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ORIGINAL ARTICLE

Radioactivity in mushrooms from selected locations in the Bohemian Forest, Czech Republic

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Abstract ^{137}Cs is one of the most important radionuclides released in the course of atmospheric nuclear weapon tests and during accidents in nuclear power plants such as that in Chernobyl, Ukraine, or Fukushima, Japan. The aim of this study was to compare ^{137}Cs and ^{40}K concentrations in particular species of mushrooms from selected locations in the Bohemian Forest (Czech: Šumava), Czech Republic, where a considerable contamination from the Chernobyl accident had been measured in 1986. Samples were collected between June and October 2014. Activities of ^{137}Cs and ^{40}K per dry mass were measured by means of a semiconductor gamma spectrometer. The ^{137}Cs values measured range from below detection limit to 4300 ± 20 Bq kg^{-1}, in the case of ^{40}K from 910 ± 80 to 4300 ± 230 Bq kg^{-1}. Differences were found between individual locations, due to uneven precipitation in the course of the movement of the radioactive cloud after the Chernobyl accident. There are, however, also differences between individual species of mushrooms from identical locations, which inter alia result from different characteristics of the soil and depths of mycelia. The values measured are compared with established limits and exposures from other radiation sources present in the environment. In general, it can be stated that the values measured are relatively low and the effects on the health of the population are negligible compared to other sources of ionizing radiation.

Keywords ^{137}Cs · Mushrooms · Contamination · Chernobyl · Nuclear weapon tests · Gamma spectrometry

Introduction

Forest ecosystems appear to be sites in which the radionuclide ^{137}Cs plays a particular role. Forest ecosystems can retain ^{137}Cs for a long time due to continuous cyclic transfer between the upper organic layer, bacteria, microfauna, microflora, and vegetation (Škrkal et al. 2013). ^{137}Cs with its physical half-life of about 30 years first came from atmospheric tests of nuclear weapons in the 1950s and 1960s, where the contamination was more or less homogeneous at mid-latitudes around 40°–50°, and amounted to 5 kBq m^{-2} (UNSCEAR 1982), and then from the Chernobyl nuclear power plant accident. The accident caused extensive contamination of the environment in many European countries including the territory of the former Czechoslovak Socialist Republic (Bučina et al. 1988). The severity of the contamination of soil with ^{137}Cs from this accident was considerably dependent on rain fall in the course of the movement of contaminated clouds. According to precipitation, the fallout varied considerably, being on average about 5 kBq m^{-2}, with local maxima of up to 100 kBq m^{-2} (UNSCEAR 1988). There were, therefore, locations in which the ^{137}Cs content in soil and plants was many times higher than in others.

Similar to ^{137}Cs, ^{134}Cs was also released into the environment after the Chernobyl accident. However, this radionuclide is not included in the present study, because it has a shorter physical half-life (2 years) than ^{137}Cs and the ^{134}Cs/^{137}Cs ratio is, therefore, indicative of the different times at which releases have occurred (Guillén and Baeza 2014), and of the time elapsed, since the releases

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occurred. Radiocaesium gradually migrates downwards through the soil and is bound to soil components, particularly to argillaceous minerals. In the soil, it also comes in contact with the mycelial network of mushrooms, is very efficiently taken up, transported to the fruit bodies, and accumulated therein (Borovička et al. 2012; Zalewska et al. 2016). One might expect that the absorption characteristics of the radioactive isotopes ^{134}Cs and ^{137}Cs as well as ^{133}Cs, the stable isotope, are identical. However, that does not seem to always be the case: it has been shown, for example, that on arable land freshly deposited caesium from the Chernobyl accident was more plant-available than "old" caesium from weapons fallout or stable caesium. With the years, the difference became much smaller. This "aging" effect of plant availability through root uptake was due to the fact that old caesium was fixed to clay minerals, and the fixation of the new caesium took some time. After a number of years, Chernobyl caesium was no longer plant available and transfer factors were small, similar to those for stable ^{133}Cs (Tsukada and Nakamura 1999). The situation is different in forest ecosystems, where there is cyclic transfer as mentioned above. Here, radioactive and stable caesium indeed tend to behave in a similar way (Rühm et al. 1999).

Mushrooms often display ^{137}Cs activities higher by an order of magnitude or more than other common food products. Therefore, despite being low on the consumption list, food products from the forest ecosystem can significantly add to the effective dose of a population. Higher ^{137}Cs activities in game can also be explained by the capacity of many mushrooms to accumulate radiocaesium (Škrkal et al. 2015).

There is some chemical similarity between caesium and potassium (K) which is the most abundant metallic element present in mushrooms (Zalewska et al. 2016). Therefore, the activities of ^{137}Cs in fruit bodies have often been compared with the corresponding natural content of ^{40}K. Potassium as an essential nutrient is homeostatically controlled, and thus, the activity of ^{40}K is relatively constant, depending on species and site (Falandysz and Borovička 2013).

Mushrooms are a popular part of the diet in many countries, particularly in central and east Europe (Šišák and Pulkrab 2009; Kalač 2010). Their consumption rate depends on the country, its gastronomic and cultural tradition, and the economic situation of the population. To give some examples, the average annual consumption is 0.5–16.8 kg in Germany, 10 kg in Poland, 4 kg in Belarus, and even 18 kg in Ukraine (Guillén and Baeza 2014). People in the Czech Republic belong to those most actively collecting and consuming mushrooms. Seventy-two percent of households are interested in mushrooms, 7 kg of mushrooms per household and year being collected on average (Šišák and Pulkrab 2009). Horyna (1991) reports an annual consumption of 5 kg. In individual cases, the consumption can be as high as 10 kg/year (Kalač 2001).

The present paper offers a comparison of ^{137}Cs and ^{40}K concentrations in mushrooms collected at selected locations of the Bohemian Forest (Czech: Šumava), where a considerable contamination was observed after the Chernobyl accident. This is an area frequently visited by people who are interested in collecting forest products. In south and south-west Bohemia, wild boars (Sus scrofa) with high amounts of ^{137}Cs in their meat occur quite frequently (Škrkal et al. 2015). The results obtained here were compared with those from locations, where the radioactive fallout was smaller. Effective doses which would be obtained through the consumption of the samples collected were calculated and compared with protection limits according to the Regulation of the State Office for Nuclear Safety No. 422/2016 Sb., on radiation protection and security of radioactive sources (No. 422/2016).

Methods

Samples were collected between June and October 2014 in the Bohemian Forest, southwest Bohemia, Czech Republic, particularly around the villages Churáňov, Zadov and Kvilda, where the highest values of the contamination of soil with ^{137}Cs had been measured in 1986 (Matzner 1997). For comparison, samples were also taken at other locations, where the radioactive fallout had been relatively low—the forest Jemčina in the Třeboň area, and the surroundings of the village Příbraz near Jindřichův Hradec. These locations are shown in Fig. 1.

A total of 122 samples of fruit bodies were processed and measured. The samples were categorised according to species and location. They were weighed in native condition, dried at room temperature, and weighed again, to determine the proportion of dry mass. Individual samples were measured separately.

In the same localities, where mushrooms were collected, soil samples were also taken, so as to be able to compare radioactivity concentrations. Soil samples had a size of $20\times20\times5$ cm (2000 cm^3). Sampling depth was 0–5 cm below the surface. The samples were left to dry air at about 19 °C until their weight did not change further. After drying, each sample was carefully freed from the greater part of the soil skeleton as well as from plant and animal remains, and was passed through a sieve to obtain fine earth. A specimen of this fine earth was used for further analysis after its exact weight had been determined.

Activities of ^{137}Cs and ^{40}K in all samples were determined by gamma spectrometry using HPGe detectors with a relative efficiency of 37% (Canberra, resolution 2.04 keV at 1.33 MeV) and 90% (Ortec, resolution

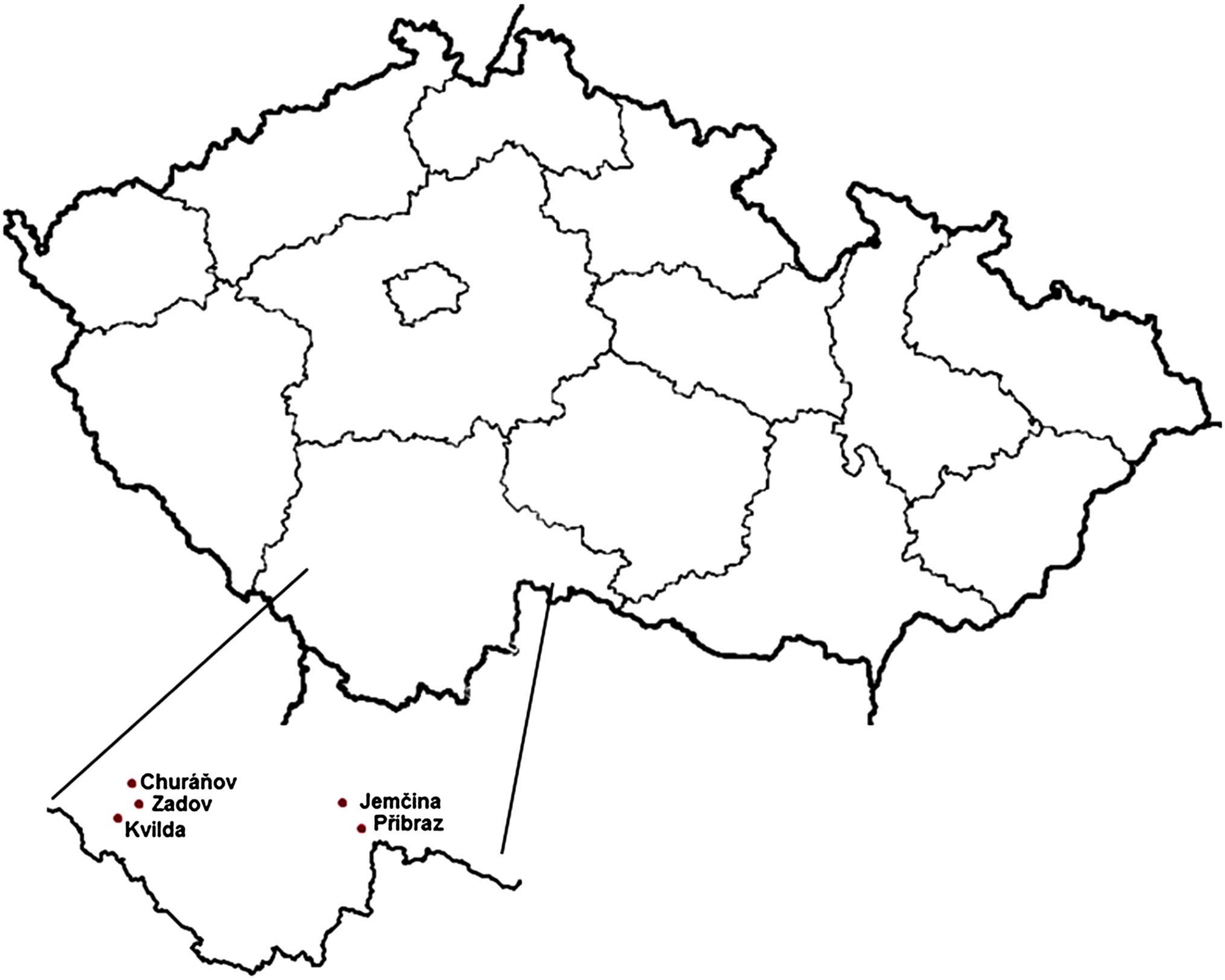

Fig. 1 Sampling location: Bohemian Forest, southwest Bohemia, Czech Republic

2.2 keV at 1.33 MeV). Mushroom samples were measured in 250 ml PET vessels or in Petri dishes, and soil samples were measured in Marinelli vessels. Peaks at energies 661.6 and 1461.6 keV were used for ^{137}Cs and ^{40}K, respectively, and efficiency calibration curve for the geometries adopted was applied. The net count rates for respective peaks were obtained by subtracting corresponding background rate, and the activity corresponding to the peaks was calculated. The relative standard deviation of the activity results was used to estimate its uncertainty. The detection limit for activity was 0.3 Bq kg^{-1} for soil and 0.8 to 18 Bq kg^{-1} for mushrooms for ^{137}Cs, and 6 Bq kg^{-1} for soil and 16–300 Bq kg^{-1} for mushrooms for ^{40}K (depending on sample mass and measurement time). The spectra obtained in the measurements were evaluated using the GAMAT software (Matzner 2003). The measuring time was 6 to 24 h.

The results of these measurements are given as means ± measurement uncertainty (one sigma). In cases where more than one fruit body was available for one species and locality, the fruit bodies were measured together and the result represents that species in that locality.

Results and discussion

The measured activities of ^{137}Cs and ^{40}K per mass unit in dry and fresh samples from individual locations are shown in Table 1. For comparison, the samples are divided into mushrooms from the order *Boletales* (B) (this group of fungi is mostly ectomycorhizal, which means that they need certain tree species in their vicinity for growth; their spores develop in small pores on the underside of the cap), and gilled mushrooms from the order *Agaricales* (A) (this

Table 1 Activity concentrations of ^{137}Cs and ^{40}K in mushroom samples and measurement uncertainty (one sigma) (*A* Agaricales, *B* Boletales, *n* number of samples)

Location	GPS	Samples/species		Activity concentration (Bq kg^{-1})			
				Dry mass		Fresh mass	
				^{137}Cs	^{40}K	^{137}Cs	^{40}K
Churáňov	N 49°4.14962′, E 13°36.60285′	*Xerocomus chrysenteron* (*n* = 4)	B	560 ± 10	910 ± 80	130 ± 2	220 ± 20
Churáňov	N 49°4.14962′, E 13°36.60285′	*Boletus edulis* (*n* = 3)	B	4300 ± 20	1020 ± 60	530 ± 3	130 ± 7
Churáňov	N 49°4.14962′, E 13°36.60285′	*Russula ochroleuca* (*n* = 4)	A	1300 ± 10	1200 ± 60	170 ± 2	160 ± 10
Churáňov	N 49°4.14962′, E 13°36.60285′	*Russula integra* (*n* = 5)	A	470 ± 20	1200 ± 200	70 ± 3	170 ± 30
Churáňov	N 49°4.14962′, E 13°36.60285′	*Cantharellus cibarius* (*n* = 6)	A	370 ± 20	2100 ± 200	24 ± 1	130 ± 10
Churáňov	N 49°4.14962′, E 13°36.60285′	Soil		310 ± 2	140 ± 7	130 ± 1	60 ± 4
Zadov	N 49°4.78338′, E 13°37.23238′	*Leccinum scabrum* (*n* = 5)	B	770 ± 10	1200 ± 80	80 ± 1	120 ± 8
Zadov	N 49°4.78338′, E 13°37.23238′	*Russula chlorides* (*n* = 2)	A	430 ± 10	1200 ± 80	50 ± 1	140 ± 8
Zadov	N 49°4.78338′, E 13°37.23238′	*Russula emetica* (*n* = 7)	A	3100 ± 20	1200 ± 60	300 ± 6	110 ± 6
Zadov	N 49°4.78338′, E 13°37.23238′	Soil		450 ± 3	380 ± 2	200 ± 1	170 ± 1
Kvilda	N 49°0.56667′, E 13°36.76667′	*Boletus luridiformis* (*n* = 4)	B	4200 ± 20	1000 ± 30	220 ± 1	50 ± 2
Kvilda	N 49°0.56667′, E 13°36.76667′	*Lactarius rufus* (*n* = 4)	A	990 ± 20	2000 ± 160	130 ± 3	260 ± 20
Kvilda	N 49°0.56667′, E 13°36.76667′	*Lactarius volemus* (*n* = 4)	A	2600 ± 30	1300 ± 150	360 ± 4	190 ± 20
Kvilda	N 49°0.56667′, E 13°36.76667′	*Russula violacea* (*n* = 5)	A	70 ± 10	1200 ± 217	10 ± 2	170 ± 30
Kvilda	N 49°0.56667′, E 13°36.76667′	*Cantharellus cibarius* (*n* = 9)	A	1000 ± 30	1500 ± 190	130 ± 3	190 ± 20
Kvilda	N 49°0.56667′, E 13°36.76667′	*Tricholoma fulvum* (*n* = 6)	A	3800 ± 30	1500 ± 120	300 ± 2	120 ± 10
Kvilda	N 49°0.56667′, E 13°36.76667′	Soil		300 ± 3	350 ± 6	110 ± 1	130 ± 2
Příbraz	N 49°2.66045′, E 14°54.98368′	*Boletus luridiformis* (*n* = 6)	B	760 ± 10	1600 ± 40	70 ± 1	150 ± 4
Příbraz	N 49°2.66045′, E 14°54.98368′	*Xerocomus chrysenteron* (*n* = 4)	B	70 ± 6	1200 ± 110	6 ± 1	110 ± 10
Příbraz	N 49°2.66045′, E 14°54.98368′	*Xerocomus pruinatus* (*n* = 4)	B	1200 ± 20	1200 ± 110	160 ± 3	170 ± 20
Příbraz	N 49°2.66045′, E 14°54.98368′	*Amanita rubescens* (*n* = 4)	A	1020 ± 20	4300 ± 230	80 ± 2	330 ± 20
Příbraz	N 49°2.66045′, E 14°54.98368′	*Laccaria amethystina* (*n* = 6)	A	80 ± 20	2900 ± 440	7 ± 2	220 ± 30
Příbraz	N 49°2.66045′, E 14°54.98368′	*Lactarius volemus* (*n* = 4)	A	40 ± 6	1000 ± 140	4 ± 1	110 ± 20
Příbraz	N 49°2.66045′, E 14°54.98368′	*Lactarius rufus* (*n* = 3)	A	280 ± 10	1900 ± 70	30 ± 1	180 ± 7
Příbraz	N 49°2.66045′, E 14°54.98368′	*Cortinarius terpsichores var. calosporus Melot* (*n* = 3)	A	700 ± 10	1200 ± 70	80 ± 1	150 ± 10
Příbraz	N 49°2.66045′, E 14°54.98368′	*Entoloma vernum* (*n* = 6)	A	1800 ± 20	1900 ± 150	280 ± 4	290 ± 20
Příbraz	N 49°2.66045′, E 14°54.98368′	Soil		40 ± 1	200 ± 4	17 ± 1	80 ± 2
Jemčina	N 49°8.44872′, E 14°51.43950′	*Boletus luridiformis* (*n* = 7)	B	400 ± 10	1300 ± 110	40 ± 1	120 ± 10
Jemčina	N 49°8.44872′, E 14°51.43950′	*Macrolepiota procera* (*n* = 2)	A	<6	970 ± 160	< 1	80 ± 10
Jemčina	N 49°8.44872′, E 14°51.43950′	*Russula ochroleuca* (*n* = 5)	A	250 ± 10	1200 ± 70	30 ± 1	130 ± 10
Jemčina	N 49°8.44872′, E 14°51.43950′	Soil		80 ± 2	250 ± 3	50 ± 1	150 ± 2

group of fungi have gills at the underside of the cap, on which the spores are produced).

Mushrooms belong to the most important components of forest ecosystems, and considerably affect the fate of radionuclides. Mushrooms play an important role in the mobilization, intake, and translocation of nutrients (Kalač 2010; Falandysz and Borovička 2013) and radionuclides (Steiner et al. 2002). They show a high capability for the accumulation of mineral nutrients and ^{137}Cs (Guillitte et al. 1994; Falandysz and Borovička 2013).

The ^{137}Cs activity per unit mass measured in the investigated mushroom samples shows a considerable spread, even within individual locations. In fungi of the order *Boletales*, ^{137}Cs contents ranged between 70 and 4300 Bq kg^{-1} dry mass (d.m.). In *Agaricales*, the values measured were lower in general; in one case, the value was even lower than the minimum significant activity (less than 6 Bq kg^{-1}), and the maximum value was 3800 Bq kg^{-1}.

The results obtained agree with those of other studies confirming considerable differences between particular species of fungi as well as the fact that the highest concentration of ^{137}Cs is present in the most favourite Boletales fungi. Dvořák et al. (2006) recommended that special attention should be paid to species accumulating ^{137}Cs such as those from the family *Boletaceae*, order *Boletales*. This is also supported by a fact that in 1986, the highest values were measured in fungi from this family, as, for example, in *Boletus* (*Xerocomus*) *badius* (UNSCEAR 1988). In the same species, the highest values of ^{137}Cs contents are also mentioned by Falandysz et al. (2015). In the present study, this particular species could not be found. However, here, the highest activity per mass unit was found in samples of *Boletus edulis* from Churáňov, 4300 Bq kg^{-1} d.m. and *Boletus luridiformis* 4200 Bq kg^{-1} d.m., from Kvilda. Interestingly, Klán et al. (1988) and Horyna and Řanda (1988) reported that mushrooms accumulating the highest amounts of radioactive caesium included those from the family *Boletaceae*, but with the exception of *B. edulis* and *Boletus aestivalis*.

A rather high activity was also measured in a sample of *Tricholoma fulvum* (3800 Bq kg^{-1} d.m.), which belongs to the gilled mushrooms, coming from the same location as the *Boletaceae* just mentioned. This high value may be related to a high ^{137}Cs concentration in the soil. Another factor could be the time over which ^{137}Cs was accumulated, i.e., the age of the mushrooms.

Kalač (2001) in his review presents a table which classifies species of mushrooms according to their ability to accumulate radiocesium: high (e.g., *Xerocomus badius, Xerocomus chrysenteron*, and *Laccaria amethystina*), moderate (e.g., *Leccinum scabrum*), and low (e.g., *B. edulis, Cantharellus cibarius, Macrolepiota procera*, and *Amanita rubescens*). This classification does not agree in all aspects with the results of the present study: as mentioned above, rather high activities were found here in *B. edulis* and *A. rubescens*, but by contrast low activities in *L. amethystina*.

In the Czech Republic, a relatively broad spectrum of mushrooms was investigated in the years 2004–2011 by Škrkal et al. (2013), who reported the highest geometric mean of ^{137}Cs concentrations in mushrooms of the family *Suillaceae* (1050 Bq kg^{-1} d.m.) and in *B. badius* (930 Bq kg^{-1} d.m.). For mushrooms of the family *Boletaceae*, which was represented by 359 samples, the geometric mean was 462 Bq kg^{-1} d.m. with a range from 0.8 to 11,800 Bq kg^{-1} d.m. For samples of *B. badius*, the geometric mean was 930 Bq kg^{-1}, for *B. edulis* 606 Bq kg^{-1} and for *B. chrysenteron* 159 Bq kg^{-1} d.m. The maximum values (11,800 Bq kg^{-1} d.m. for *B. edulis* and 8890 Bq kg^{-1} d.m. for *B. chrysenteron*, respectively) were higher than in any of the cases investigated in the present study. Considering the physical half-life of caesium, the lower activity concentration may simply be related to the year of sampling. Other reasons for these differences are known to be mycelium location (Rühm et al. 1997) and the dynamics of radiocaesium in different types of forest soil (Rühm et al. 1996). Absolute radiocaesium activities tend to vary considerably in fruit bodies of the same species depending on year and locality (Rühm et al. 1998). Mushrooms found in the Šumava region showed higher radiocaesium concentrations than those from the area near Jindřichův Hradec or near Újezd (Havránek and Havránková 2008). In the samples of gilled mushrooms, the concentration of ^{137}Cs was lower, namely, between less than the minimum significant activity and 5980 Bq kg^{-1} d.m., with an average of 39 Bq kg^{-1} d.m. (Škrkal et al. 2013).

As mentioned above, Dvořák et al. (2006) reported the highest concentration of ^{137}Cs in mushrooms of the family *Boletaceae*, values ranging from 32 to 6263 Bq kg^{-1} d.m., where the highest values belonged to *X. badius* (6263 and 6240 Bq kg^{-1} d.m.) from the localities of Staré and Nové Ransko. Their report makes it also clear, however, that ^{137}Cs concentrations can be quite different in one and the same locality, as another samples of *X. badius* contained only 400 Bq kg^{-1} d.m. In samples from Slovakia, the highest concentrations were found in *S. luteus* (966 Bq kg^{-1} ^{137}Cs d.m.), or—within the family of *Boletaceae*—in *X. badiux* a *B. edulis* (720, resp. 716 Bq kg^{-1} d.m.).

A similarly high concentration as in the present study was found by Falandysz et al. (2015) in samples of *B. edulis* collected in the year 2000 in the Sudetes region (southwestern Poland), 5722 Bq kg^{-1} d.m. in the cap, and 3485 Bq kg^{-1} d.m. in the stipes, and a somewhat lower concentration of 1358 Bq kg^{-1} d.m. was measured in samples from Pomerania in the year 2007. Three years later in the same region, measured activities in *B. edulis* were 497 Bq kg^{-1} for the cap and 265 Bq kg^{-1} for the stipes. The study compared these values with results obtained for mushrooms of the same species collected in China (Yunnan) in the years 2011–2014, where the concentrations were just a few Bq kg^{-1} d.m.

Finally, in a study which compared mushrooms from different countries (Szántó et al. 2007), the concentration of ^{137}Cs ranged from 0.6 to 4300 kg^{-1} d.m., for *B. edulis*, with 420 Bq kg^{-1} in the sample from the Czech Republic, 390 Bq kg^{-1} in the sample from Belgium, and 45 Bq kg^{-1} in the sample from Hungary. These values are an order of magnitude smaller than those in the sample from the Šumava region collected in the present study. The concentration of ^{137}Cs d.m. in *C. cibarius* from Belgium was 370 Bq kg^{-1} d.m. which is similar to the present values for the sample from Kvilda, Šumava region (370 Bq kg^{-1} d.m.), but smaller than that for the sample from Churáňov (1000 Bq kg^{-1} d.m.).

The paper of Falandysz et al. (2016) presents some results for *Cantherelle* mushrooms in Poland. The activity concentrations of ^{137}Cs in samples of this mushroom from different places in Poland varied from 64 ± 3 to 1600 ± 47 Bq kg^{-1} d.m. in 1997–2004 and 4 ± 1 to 1400 ± 15 Bq kg^{-1} d.m. in 2006–2013.

The ^{137}Cs concentration in mushrooms depends on the depth and structure of mycelia and the vertical activity distribution (which in turn is related to the time elapsed since the first contamination) (Byrne 1998; Rühm et al. 1998; Duff and Ramsey 2008; Gwynn et al. 2013; García et al. 2015). The ability of fungi to accumulate ^{137}Cs is also affected by a number of other factors, such as the type of the soil and its moisture, the mode of nutrition (for example, saprophytic versus symbiotic), the type of the forest, etc (for example, Horyna and Řanda 1988; Guillette et al. 1994; Gwynn et al. 2013; Lehto et al. 2013; Guillén and Baeza 2014). The concentration of ^{137}Cs is also dependent on the part of the fungus: radiocaesium is unevenly distributed and different concentrations are found in different parts of the fungus (Heinrich 1993; Kalač 2001). No dependence of the ^{137}Cs concentration in fungi on the altitude above the sea level has been demonstrated (Dvořák et al. 2006).

Comparing different locations, it is obvious that samples of mushrooms collected in the Bohemian Forest show higher ^{137}Cs values than those from other areas. The difference between individual locations, even on a small scale, is probably caused by non-homogeneous Chernobyl fallout (the precipitations affected only part of the territory) and by local conditions (e.g., the presence of deciduous trees, which are able to retain more radioactive fallout due to the large surface of their crown and thus enhance the contamination in the immediate vicinity after the leaves fall), and thus by different concentrations of ^{137}Cs in the soil.

To correlate ^{137}Cs concentrations in the soil substrate and in mushrooms, the activity of ^{137}Cs per mass unit was also determined in the soil (Table 1). Soil samples taken in the Bohemian Forest show higher activities (Kvilda 300 ± 2 Bq kg^{-1}, Churáňov 310 ± 2 Bq kg^{-1}, Zadov 450 ± 3 Bq kg^{-1}) compared to those from localities, where the Chernobyl fallout was lower (Jemčina 80 ± 1 Bq kg^{-1}, Příbraz 40 ± 1 Bq kg^{-1}). The results exhibit a direct proportionality between the activity in mushrooms and that in the soil substrate. This is also mentioned by Bulko et al. (2014). The higher the ^{137}Cs concentration in the soil, the higher amounts are also present in the mushroom.

Transfer factors and concentration ratios are a popular approach to quantify the transfer of radionuclides from soil to green plants or fungal fruit bodies. The transfer factor is defined as the ratio of the activity concentration in fungal fruit bodies or green plants divided by the activity concentration of the specific soil layer exploited by the mycelium. This has proven to be a useful concept, especially in connection with dynamic radioecological models. It is implicitly assumed that the radionuclide concentrations in green plants or fungal fruit bodies are directly proportional to soil contaminations (Steiner et al. 2002). It has to be mentioned, however, that it is difficult to estimate the transfer factor of radiocaesium for samples growing in forest and natural ecosystems because of heterogeneity in radiocaesium distribution in the forest soil column and also because of the varying depth of plants roots and fungal mycelia (Yoshida et al. 2004.).

The ^{137}Cs activity per mass unit was compared with that of the natural radionuclide ^{40}K. The latter is the most extensively studied of all naturally occurring radionuclides, and it is usually determined simultaneously together with radiocesium. As potassium is an essential nutrient, its concentration is homeostatically controlled in cells, its range of variation is limited and common values reported for ^{40}K are in the range 1000–2000 Bq kg^{-1}d.m. (Guillén and Baeza 2014). The activity of ^{40}K per mass unit and concentration of potassium in mushrooms is more or less the same in all samples (Table 1). This is similar to what has been observed in other plants, since potassium is one of principal elements in living organisms (Baeza et al. 2004; Kuwahara et al. 2005). The values measured in the present study ranged between 1000 and 2000 Bq kg^{-1} d.m. with the exception of just four samples, which is in agreement with Guillén and Baeza (2014). In one of these exceptional cases, the value was somewhat lower (910 Bq kg^{-1} d.m.)—a sample of *Boletus chrysenteron* from the location Churáňov. Values higher than 2000 Bq kg^{-1} d.m. were found in three samples. In one case, the value was only moderately exceeded (2100 Bq kg^{-1} d.m.)—in *C. cibarius* from Churáňov. In *Laccaria amethystine*, the activity of ^{40}K per mass unit was 2900 Bq kg^{-1} d.m., and the highest value (4300 Bq kg^{-1} d.m.) was measured in *A. rubescens*. These two cases were mushrooms from the locality Příbraz. It is possible that the high concentration of ^{40}K in these samples results from the use of fertilisers in the vicinity. In addition to fertilisers, the ^{40}K concentration is also affected by the geological structure of the area, the method of soil cultivation and many other factors (Kuwahara et al. 2005). Similar concentrations of ^{40}K in mushrooms as found in the present study have been reported by other authors (e.g., Mietelsky et al. 1994; Baeza et al. 2004; Falandysz et al. 2015, 2016).

Although caesium is a chemical analogue of potassium, no correlation between ^{137}Cs and ^{40}K was found in the present study. This is in agreement with results reported by Ban-Nai et al. (2004), Guillén and Baeza (2014), Rakič et al. (2014) and others. It suggests that there are different mechanisms of absorption for the two elements (Mietelsky et al. 1994; Baeza et al. 2004; Guillén and Baeza 2014). No difference regarding nutritional mechanism has been reported (Guillén and Baeza 2014).

To enhance the understanding of the relevance of contamination through mushroom consumption, the effective dose for an individual who eats 10 kg of mushrooms in the course of 1 year was estimated. This amount was chosen in agreement with other studies (Klán et al. 1988; Kalač 2001; Borovička et al. 2012; Škrkal et al. 2013) which mention 10 kg as being in the high range, but not entirely atypical for the Czech Republic. The highest activity per mass unit found in the present was used in the calculation, i.e., a ^{137}Cs activity per mass unit of 530 Bq kg^{-1} in fresh mass found in a sample of *B. edulis* from the location Churáňov in the Bohemian Forest. When taking into account the conversion factor of 1.3 × 10^{-8} Sv/Bq for the intake of ^{137}Cs (ICRP 2012), a value for the effective dose of about 70 µSv per year was obtained. This is quite far below the established radiation protection limit for the general population of 1 mSv (Regulation of the State Office for Nuclear Safety 2016). For comparison, Horyna (1991) argued that the typical annual consumption of mushrooms is closer to 5 kg, and assumed an average activity of 300 Bq kg^{-1} in the native condition. The resulting effective dose in this case would be only 20 µSv. Škrkal et al. (2013) for their dose calculation assumed a range of intakes from 0.5 to 480 Bq annually and an annual consumption of 1.9 kg of fresh mushrooms which resulted in effective doses of 0.006–6 µSv.

For the present estimate of effective doses, a very conservative approach was chosen, as it is usually done by assuming a worst case scenario, i.e., the highest measured activity concentration in mushrooms, maximum annual consumption, and use of the mushrooms without cooking or other processing. The same approach was taken by other authors, e.g., Guillén and Baeza (2014), who reported a range of effective doses from mushroom consumption in different countries from 1.47 × 10^{-4} to 150 µSv, with 1.4 × 10^{-5} µSv for the Czech Republic.

As already mentioned, the amount of mushrooms consumed is a key factor in dose estimation. Since mushrooms are usually not a major part of alimentation, there is only little data about their consumption (Guillén and Baeza 2014; Škrkal et al. 2015). However, some surveys of mushroom consumption have been carried out. The range of consumption for different countries is 0–20 kg per year, in Great Britain up to 26 kg per year and in Norway up to 58 kg per year (Guillén and Baeza 2014).

Whereas the above estimate of the effective dose due to ingestion is quite conservative, mushrooms are not usually eaten raw. They are generally cooked and consumed immediately or preserved (Guillén and Baeza 2014). Some cooking procedures (for example boiling, pickling, salting) can significantly reduce the radionuclide content of mushrooms (Klán et al. 1988; Kalač 2001; Guillén and Baeza 2014; Falandysz et al. 2015, 2016). As part of the present study, some tentative measurements were performed on samples of *B. edulis* and *L. scabrum* boiled in distilled or drinking water for 30 min. In the case of *B. edulis*, the ^{137}Cs concentration was reduced by 96% in distilled and 90% in drinking water; for *L. scabrum*, the corresponding values were 87 and 65%, respectively. In the latter case, the findings are in good agreement with those of Guillén and Baeza (2014), namely, 40–87%. Klán et al. (1988) reported that "during cooking of *X. badius* and *X. chrysenteron* slices, 80 and 87% ^{137}Cs was released into cooking water after 5 and 20 min, respectively". In the case of *B. edulis*, values obtained in the present study are somewhat higher, but still similar. On the other hand, it should be kept in mind that there are certainly procedures of meal preparation that save nearly all ^{137}Cs of the mushrooms in the meal (Škrkal et al. 2013).

Conclusion

This study shows that the ^{137}Cs concentration in mushrooms from the Bohemian Forest 30 years after the Chernobyl accident are still significant. The values of activities per mass unit of dry mass were in the order of hundreds to thousands of Bq kg^{-1}. The highest values measured were found in *Boletaceae*, which is in agreement with values reported in the previous studies. The highest activity concentration was registered in samples of *B. edulis* from Churáňov (4300 Bq kg^{-1} d.m.) and samples of *B. luridiformis* from Kvilda (4200 Bq kg^{-1} d.m.). A conservative approach under the assumption that 10 kg of fresh mushrooms are consumed annually leads to an estimate for the annual effective dose of about 70 µSv. The annual effective doses expected from ingestion of these products, even for "mushroom lovers" are nevertheless negligible compared to doses from other sources of ionizing radiation, and reach only a small fraction of the radiation protection limit for the general population of 1 mSv per year. In comparison, one may refer to the overall annual effective dose from natural sources of ionizing radiation, which is 2.4 mSv on average worldwide (UNSCEAR 2010); for the Czech Republic, it is 3.4 mSv due to a considerably higher contribution from radon (Klener 2000).

The ^{40}K activities found in the samples measured here were very similar one to another with just a few exceptions. Measured values were mostly in the range of 1000–2000 Bq kg^{-1} d.m. Particularly, high values in samples from Příbraz (*A. rubescens*—4300 Bq kg^{-1} d.m.) were apparently associated with the use of fertilizer. Potassium ^{40}K is evenly distributed throughout the body and its level is kept constant by homeostasis and is thus less of a concern for human health than ^{137}Cs (De Castro et al. 2012).

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