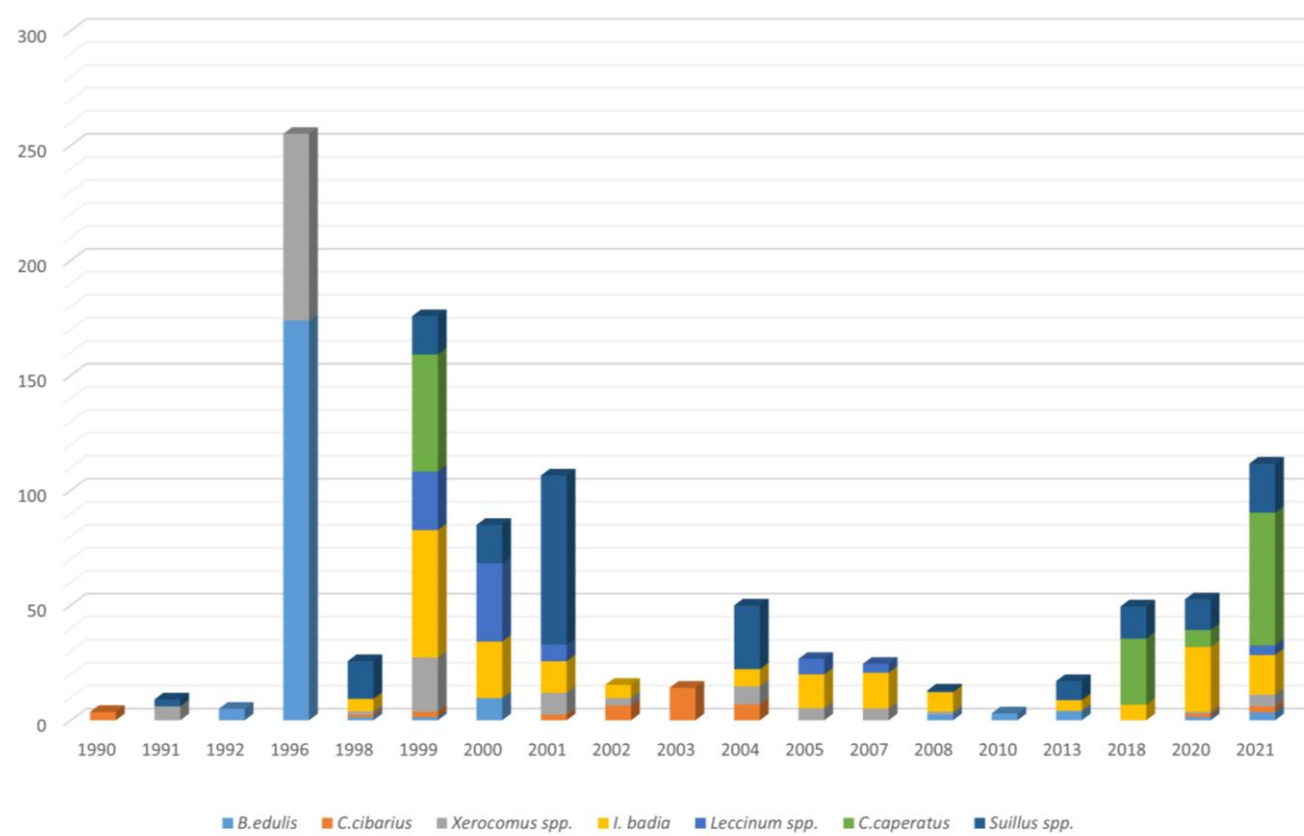

Fig. 2. The change of BCFs in some culinary-medicinal species during the post-Chernobyl period

Table 5. Geometrical mean values of BCFs of wild mushrooms from Vyshhorod district during 1990–2021

Species	BCF, geometric mean
A. pyriforme, C. squamosus, R. flava, C. amianthinum, L. perlatum, P. flaccida, R. vesca, C. rivulosa, T. versicolor, C. perennis, Ch. rhacodes, A. sylvaticus, F. betulina, Ph. squarrosa, M. procera, P. cotonea	<0.5
L. aurantiacum, S. crispa, C. infundibuliformis, R. integra, H. aurantiaca, L.vellereus, C. nebularis, A. mellea, H. capnoides, A. fulva, P. cervinus, R. aurea	0.6–1.0
F. hepatica, L. proxima, A. giganteus, H. lateritium, N. lepideus, H. rubellus, M. caninus, G. junonius, A. pantherina, R. cyanoxantha, S. aeruginosa, A. rubescens, R. vinosa, T. terreum, R. prolixa, L. laccata, R. maculata, K. mutabilis, H. fasciculare, A. muscaria, R. stricta, R. foetens, H. eburneus, X. subtomentosus, C. cibarius, R. aeruginea	1.1–3.0
R. xerampelina, R. amethystina, R. ochroleuca, R. butyraceae, B. edulis, A. citrina, Ph. glaucopus, X. chrysenteron, T. rutilans, T. portentosum, R. adusta, R. queletii, S. granulatus, C .trivialis, L. scabrum, L . connata, L. turpis, A. phalloides, C. olivaceofuscus, S. verrucosum, S. grevillei, T. felleus	3.1–9.0
G. glutinosus, I. badia, T. saponaceum, R. emetica, T. equestre, S. bovinus, C. caerulescens, A. vaginata, C. venetus, P. involutus, S. luteus, T. atrotomentosa, S. luridus, A. clavipes	9.1-20.0
L. deliciosus, L. rufus, T. fulvum, L. helvus, C. caperatus, C. praestans, S. imbricatus, C. duracinus, L. piperatus	20.1–50.0
C. semisanguineus, C. subferrugineus	>50

The geometric mean value of BCF for representatives of the genus *Cortinarius* was 21.30 (from 5.91 in *C. trivialis* up to 136.31 in *C. subferrugineus*), in the genus *Lactarius* – 18.43 (0.73 in *L. vellereus* up to 46.34 in *L. piperatus*), in Boletaceae spp. – 6.68 (from 0.53 in *L. aurantiacum* up to 15.61 in *S. luridus*), in *Russula* spp. – 2.64 (from 0.10 in *R. vesca* up to 10.86 in *R. emetica*), in *Amanita* spp. – 2.47 (from 0.83 in *A. fulva* up to 7.99 in *A. phalloides*). Also, high values of geometric mean value were noted for *P. involutus* – 14.51, and *S. imbricatus* – 39.41.

A comparison of average geometric BCF values made it possible to identify species with the highest accumulating capacity for radiocaesium – these are some representatives of the families Cortinariaceae, Tricholomataceae, Boletaceae, Russulaceae, Paxillaceae, and Bankeraceae.

The potential risk of radioactivity to human health is expressed as the effective dose in mSv per year. Based on the obtained data, we calculated the potential average dose of internal irradiation considering only the part connected with ^{137}Cs by consumption of some popular culinary-medicinal species in 2020–2021, by taking the average annual consumption of an adult inhabitant of Ukrainian Polissya (5 kg of fresh mushrooms) and a culinary processing coefficient of 0.5 (Table 6).

A potential calculated annual effective dose reached high values in *I. badia and Suillus* spp. – 0.070 and 0.054 mSv, respectively, which indicates a relatively low dose as a result of consuming wild mushrooms in these localities compared to other localities of Ukrainian Polyssia that have higher levels of soil contamination with radionuclides (GRODZINSKAYA ET AL., 2022; GABRIEL ET AL., 2023).

Table 6. Potential annual doses of internal irradiation (mSv/y) due to consumption of *Boletus edulis, Imleria badia, Cantharellus cibarius, Suillus* spp., *Cortinarius caperatus, Tricholoma equestre* by adults from the monitoring localities of Vyshhorod district in 2020–2021 due to the effect of ^{137}Cs only

Species	Min ^{137}Cs activity, Bq/kg dm	Min Dose, mSv/y	Max ^{137}Cs activity, Bq/kg dm	Max Dose, mSv/y
Boletus edulis	890	0.003	1468	0.005
Imleria badia	2668	0.009	21439	**0.070**
Cantharellus cibarius	539	0.002	2119	0.007
Suillus spp.	2175	0.007	16620	**0.054**
Xerocomus spp.	934	0.003	8213	0.027
Cortinarius caperatus	7983	0.026	12130	0.039
Tricholoma equestre	3466	0.011	13512	0.044

4. Conclusions

The levels of ^{137}Cs–activity in wild mushrooms of the Vyshhorod district varied over the years 1990–2021 depending on a complex of biotic and abiotic factors, such as mushroom species specificity, ecological affiliation, radioecological situation in the sampling sites, and showed a clear tendency to decrease over time. However, it should be noted that while in the first post-accident years up to 74% of mushroom samples showed an excess of permissible radiocaesium levels, as adopted in Ukraine (2500 Bq/kg dm), in recent years about half of all studied mushroom samples continue to exceed PL.

According to the value of the calculated potential annual effective dose in 2020–2021, the most popular edible species of mushrooms among the residents of Ukrainian Polissia can be presented in the following sequence – *B. edulis* < *C. cibarius* < *Xerocomus* spp. < *C. caperatus* < *T. equestre* < *Suillus* spp. < *I. badia.*

Especially high levels of radiocaesium activity are preserved in mycosymbiotrophs from the families Cortinariaceae, Bankeraceae (*S. imbricatus),* Tricholomataceae *(T. equestre, T. fulvum, A. clavipes),* Russulaceae (*Lactarius* spp.*), Boletaceae (I. badia, Suillus spp.),* and Paxillaceae *(P. involutus)*.

I. badia, P. involutus and *L. rufus*, are widely distributed in the territory of Ukrainian Polissya, and were recommended by us earlier as bioindicators of radiocaesium contamination of forest ecosystems (Grodzinskaya et al. 2011, 2013), and retain their relevance until recently.

Considering the extremely high level of variability of radioecological data, and the heterogeneity of contamination of the territory of Ukrainian Polissya, it is worth noting that during harvesting or mass gathering of wild mushrooms, even in territories with pollution < 37 kBq/m^2, mandatory radiation control is recommended.

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