Czech Mycology 75(2): 117–137, September 12, 2023 (online version, ISSN 1805-1421)

Radioactive contamination of mushrooms from Polis'ke Forestry (Kyiv Region, Ukraine) long after the Chornobyl accident

Jiří Gabriel[1], Ganna A. Grodzynska[2]*, Vitaliy B. Nebesnyi[2], †Volodymyr P. Landin[3]

[1] Institute of Microbiology, Czech Academy of Sciences, Videňská St 1083, Praha, CZ-14220, Czech Republic
[2] Institute for Evolutionary Ecology, National Academy of Sciences of Ukraine, Acad. Lebedeva St 37, Kyiv, UA-03143, Ukraine
[3] Institute for Safety Problems of Nuclear Power Plants, National Academy of Sciences of Ukraine, Lysogirs'ka St 12, Kyiv, UA-03028, Ukraine
*corresponding author: a.grodzinskaya@gmail.com

Gabriel J., Grodzynska G.A., Nebesnyi V.B., Landin V.P. (2023): Radioactive contamination of mushrooms from Polis'ke Forestry (Kyiv Region, Ukraine) long after the Chornobyl accident. – Czech Mycol. 75(2): 117–137.

A study of the radiocaesium activity in fruitbodies of 54 mushroom species from 18 locations of Polis'ke Forestry complex was carried out with γ-spectrometry. In some mushroom samples, strontium was determined with a radiochemical method. However, the mushrooms accumulated ^{137}Cs one to three orders of magnitude more actively than ^{90}Sr.

The highest levels of ^{137}Cs activity, recorded in *Lactarius rufus*, *Imleria badia*, *Paxillus involutus* and *Cortinarius praestans* from the forest area at the settlement of Polis'ke in 1998 and 2000, exceeded 1 MBq/kg dry mass. By 2018, the activity of ^{137}Cs in 60.0% and 37.84% of mushroom samples in the Zelenopolyans'ke and Steshchyns'ke Forestries, respectively, exceeded the maximum permissible level valid in Ukraine, 2,500 Bq/kg dry mass. Significant differences in the levels of contamination of the same species are noted not only at different locations, but also within the same sampling site, which is probably associated with a complex of factors which are difficult to assess, such as extremely heterogeneous nature of contamination, depth of mycelium in the soil layer, and microclimatic conditions in the place where individual fruitbodies grow.

The data obtained indicate a persistent risk to the population due to internal exposure as a result of uncontrolled consumption of wild mushrooms in this region. In 2018, the potential equivalent dose per year (contribution of ^{137}Cs only) reached maximum values of 0.239 mSv in *Suillus* spp. and 0.130 mSv in *Imleria badia* from Zelenopolyans'ke Forestry.

Key words: anthropogenic radionuclides, accumulation, fungi, dose, Polissya.

Article history: received 2 May 2023, revised 8 August 2023, accepted 14 August 2023, published online 12 September 2023.

DOI: https://doi.org/10.33585/cmy.75202

Gabriel J., Grodzynska G.A., Nebesnyi V.B., Landin V.P. (2023): Radioaktivní kontaminace hub z polesí Poliske (Kyjevská oblast, Ukrajina) s odstupem času po černobylské havárii. – Czech Mycol. 75(2): 117–137.

Studium aktivity radiocesia v plodnicích 54 druhů hub z 18 lokalit v komplexu polesí Poliske bylo provedeno γ-spektrometrií. V některých vzorcích hub bylo radiochemickou metodou stanoveno i stroncium, nicméně houby akumulovaly ^{137}Cs o jeden až tři řády aktivněji než ^{90}Sr.

Nejvyšší úrovně aktivity ^{137}Cs, zaznamenané v letech 1998 a 2000 u *Lactarius rufus*, *Imleria badia*, *Paxillus involutus* a *Cortinarius praestans* z lesní oblasti v osadě Poliske, přesáhly hodnotu 1 MBq na kilogram sušiny. V roce 2018 překročila aktivita ^{137}Cs u 60.0 % vzorků hub ze Zelenopoljanského polesí a u 37,84 % vzorků ze Steščynského polesí 2 500 Bq/kg sušiny, což je maximální úroveň přípustná na Ukrajině. Značné rozdíly v úrovni kontaminace stejných druhů hub byly zaznamenány nejen na různých lokalitách, ale i v rámci téhož odběrového místa, což je zjevně spojeno s komplexem těžko kontrolovatelných faktorů – extrémně heterogenní povahou kontaminace, hloubkou mycelia v půdní vrstvě a mikroklimatickými podmínkami v místě růstu jednotlivých plodnic.

Získaná data naznačují přetrvávající nebezpečí pro obyvatelstvo (vnitřní expozice) v důsledku nekontrolované konzumace lesních hub v této oblasti. V roce 2018 dosáhla potenciální ekvivalentní dávka za rok maximální hodnoty 0,239 mSv v plodnicích *Suillus* spp. a 0,130 mSv v *Imleria badia* ze Zelenopoljanského polesí.

INTRODUCTION

After the Chornobyl Nuclear Power Plant (ChNPP) disaster (26 April 1986), the active emission of radionuclides from the destroyed reactor, which lasted more than 10 days, in combination with changing weather conditions and the diversity of the landscape, led to an extremely heterogeneous and complex radioactive fallout in terms of density, composition and physicochemical parameters on the territory of Ukraine and a number of affected European countries. Radioecological monitoring to obtain data on the levels and main trends in the accumulation of radionuclides by mushroom fruitbodies, as well as on possible dose burdens due to the consumption of edible and medicinal plants and mushrooms from areas with different levels of contamination, even many years after the ChNPP accident, remains quite important.

Studies of the accumulation of radionuclides from soil in mushrooms have mainly focused on radiocaesium [^{137}Cs ($T_{1/2}$ = 30.07 years), in the first post-accident years in combination with ^{134}Cs], and partly on ^{90}Sr ($T_{1/2}$ = 28.79 years), as they were regarded to be the main radionuclides in radiation doses. Considering that the half-life of these radionuclides has passed, one should expect a significant drop in the levels of contamination of mushrooms, so a study of this process after more than three decades is of particular interest.

Many species of mushroom are valuable due to their unique aroma and taste, variety and richness of their nutritional components, and pharmacological properties as well. To date, more than 130 therapeutic effects of mushrooms (including antitumor, hepatoprotective, antioxidative, antidiabetic, cardiovascular, antibacterial, antiviral, detoxifying, cholesterol-lowering, anti-obesity, anti-aging, neuroregenerating effects, etc.) have been described (Wasser 2011, 2012, Gabriel 2016).

Since wild mushrooms are a traditional and popular product with Slavic peoples, rejection of the usual food cravings is quite difficult. For residents of Ukraine (especially of Ukrainian Polissya), wild mushrooms are not only an essential part of their diet, but also provide additional income to the rural population.

The key role of micro- and macromycetes is not only in their participation in the processes of biogenic migration of radionuclides in soils, but also in the immobilisation and increase of significant number of radionuclides in the soil mycelial biomass (Dighton et al. 1991, Gadd 1996, Steiner et al. 2002, Kalač 2012, 2019, Falandysz et Borovička 2013).

The forests of Ukrainian Polissya, which suffered from the disaster most severely, are still a constant source of radiation danger to the population. The area of our research, Kyivs'ke Polissya (KP), is a part of Ukrainian Polissya which covers the northern part of the Kyiv Region and the eastern part of the Zhytomyr Region. Geomorphologically, it is a moraine-hilly plain. KP is crossed by rivers flowing into the Dnipro, and its most water-rich tributary, the Prypiat'. Soils are mainly sod-podzolic, there are also peaty and grey forest soils. In the past, this area was almost completely covered by forests, interrupted only by wetlands. At present, forest cover ranges from 10 to 60%. Pine and oak forests predominate, with hazel and hawthorn in the undergrowth. The most important natural wealth of KP includes berries and mushrooms. The Chornobyl disaster had a significant negative impact on the KP. Currently, part of the KP is part of the exclusion zone, from where people have been resettled and where farming is prohibited. Before the accident, the Polis'ke Forestry was 62 thousand hectares large, after the accident a significant part of it was transferred to the zone of unconditional resettlement, as a result of which the current area is 16.3 thousand hectares (Maslyak 2012).

Extensive studies of the radioactive contamination of mushrooms after the Chornobyl disaster have convincingly demonstrated that some of them are active accumulators and discussed their possible use as indicators in biomonitoring of radiocaesium contamination (Haselwandter et al. 1988, Fraiture et al. 1990, Wasser et Grodzinskaya 1993, Haselwandter et Berreck 1994, Kalač 2001, 2012, Grodzinskaya et al. 2003, 2011, Guillén et Baeza 2014, Tucaković et al. 2018). In particular, radioecological monitoring of Ukrainian mushrooms has shown that some samples from the Chornobyl exclusion zone and from locations adjacent to it have remained highly contaminated throughout the post-accident period, in some cases reaching 10^5–10^7 Bq/kg dry mass, which poses a real long-term danger to part of the population employed in agriculture and forestry (Grodzinskaya et al. 1995, 2013, 2022).

The aim of this study was to assess the levels of accumulation of anthropogenic radionuclides by wild mushrooms and their potential danger to the population in territories adjacent to the exclusion zone many years after the Chornobyl disaster.

MATERIAL AND METHODS

Fruitbodies of 54 species of wild mushroom and average soil samples (0–5 cm of upper mineral soil layer, taken by means of the envelope method) were collected at 18 locations of the Zelenopolyans'ke and Steschyns'ke Forestries, which, with two other ones (Krasiatyts'ke and Raduns'ke Forestries), now fall under the Polis'ke Forestry state enterprise in the Kyiv Region of Ukraine, and in the forest area of the settlement of Polis'ke (Tab. 1, Fig. 1). The sampling sites were approximately 25 × 25 m in size.

Tab. 1. Coordinates of mushroom sampling locations in Polis'ke Forestry.

Sampling sites	Latitude	Longitude	Altitude (m a.s.l.)
Zelenopolyans'ke Forestry			
Forest quarter 2	51°14'33" N	29°30'08" E	129
Forest quarter 3	51°14'32" N	29°30'21" E	127
Forest quarter 5	51°14'42" N	29°31'16" E	127
Forest quarter 9	51°14'17" N	29°29'59" E	130
Forest quarter 13	51°14'03" N	29°32'07" E	127
Forest quarter 17	51°13'30" N	29°30'14" E	131
Forest quarter 18	51°13'30" N	29°30'30" E	136
Forest quarter 22	51°13'09" N	29°30'25" E	137
Forest quarter 24	51°13'32" N	29°31'36" E	131
Forest quarter 28	51°14'09" N	29°32'05" E	124
Forest quarter 32	51°13'49" N	29°35'10" E	128
Forest quarter 40	51°13'06" N	29°31'47" E	133
Forest quarter 63	51°12'34" N	29°37'54" E	132
Steshchyns'ke Forestry			
Forest quarter 6	51°13'44" N	29°43'22" E	125
Forest quarter 18	51°08'47" N	29°39'40" E	140
Forest quarter 34	51°09'15" N	29°42'59" E	142
Forest quarter 39	51°08'44" N	29°39'56" E	143
Settlement of Polis'ke	51°13'35" N	29°24'52" E	135

Mushrooms (2 to 25 complete fruitbodies per species) were carefully cleaned from plant and soil debris, dried at 60 °C, ground to a fine dispersion, dried again at 80 °C for 24 hours, then placed in polyethylene bags with a zip lock. The same procedure was used for the soil samples. The prepared samples were stored in these bags under dry and clean conditions (at 20–22 °C) until analysis, for 1 month. We used γ-spectrometry (Ge-detector Canberra GLX 4019, Mirion Technologies, Atlanta, USA) to determine ^{137}Cs-activity in fruitbodies of 54 mushroom species (Tab. 2). The currently valid names of mushrooms including author names are listed according to 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).

Fig. 1. Map of Ukraine with locations of sampling sites.

The sample measurement time ranged from 6 to 36 hours. The measurement error of ^{137}Cs was usually less than 10%. In some mushroom samples, the activity of ^{90}Sr was determined with the radiochemical method based on ^{90}Y accumulation according to the standard method (Anonymus 1994).

To assess the intensity of radionuclide accumulation by fruitbodies, we calculated the bioaccumulation factor (BAF), 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 et Borovička 2013). Levels of soil contamination were determined both using the results of our field measurements and the officially published maps of radiation contamination of Ukraine (Kholosha et al. 2012).

For assessment of the potential risk to human health, the possible average dose of internal irradiation was calculated according to the formula:

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

where $\boldsymbol{H_{int}}$ – dose of internal irradiation; $\boldsymbol{c}$ – specific activity of ^{137}Cs in Bq/kg of crude weight; $\boldsymbol{d_{int}}$ – coefficient to calculate the consumption of mushrooms by an adult (1.3×10^{-5} mSv/Bq for ^{137}Cs); $\boldsymbol{e}$ – estimated volume of annual consumption of mushrooms (5 kg per person per year); $\boldsymbol{k}$ – coefficient of culinary processing (0.5) (Grodzinskaya et al. 2022).

Tab. 2. List of the studied species.

Species	Edibility
Agaricus sylvaticus Schaeff.	edible
Amanita citrina Pers.	poisonous
Amanita muscaria (L.) Lam.	poisonous
Amanita pantherina (DC.) Krombh.	poisonous
Amanita rubescens Pers.	edible
Armillaria mellea (Vahl) P. Kumm.	edible
Boletus edulis Bull.	edible
Bovistella utriformis (Bull.) Demoulin et Rebriev	edible
Cantharellus cibarius Fr.	edible
Chlorophyllum rhacodes (Vittad.) Vellinga	edible
Chroogomphus rutilus (Schaeff.) O.K. Miller	edible
Cortinarius praestans (Cordier) Gillet	edible
Cortinarius semisanguineus (Fr.) Gillet	poisonous
Daedaleopsis confragosa (Bolton) J. Schröt.	inedible
Entoloma sericeum Quél.	inedible
Fomitopsis betulina (Bull.) B.K. Cui, M.L. Han et Y.C. Dai	inedible
Hohenbuehelia petaloides (Bull.) Schulzer	edible
Hygrophoropsis aurantiaca (Wulfen) Maire	inedible
Hypholoma capnoides (Fr.) P. Kumm.	edible
Hypholoma fasciculare (Huds.) P. Kumm.	poisonous
Gymnopilus junonius (Fr.) P.D. Orton	inedible
Imleria badia (Fr.) Vizzini	edible
Infundibulicybe gibba (Pers.) Harmaja	edible
Lactarius helvus (Fr.) Fr.	inedible
Lactarius rufus (Scop.) Fr.	conditionally edible
Lactarius turpis (Weinm.) Fr.	conditionally edible
Lactifluus piperatus (L.) Russel	conditionally edible
Lactifluus vellereus (Fr.) Kuntze	conditionally edible
Leccinum aurantiacum (Bull.) Gray	edible
Leccinum holopus (Rostk.) Watling	edible
Leccinum scabrum (Bull.) Gray	edible
Lycoperdon perlatum Pers.	edible
Macrolepiota procera (Scop.) Singer	edible
Neoboletus erythropus (Pers.) C. Hahn	conditionally edible
Paxillus involutus (Batsch) Fr.	poisonous
Rhodocollybia maculata (Alb. et Schwein.) Singer	inedible
Russula adusta (Pers.) Fr.	conditionally edible
Russula aeruginea Lindblad ex Fr.	edible
Russula amethystina Quél.	edible
Russula cyanoxantha (Schaeff.) Fr.	edible
Russula ochroleuca Fr.	edible
Russula vesca Fr.	edible
Russula violeipes Quél.	edible
Russula xerampelina (Schaeff.) Fr.	edible
Suillus bovinus (L.) Roussel	edible
Suillus granulatus (L.) Roussel	edible
Suillus grevillei (Klotzsch) Singer	edible
Suillus luteus (L.) Roussel	edible
Tricholoma equestre (L.) P. Kumm.	edible
Tricholoma portentosum (Fr.) Quél.	edible
Tricholoma saponaceum (Fr.) P. Kumm.	inedible
Tricholoma fulvum (DC.) Bigeard et H. Guill.	edible
Tylopilus felleus (Bull.) P. Karst.	inedible
Xerocomellus chrysenteron (Bull.) Šutara	edible

RESULTS AND DISCUSSION

General assessment

Previous analysis of literature and authors' data allowed for grouping a complex of factors determining the degree of radioactive contamination of mushrooms (Haselwandter et Berreck 1994, Yoshida et Muramatsu 1994, Grodzinskaya et al. 1995, 2003, 2013, Byrne 1998, Gillett et Crout 2000, Kalač 2001, 2012, Steiner et al. 2002, Baeza et al. 2006, Duff et Ramsey 2008, Falandysz et Borovička 2013, Škrkal et al. 2013, Guillén et Baeza 2014, Grodzynska 2017, etc.):

- atmospheric pollution, dust transfer, meteorological factors (precipitation, wind direction)
- soil radionuclide contamination gradient, pH, humidity, physical and chemical composition, soil type, microclimatic conditions, landscape features
- depth of mycelium in the soil layer
- mycosymbiotrophic interaction
- species specificity of accumulation
- ecological confinement of species
- stage of development of the fruitbody
- controlled factors and factors not accounted for

There are some factors which can be measured and taken into account, for example the density of contamination (although it is very patchy and uneven!), whereas other ones cannot be taken into account since their influence has not yet been identified or has been ignored so far. For example, it is impossible to foresee a specific amount of precipitation at a given sampling site, to consider the effect of a fruiting wave on the level of contamination of the fruitbodies, etc.

Regarding the latter issue, it was observed in cultivated *Agaricus bisporus* that fruitbodies from the first flush had the highest level of most mineral elements (Koyyalamudi et al. 2013). The following hypothesis could thus be formulated: if there is a gap in the fruiting of wild species (one of more years without fructification), the initial wave will be high in minerals – possibly including radioactive elements[1]. Unfortunately, fruiting waves can be regarded significant but difficult to observe factors (at least without stationary observations in the field) affecting the level of contamination of fruitbodies. In this case, due to the remote locations

[1] However in culture, fungal mycelium lives for not more than a few months, and the process of accumulation of radionuclides or trace elements from particular substrates (media) is more or less predetermined. In nature, mycelium in the soil can exist from many years to an almost infinite period of time. Therefore, the processes of accumulation of radionuclides by natural mycelium are a complex spatiotemporal process, including multiple processes of migration of natural and anthropogenic radionuclides, other metals, as well as their antagonistic or synergistic interactions and competition in the formation of complexes with soil components (organic and clayey), etc.

of the sampling sites, the samples were taken once a year. Therefore, we are not able to judge which fruiting wave the fruitbodies belong to.

In general, the level of bioaccumulation of radionuclides by mushrooms depends on the specific radioecological situation at a sampling site, species specificity and ecological confinement of the species. At the same time, the high degree of variability observed in the obtained data indicates a complex resulting effect of certain and uncertain (uncontrollable) factors, which complicates the predictive assessment of mushroom contamination levels.

Our previous studies have shown high activity concentrations of ^{137}Cs in mycorrhizal species from Drevlyanskyi Nature Reserve, a territory adjacent to the Chornobyl zone (settlement of Narodychi, Zhytomyr Region, Ukraine), which has persisted until recent years (values in kBq per kg DM): *Imleria badia* – up to 2,680, *Tricholoma equestre* – up to 1,420, *Lactarius rufus* – up to 601.7, *Sarcodon imbricatus* – up to 464.8, *Suillus bovinus* – up to 118.2, *Leccinum scabrum* – up to 117.0, *Boletus edulis* – up to 95.80 (Grodzinskaya et al. 2022).

Activity of ^{137}Cs in mushroom fruitbodies in the 1990s

A γ-spectrometric study of the ^{137}Cs-activity of wild mushrooms from the Polis'ke Forestry site, located near the ChNPP zone, showed high levels of contamination (Tabs 3–6). According to officially published maps, ^{137}Cs contamination of the soil in the territories where the Zelenopolyans'ke Forestry is located was estimated within the limits of 10–100 kBq/m^2 (0.27–2.7 Ci/km^2; 10 May 1986), and 4–40 kBq/m^2 (0.1–1.08 Ci/km^2; 10 May 2011). For Steshchyns'ke Forestry, ^{137}Cs contamination was estimated within the limits 10–40 kBq/m^2 (0.27–1.08 Ci/km^2; 10 May 1986) and 4–20 kBq/m^2 (0.1–0.54 Ci/km^2; 10 May 2011) (Kholosha et al. 2012). In 1995 and 1996, the highest levels of ^{137}Cs-activity were found in fruitbodies of symbiotrophic species *Imleria badia* and *Paxillus involutus*, collected at Quarter 32 of Zelenopolyans'ke Forestry (Tab. 3). While the gamma-background of the air at this locality was 0.4 mSv/h, in other quarters it was in the range of 0.17–0.21 mSv/h. Considering that the maximum allowed level of ^{137}Cs for mushrooms, as adopted in Ukraine, is 2,500 Bq/kg DM (Anonymus 2006), the exceedance of this level in *P. involutus* and *I. badia* fruitbodies from Quarter 32 in 1996 were more than 95.2 and 92.4-fold, respectively. Notably, the low contamination of *Lycoperdon perlatum*, as compared to other species, is consistent with previous data, which also indicated that saprotrophs as well as xylotrophs (*Agaricus* spp., *Macrolepiota* spp., *Coprinus* spp., *Bovistella* spp., *Lycoperdon* spp., *Calvatia gigantea* (Batsch) Lloyd, *Armillaria mellea*, *Fistulina hepatica* (Schaeff.) With., *Sparassis crispa* (Wulfen) Fr., *Kuehneromyces mutabilis* (Schaeff.) Singer, *Pleurotus ostreatus* (Jacq.) P. Kumm., *Fomitopsis betulina* and *Pholiota* spp.), accumulated significantly lower amounts of radiocaesium than symbiotrophs (Grodzinskaya et al. 2013, 2019, Grodzynska 2017). The activity of ^{137}Cs varied over about 1 or 2 orders of magnitude between different species from the same sampling site in 1995, and reached up to 3 orders of magnitude for samples collected in the entire Zelenopolyans'ke Forestry. Differences were also observed in contamination rates of the same species collected at one locality (Tab. 3).

Tab. 3. Activity concentration of ^{137}Cs in mushrooms in 1995–1999 in Zelenopolyans'ke Forestry.

Species	Forest quarter	Number of fruitbodies	^{137}Cs activity (kBq/kg dry mass)
1995			
Russula cyanoxantha	9	6	45.88
Russula vesca	17	5	31.01
Imleria badia	18	9	114.0
Lactifluus vellereus	18	4	21.94
Leccinum scabrum	18	6	44.77
Paxillus involutus	18	8	16.98
Russula xerampelina	18	5	32.90
Imleria badia	32	7	128.4
Lactifluus vellereus	32	5	76.59
Lactifluus vellereus	40	5	11.30
Lycoperdon perlatum	40	9	0.11
Russula amethystina	40	5	3.80
Suillus luteus	40	8	27.08
*Imleria badia**	63	10	21.76
*Imleria badia**	63	9	14.39
Lactifluus vellereus	63	5	1.41
Leccinum scabrum	63	4	2.33
Lycoperdon perlatum	63	11	0.74
Paxillus involutus	63	6	3.77
Russula cyanoxantha	63	4	1.90
1996			
Boletus edulis	28	3	44.22
Leccinum scabrum	28	5	15.83
Imleria badia	32	10	231.0
Lactarius turpis	32	4	18.40
Paxillus involutus	32	7	238.0
Suillus luteus	32	9	95.50
1999			
Agaricus sylvaticus	13	4	0.85
*Boletus edulis**	18	3	4.18
*Boletus edulis**	18	2	7.30
*Cantharellus cibarius**	18	13	11.99
*Cantharellus cibarius**	18	9	26.00

Species	Forest quarter	Number of fruitbodies	^{137}Cs activity (kBq/kg dry mass)
Paxillus involutus	18	6	5.94
*Suillus luteus**	18	6	18.44
*Suillus luteus**	18	5	24.20
Boletus edulis	22	4	5.59
Boletus edulis	24	2	4.90
Imleria badia	24	12	17.60
Paxillus involutus	24	5	43.30
Russula cyanoxantha	24	7	35.10
Russula xerampelina	24	6	20.70
Suillus luteus	24	9	30.80
Russula xerampelina	28	4	54.00

* Different levels of radiocaesium accumulation were recorded in fruitbodies of the same species collected from one sampling site. The groups of sampled fruitbodies were collected at a certain distance from each other.

Due to the very high variability in the levels of radiocaesium contamination of mushrooms, we calculated the geometric mean. For all samples collected in Zelenopolyans'ke Forestry in 1995–1999 together, the geometric mean of ^{137}Cs activity amounted to 13.90 kBq/kg DM, more particularly 12.92 kBq/kg DM in *Russula* spp., 28.06 kBq/kg DM in *Boletales* (with higher geometric means in *Imleria badia* – 63.82, and *Suillus luteus* – 43.03 kBq/kg DM).

Between 1998 and 2000, we analysed mushrooms from the forest area located in Polis'ke (at 52.2 km distance from ChNPP), and found a ^{137}Cs contamination within the limits of 100–555 kBq/m^2 (2.7–15 Ci/km^2; 10 May 1986) and 100–185 kBq/m^2 (2.7–5 Ci/km^2; 10 May 2011) (Kholosha et al. 2012), which were the highest in this study. Only since 1999 this settlement (now called an 'abandoned town', which used to be the centre of the Polis'ky District) has been included in the zone of unconditional resettlement.

In 1998, the highest activities of ^{137}Cs at this location were found in *Lactarius rufus* (up to 3,654 kBq/kg DM), *Imleria badia* (up to 1,929 kBq/kg DM) and *Paxillus involutus* (up to 1,630 kBq/kg DM), while these species reached the highest BAF values: up to 111.7, 153.6, and 196.9, respectively (Tab. 4). At this location, the exceedance of permissible levels in valuable edible species, usually collected in large quantities by the Ukrainian population, reached alarming values: in *I. badia* up to 771.6 times, *Leccinum scabrum* 184.5, *Tricholoma equestre* 161.5 and *S. luteus* 114.3 times.

Tab. 4. Activity concentration of ^{137}Cs at the settlement of Polis'ke in 1998–2000.

Species, soil	Number of fruitbodies	^{137}Cs activity (kBq/kg dry mass)	BAF ^{137}Cs
1998			
Amanita muscaria	3	113.9	23.01
Lactarius helvus	4	186.0	37.58
Lactarius rufus	7	172.0	34.75
Lactarius turpis	2	15.85	3.200
Leccinum aurantiacum	4	4.34	0.877
Paxillus involutus	6	974.6	196.9
Russula sp.*	3	438.9	88.67
Russula sp.*	3	116.5	23.54
Russula ochroleuca	5	361.2	72.97
Suillus luteus	7	285.8	57.74
*Imleria badia**	6	369.2	74.59
*Imleria badia**	4	760.5	153.6
Soil**		4.95	
Amanita muscaria	3	33.82	1.033
Lactarius rufus	6	3,654	111.7
Lactarius turpis	3	106.2	3.247
Macrolepiota procera	4	3.37	0.103
Soil**		32.71	
Amanita citrina	5	362.6	2.662
Amanita muscaria	3	26.54	0.188
Lactarius rufus	6	741.7	5.446
Lactarius turpis	3	104.2	0.765
Paxillus involutus	4	558.9	4.104
Russula xerampelina	3	76.92	0.565
Imleria badia	5	1,894	13.91
Soil**		136.2	
Amanita muscaria	3	61.46	1.097
Amanita rubescens	2	298.7	5.332
Gymnopilus junonius	6	8.13	0.145
Hohenbuehelia petaloides	3	95.34	1.702
Leccinum aurantiacum	4	103.5	1.848
Leccinum scabrum	3	461.2	8.233
Paxillus involutus	4	1,630	29.10
Fomitopsis betulina	2	18.67	0.333
Russula sp.	3	444.3	7.931
Tricholoma equestre	8	403.7	7.206
Imleria badia	6	1,929	34.43
Soil**		56.02	
1999			
Amanita citrina	5	11.14	1.605

Species, soil	Number of fruitbodies	^{137}Cs activity (kBq/kg dry mass)	BAF ^{137}Cs
Amanita muscaria	4	1.90	0.274
Cortinarius praestans	4	432.1	62.26
Lactarius turpis	2	78.98	11.38
Lactifluus piperatus	3	103.3	14.88
Paxillus involutus	5	44.34	6.389
Russula adusta	4	4.05	0.584
Suillus grevillei	7	0.21	0.030
Soil**		6.94	
2000			
Amanita muscaria	3	29.50	1.758
Boletus edulis	4	76.80	4.577
Cortinarius praestans	5	1,323	78.84
Hypholoma capnoides	16	29.10	1.734
Imleria badia	6	89.90	5.358
Lactarius rufus	7	204.0	12.16
Lactarius turpis	3	20.90	1.246
Lycoperdon perlatum	9	12.47	0.743
Neoboletus erythropus	2	325.0	19.37
Paxillus involutus	4	285.0	16.98
Russula aeruginea	3	117.0	6.973
Russula xerampelina	5	81.20	4.839
Suillus granulatus	5	29.00	1.728
Suillus luteus	4	222.0	13.23
Tricholoma equestre	8	52.30	3.117
Soil**		16.78	

* Different levels of radiocaesium accumulation were recorded in fruitbodies of the same species collected from one sampling site. The groups of sampled fruitbodies were collected at a certain distance from each other.
** Soil samples were taken when collecting groups of species growing nearby. As can be seen, even in the conditions of one locality, also average values of the soil samples differed greatly from each other.

In 1999, ^{137}Cs activity was the highest in *Cortinarius praestans* at 432.1 kBq/kg DM (BAF 62.26), *Lactifluus piperatus* at 103.3 (BAF 14.88) and in *Lactarius turpis* at 78.98 kBq/kg DM (BAF 11.38) (Grodzinskaya et al. 2003).

At this locality, in 2000, the exceedance of permissible levels for valuable edible species also reached alarming proportions: in *C. praestans* 529.2 times, *Suillus luteus* 88.80 times, *Russula aeruginea* 46.80 times, *Imleria badia* 35.96 times, *Boletus edulis* 30.72 times, and *Tricholoma equestre* 20.92 times. Even in the case of minimal contamination in *Lycoperdon perlatum* (12.47 kBq/kg DM), the level was five times higher than permissible. Fruitbodies of *C. praestans* were the most contaminated at this sampling site (1,323 kBq/kg DM, BAF 78.84).

The geometric mean of ^{137}Cs for all mushroom samples from Polis'ke in 1998–2000 was 94.48 kBq/kg DM, more particularly 42.16 kBq/kg DM in *Amanita* spp., 99.78 in *Boletales* (with the highest geometric means in *I. badia* at 469.7 and *Leccinum scabrum* at 461.2 kBq/kg DM), 111.7 kBq/kg DM in *Russula* spp. (361.2 in *R. ochroleuca*), 143.4 in *Lactarius* spp. (555.3 in *L. rufus*), 445.4 kBq/kg DM in *Paxillus involutus* and 756.1 kBq/kg DM in *C. praestans*.

Previously, increased levels of radiocaesium contamination were also reported in representatives of *Cortinariaceae* (Haselwandter et al. 1988, Klán et al. 1988, Yoshida et Muramatsu 1994, Grodzinskaya et al. 2003, 2011, Zalewska et al. 2016, Grodzynska 2017). Falandysz et al. (2019) noted that *Cortinarius caperatus* appears to efficiently bioconcentrate ^{137}Cs from contaminated soil substrata. The authors attribute this phenomenon to the gradual leaching of ^{137}Cs into the lower layers of surface soils and the ability of the mycelium of this species to penetrate into relatively great depths, which may be the cause of persistent high activity values.

Also in this study, high levels of radiocaesium contamination were found in *I. badia*. It should be noted that 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 other European countries, which explains the increased interest in it (Mietelski et al. 1994, Grodzinskaya et al. 2003, 2011, Malinowska et al. 2006, Falandysz et al. 2015, Szymańska et Strumińska-Parulska 2020, Harkut et al. 2021, Ernst et al. 2021).

Activity of ^{137}Cs and ^{90}Sr in mushroom fruitbodies in the 2010s

In samples from Zelenopolyans'ke Forestry in 2013, high activities of ^{137}Cs were found in *Imleria badia* (213.0 kBq/kg DM, BAF 136.4), *Cortinarius semisanguineus* (130.0 kBq/kg DM, BAF 83.23) from Quarter 3, and in *Chroogomphus rutilus* (128.0 kBq/kg DM, BAF 47.06) and *Amanita pantherina* (84.50 kBq/kg DM, BAF 31.07) from Quarter 5 (Tab. 5).

On average, mushrooms accumulate ^{137}Cs 100 times more actively than ^{90}Sr. In *Daedaleopsis confragosa* (0.309 kBq/kg DM, BAF 3.396), *Amanita* spp. (up to 0.288 kBq/kg DM, BAF up to 10.17), and *C. rutilus* (0.218 kBq/kg DM, BAF 2.057), increased accumulation of ^{90}Sr was observed compared with other species (Tab. 5). High BAFs for radiostrontium were observed also in *Bovistella utriformis* (5.435), *Boletus edulis* (4.826), and *Cantharellus cibarius* (4.783) from Quarter 17.

The geometric mean value of ^{90}Sr for all mushrooms from Zelepolyans'ke Forestry in 2013 was 0.075 kBq/kg DM, for *Amanita* spp. 0.113, *C. cibarius* 0.109, *Boletales* 0.058 and *Cortinarius* spp. 0.037 kBq/kg DM. Since the $^{137}Cs/^{90}Sr$ ratio was relatively high in some species (*I. badia*, *C. semisanguineus*, *Russula ochroleuca*, *Paxillus involutus*, *Cortinarius praestans*), it can be assumed that these species are selective accumulators of radiocaesium.

Tab. 5. Activity concentrations of ^{137}Cs and ^{90}Sr in mushrooms and soils in Zelenopolyans'ke Forestry in 2013.

Species, soil	Forest quarter	Number of fruitbodies	^{137}Cs activity (kBq/kg dry mass)	BAF ^{137}Cs	^{90}Sr activity (kBq/kg dry mass)	BAF ^{90}Sr	^{137}Cs/^{90}Sr
Amanita muscaria	3	6	4.180	2.676	0.033	0.292	126.7
Cortinarius semisanguineus	3	4	130.0	83.23	0.030	0.265	4,333
Imleria badia	3	8	213.0	136.4	0.027	0.239	7,889
Leccinum holopus	3	6	10.10	6.466	0.085	0.752	118.8
Leccinum scabrum	3	4	10.80	6.914	0.083	0.734	130.1
Russula ochroleuca	3	9	79.10	50.64	0.032	0.283	2,472
Suillus granulatus	3	12	83.40	53.39	0.104	0.920	801.9
Soil	3		1.562		0.113		13.82
Amanita citrina	5	6	24.40	8.971	0.252	2.377	96.83
Amanita pantherina	5	3	84.50	31.07	0.288	2.717	293.4
Cantharellus cibarius	5	16	3.719	1.367	0.108	1.019	34.44
Cortinarius semisanguineus	5	5	75.40	27.72	0.033	0.311	2,285
Chroogomphus rutilus	5	4	128.0	47.06	0.218	2.057	587.2
Rhodocollybia maculata	5	9	2.600	0.956	0.071	0.670	36.62
Soil	5		2.720		0.106		25.66
Amanita muscaria	17	3	12.30	8.662	0.234	10.170	52.56
Suillus bovinus	17	8	15.14	10.66	–	–	–
Boletus edulis	17	6	8.960	6.310	0.111	4.826	80.72
Bovistella utriformis	17	5	2.190	1.542	0.125	5.435	17.52
Cantharellus cibarius	17	14	6.200	4.366	0.110	4.783	56.36
Cortinarius praestans	17	7	51.00	35.92	0.050	2.174	1,020
Paxillus involutus	17	5	52.30	36.83	0.034	1.478	1,538
Soil	17		1.420		0.023		61.74
Amanita pantherina	18	4	9.820	6.062	0.020	0.220	491.0
Amanita rubescens	18	5	9.750	6.019	0.189	2.077	51.59
Boletus edulis	18	7	12.10	7.469	0.031	0.341	390.3
Daedaleopsis confragosa	18	3	7.260	4.481	0.309	3.396	23.50
Leccinum holopus	18	3	13.20	8.148	0.033	0.363	400.0
Suillus luteus	18	9	7.310	4.512	0.057	0.626	128.2
Tylopilus felleus	18	4	22.80	14.07	0.062	0.681	367.7
Soil	18		1.620		0.091		17.80

Significant differences in the levels of contamination of the same species are noted not only at different locations, but also within the same sampling site, which is obviously associated with a complex of factors difficult to assess – the extremely heterogeneous (mosaic) nature of contamination, the depth of mycelium in the soil layer, and microclimatic conditions in the place where individual fruitbodies grow. Similar differences between different fungal species from identical locations have been noted from the Czech Republic (Čadová et al. 2017).

In 2018, the fruitbodies most contaminated with ^{137}Cs in Zelenopolyans'ke Forestry were found in *Suillus granulatus* (73.42 kBq/kg DM, BAF 392.6) from Quarter 3 and *Imleria badia* from Quarter 5 – at up to 40.09 kBq/kg DM (BAF up to 18.02) (Tab. 6). In Steshchyns'ke Forestry, high activities of ^{137}Cs were found in fruitbodies growing in Quarter 39, e.g. *Tricholoma fulvum* at 56.52 kBq/kg DM (BAF 27.38), *Paxillus involutus* at up to 49.33 (BAF 23.90), and *I. badia* up to 39.85 kBq/kg DM (BAF 19.31).

It should also be noted for the data of 2018 that there is significant difference in the level of contamination of two mushroom samples from a single site (each containing about 6–9 fruitbodies): in *I. badia* by a factor of 1.790 and 1.985 (Zelenopolyans'ke Forestry, Quarters 5 and 18, respectively) to 12.52 and 34.29 (Steshchyns'ke Forestry, Quarters 34 and 39, respectively). In fruitbodies of *P. involutus* from Steshchyns'ke Forestry this factor was 1.627 (Quarter 18) to 6.644 (Quarter 39); in *Suillus luteus* it was 4.8 (Quarter 18).

In the first post-Chornobyl period, mushroom samples exceeded the maximum permissible levels in 75–100% of cases, but in 2018 we have seen a certain decrease in this value: 60.0% of mushroom samples in Zelenopolyans'ke and 37.84% in Steshchyns'ke Forestry exceeded this limit. Only 11.54% of mushroom samples in 2013 exceeded permissible level for ^{90}Sr in dry mushrooms, as adopted in Ukraine (250 Bq/kg DM; Anonymus 2006).

The geometric mean value of ^{137}Cs for all mushrooms from Zelenopolyans'ke and Steshchyns'ke Forestries in 2013–2018 was 4.842 kBq/kg DM, more particularly 2.722 in *Amanita* spp., 6.429 in *Russula* spp. (the highest value in *R. ochroleuca*: 79.10), 7.644 in *Boletales* (in particular 22.80 in *Tylopilus felleus* and 18.31 in *Suillus granulatus*), 15.82 in *Paxillus involutus*, 56.52 in *Tricholoma fulvum* and 79.37 in *Cortinarius* spp. (99.01 kBq/kg DM in *C. semisanguineus*).

The potential risk of radioactivity to human health is expressed as the equivalent dose in mSv per year. The acceptable annual burden for an adult human, recommended in Anonymus (1997), is 1 mSv. 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 culinary-medicinal species *Boletus edulis*, *Imleria badia* and *Suillus* spp. fruitbodies in 2018, taking the average annual consumption of an adult inhabitant of Kyivs'ke Polissya (5 kg of fresh mushrooms) and a culinary processing coefficient of 0.5 (for details see Grodzinskaya et al. 2022) (Tab. 7).

Tab. 6. Activity concentration of ^{137}Cs in mushrooms in Zelenopolyans'ke and Steshchyns'ke Forestries in 2018.

Species, soil	Forest quarter	Number of fruitbodies	^{137}Cs activity (kBq/kg dry mass)	BAF
Zelenopolyans'ke Forestry				
Amanita muscaria	2	4	1.510	7.626
Amanita pantherina	2	3	1.021	5.157
Hygrophoropsis aurantiaca	2	17	0.189	0.955
Hypholoma capnoides	2	25	5.243	26.48
Lactarius rufus	2	12	6.616	33.41
Soil	2		0.198	
Suillus granulatus	3	8	73.42	392.6
Suillus luteus	3	7	22.59	120.8
Soil	3		0.187	
*Imleria badia**	5	9	22.40	10.07
*Imleria badia**	5	6	40.09	18.02
Macrolepiota procera	5	6	0.494	0.222
*Paxillus involutus**	5	5	33.61	15.11
*Paxillus involutus**	5	9	32.22	14.48
Russula amethystina	5	7	15.89	7.142
Soil	5		2.225	
Amanita muscaria	17	4	2.294	29.04
Imleria badia	17	10	12.98	164.3
Boletus edulis	17	3	1.123	14.22
Hypholoma capnoides	17	22	1.769	22.39
Lactarius turpis	17	3	0.507	6.418
Tricholoma saponaceum	17	4	1.150	14.56
Soil	17		0.079	
Amanita citrina	18	6	2.964	5.571
*Imleria badia**	18	8	24.93	46.86
*Imleria badia**	18	9	12.56	23.61
Hygrophoropsis aurantiaca	18	12	0.184	0.346
Tricholoma saponaceum	18	3	10.83	20.36
Soil	18		0.532	
Imleria badia	28	5	31.53	35.15
Soil	28		0.897	
Steshchyns'ke Forestry				
Imleria badia	6	8	1.415	0.737
Suillus luteus	6	5	1.308	0.681
Soil	6		1.920	
Amanita muscaria	18	4	0.278	0.269
Imleria badia	18	9	1.488	1.438
Entoloma sericeum	18	3	2.355	2.275

Species, soil	**Forest quarter**	**Number of fruitbodies**	**^{137}Cs activity (kBq/kg dry mass)**	**BAF**
Fomitopsis betulina	18	3	0.110	0.106
Hypholoma fasciculare	18	25	0.455	0.440
*Paxillus involutus**	18	6	13.06	12.62
*Paxillus involutus**	18	9	8.028	7.757
Russula violeipes	18	5	1.089	1.052
Russula cyanoxantha	18	7	8.890	8.589
Suillus granulatus	18	4	5.467	5.282
*Suillus luteus**	18	9	1.427	1.379
*Suillus luteus**	18	6	6.794	6.564
Soil	18		1.035	
Amanita muscaria	34	6	0.127	0.266
Amanita pantherina	34	4	0.322	0.675
Chlorophyllum rhacodes	34	5	0.204	0.428
*Imleria badia**	34	7	5.258	11.02
*Imleria badia**	34	10	0.420	0.881
Paxillus involutus	34	8	1.806	3.786
Russula cyanoxantha	34	4	0.903	1.893
Suillus granulatus	34	7	7.645	16.03
Tricholoma portentosum	34	5	9.449	19.81
Xerocomellus chrysenteron	34	6	0.197	0.413
Soil	34		0.477	
Amanita citrina	39	4	0.120	0.058
Armillaria mellea	39	22	0.089	0.043
Boletus edulis	39	2	1.698	0.823
*Hygrophoropsis aurantiaca**	39	9	2.649	1.283
*Hygrophoropsis aurantiaca**	39	13	1.450	0.703
*Imleria badia**	39	9	39.85	19.31
*Imleria badia**	39	6	1.162	0.563
Infundibulicybe gibba	39	11	0.724	0.351
*Paxillus involutus**	39	9	7.425	3.597
*Paxillus involutus**	39	7	49.33	23.90
Suillus granulatus	39	9	8.040	3.895
Tricholoma fulvum	39	12	56.52	27.38
Tricholoma portentosum	39	8	0.851	0.412
Soil	39		2.064	

* Different levels of radiocaesium accumulation were recorded in fruitbodies of the same species collected from one sampling site. The groups of sampled fruitbodies were collected at a certain distance from each other.

Tab. 7. Potential annual doses of internal radiation (mSv/y) due to consumption of *Boletus edulis*, *Imleria badia* and *Suillus* spp. by adults from Zelenopolyans'ke and Steshchyns'ke Forestries (Polis'ke Forestry state enterprise) in 2018, due to the effect of ^{137}Cs only.

^{137}Cs activity (kBq/kg dry mass)	Dose (mSv/y)	^{137}Cs activity (kBq/kg dry mass)	Dose (mSv/y)	^{137}Cs activity (kBq/kg dry mass)	Dose (mSv/y)
Zelenopolians'ke Forestry					
Boletus edulis		***Imleria badia***		***Suillus* spp.**	
1.123	0.004	Min. 12.98 Max. 40.09	Min. 0.042 Max. 0.130	Min. 22.59 Max. 73.42	Min. 0.073 Max. 0.239
Steshchyns'ke Forestry					
Boletus edulis		***Imleria badia***		***Suillus* spp.**	
1.698	0.006	Min. 1.415 Max. 39.85	Min. 0.005 Max. 0.130	Min. 1.308 Max. 8.040	Min. 0.004 Max. 0.026

In 2018, the potential annual equivalent dose reached maximum values of 0.239 mSv in *Suillus* spp. and 0.130 mSv in *I. badia*, both from Zelenopolyans'ke Forestry.

CONCLUSIONS

The radioactive contamination of wild mushrooms from areas of Kyivs'ke Polissya close to the ChNPP zone continues to be a source of increased risk to human health because of possibly acquiring significant internal radiation doses in case of their uncontrolled consumption.

Whereas 75–100% of mushrooms from the Polis'ke Forestry state enterprise showed an exceedance of permissible radiocaesium level during the first post-Chornobyl period (up to and including the year 2000), this number decreased to 60.0% for Zelenopolyans'ke and 37.84% for Steshchyns'ke Forestry, respectively, by 2018.

Despite the relatively low levels of soil contamination with radiocaesium (40.7–74 kBq/m^2, 1.1–2 Ci/km^2) found at most Polis'ke Forestry sites, the potential annual equivalent dose (only due to ^{137}Cs) reached maximum values of 0.239 mSv in *Suillus* spp. and 0.130 mSv in *Imleria badia*, both from Zelenopolyans'ke Forestry, in 2018. Therefore mushroom picking cannot be recommended due to continued potential risk.

At the same time, the need for radiation monitoring of not only ‘gifts of the forest’, but also of other organisms, is particularly relevant in the current circumstances due to increasing forest fires in the Chornobyl zone, and the risk of military actions of the Russian Federation aimed at nuclear facilities in Ukraine.

ACKNOWLEDGEMENTS

This study was partly carried out under joint Ukrainian-Czech research project "Changes in fungal communities and physiology of bacteria, macro- and micromycetes under the radiation stress" (2014–2016) for the M.G. Kholodny Institute of Botany NASU and the Institute of Microbiology of the CAS.

We will always remember our colleague, co-author of this study – Dr. Sci V.P. Landin (26 August 1947 – 9 February 2023), prominent Ukrainian scientist, professional in forest and agriculture radioecology and soil science, author of more than 200 publications. He was a noble, wise and infinitely kind man. In 1986, he participated in the liquidation of the consequences of the Chornobyl disaster, and then developed a methodology for the rehabilitation and balanced use of radioactively contaminated forest ecosystems which he applied in large-scale radioecological investigations of 4.5 million hectares of forest in 18 regions of Ukraine.

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