

Artificial ^{137}Cs and natural ^{40}K in mushrooms from the subalpine region of the Minya Konka summit and Yunnan Province in China

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Abstract A study on ^{137}Cs pollution and activity concentrations of ^{40}K in mushrooms of the genera *Cortinarius*, *Leccinum*, *Russula*, *Tricholoma*, *Tylopilus*, and *Xerocomus* from two neighboring regions in southwest China in 2010–2013 revealed different patterns of pollution with ^{137}Cs , which seemed to be highly dependent on climate conditions. *Tricholoma matsutake* was collected in Yunnan before and after the Fukushima Dai-ichi nuclear accident and showed similar contamination with ^{137}Cs . Mushrooms from the elevation of 2800–3480 m above sea level on the east slope of Minya Konka and forest topsoil showed higher contamination with ^{137}Cs than mushrooms from the highlands of Yunnan. In detail, the activity concentration of ^{137}Cs in caps of mushrooms from Minya Konka were in the range 62 ± 6 – $280 \pm 150 \text{ Bq kg}^{-1}$ dry biomass and from Yunnan at < 4.4 – $83 \pm 3 \text{ Bq kg}^{-1}$ dry biomass. The climate in the region of the Minya Konka is much colder than in Yunnan, which seems to favor deposition of ^{137}Cs at higher altitudes from global atmospheric circulation. The activity concentration of ^{40}K in mushrooms and soils highly exceeded that of ^{137}Cs . The assessed annual effective doses for ^{137}Cs in 1 kg of consumed

mushrooms of the genera *Leccinum* and *Xerocomus* in Yunnan were low, i.e., in the range < 0.0043 – $0.049 \pm 0.004 \mu\text{Sv}$, while those for ^{40}K were 0.26 ± 0.02 – $0.81 \pm 0.09 \mu\text{Sv}$.

Keywords Asia · Forest · Mushrooms · Topsoil · Radiocaesium · Potassium

Introduction

One of the most important anthropogenic radioactive contaminants in the environment is caesium 137 (^{137}Cs). It has a relatively long half-life of 30.05 years while the half-life of isotope ^{134}Cs is 2.07 years. ^{137}Cs contaminated the environment worldwide as a result of the nuclear weapon detonations and nuclear power plant accidents. The atmospheric nuclear weapon detonations were conducted largely in the northern hemisphere from 1945 until the end of the 1970s, in West China up to 1980 and also in the South Pacific Ocean (Präválie 2014). Further, the nuclear power plant accident in Chernobyl in 1986 caused a serious radioactive contamination in Europe and beyond. A recent large-scale accident in the Fukushima Dai-ichi in 2011 also caused the release of significant amounts of radionuclides, mainly iodine and caesium isotopes (Steinhauser et al. 2014).

Food safety after Fukushima became the most pressing and most current issue with respect to radionuclide contaminations, since the results of food monitoring campaigns in Japan showed a specific contamination with ^{137}Cs of mushrooms and meat of game animals, such as wild boars (*Sus scrofa*), which eat mushrooms (Merz et al. 2015). Many mushrooms growing in the wild are known to be highly prone to contamination with artificial or natural radioactive compounds but also with heavy metals deposited or contained in

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the top layer of forest soils due to geochemical anomalies of parent soil material (Falandysz et al. 2017; Kirchner and Dailliant 1998; Vaaramaa et al. 2009). Mushrooms from the wild are valued as organic food, and they still accumulate radionuclides and especially ^{137}Cs from the environment as a result of atmospheric nuclear weapon detonations and after major nuclear accidents (Betti et al. 2017; Chatterjee et al. 2017; Cocchi et al. 2017; Grodzinskaya et al. 2013; Letho et al. 2013; Saniewski et al. 2016; Steinhauser and Steinhauser 2016; Strumińska-Parulska et al. 2016).

Radioactive debris from nuclear detonations in the atmosphere at the high concentrations were observed in the stratosphere, and those from the accident in Chernobyl were spread largely near ground level and in a smaller portion also at the altitude of up to 15 km (Kownacka 2001). ^{137}Cs from the explosions in the atmosphere was spread throughout the atmosphere and deposited worldwide by means of both wet precipitation and dry deposition. It generally disappears from the stratosphere within a year after an event (Kownacka and Jaworowski 1994). Atmospheric removal of ^{137}Cs following the Chernobyl accident was high at locations with heavy rain and caused hot spot pollution of soils in some parts of Europe (Smith 1994; Strzelecki et al. 1993). Mountain ecosystems can be specifically prone to radioactive fallout after nuclear weapon detonations in the atmosphere and after major nuclear accidents (Salt 2007).

Little or nothing is known on radioactive fallout in the high montane regions of the World. We hypothesize that the subalpine area of Minya Konka (also called Mount Gongga or Gongga Shan) because of its Himalayan dimension, colder climate and geographical location, is more prone to contamination with ^{137}Cs , and that forest soils and mushrooms there are more affected, when compared to neighboring areas at lower elevation, e.g., Yunnan Province, which borders to the Minya Konka region from the south. The Minya Konka region can receive some artificial radionuclides from nuclear detonations in the atmosphere and nuclear power plant accidents largely via the air mass currents at high altitudes from the global westerly circulation rather than from the East Asian and Indian monsoons. Those monsoons carry air masses and possible contaminants into the eastern regions of the Tibetan Plateau and Minya Konka in the Sichuan Province from the Pacific Ocean and regions of southern or southeastern Asia. To verify the hypothesis, both mushrooms and forest soil were sampled from the eastern slope in the subalpine area of Minya Konka and across Yunnan Province of China. They were examined for activity concentrations of ^{137}Cs and in parallel also for natural ^{40}K using a gamma spectrometer with a high purity germanium detector. In addition, information on ^{137}Cs contamination and ^{40}K accumulated in the flesh of some *Cortinarius*, *Leccinum*, *Russula*, *Tricholoma*, *Tylopilus*, and *Xerocomus* species from those two regions of different geography, topography, and climate conditions in southwest China,

for which no previous information is available, were discussed.

Materials and methods

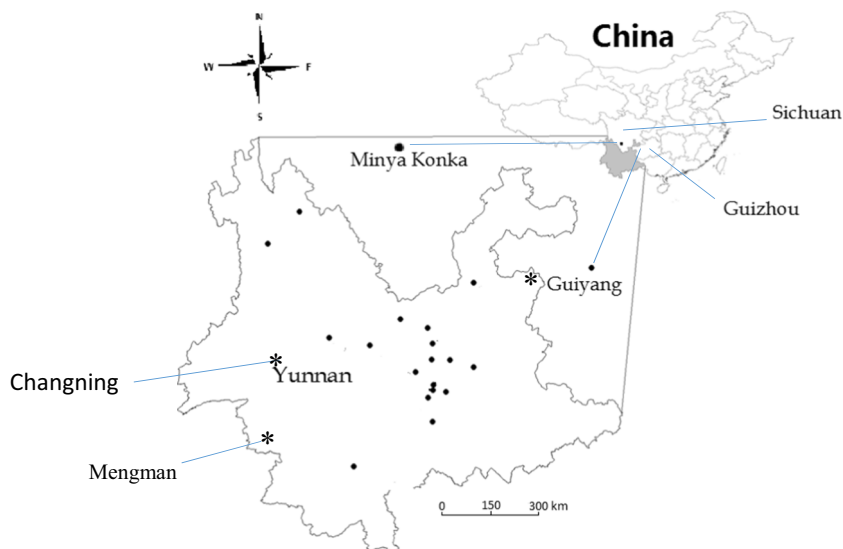
Two forest topsoil (dark soil) samples collected from the region of Minya Konka in 2012 and two red soils cores collected in Yunnan in 2016 and several species of mushrooms collected there were available for study (Fig. 1). Mushroom names in this study follow the nomenclature of Species Fungorum (Species Fungorum 2015). Mushrooms examined in this study include *Cortinarius bovinus* Fr. and *C. collinitus* Fr., *Leccinum atrostitipatum* Smith et Watling—current name *Leccinum versipelle* (Fr. & Hök) Snell, *L. chromapes* (Forst.) Sing, *L. extremiorientale* (L.Vass.) Singer, *L. griseum* (Quél.) Sing, *L. rugosiceps* (Peck) Sing, *L. scabrum* (Bull.) Gray, *L. variicolor* Watling and *L. versipelle* (Fr. & Hök) Snell, *Russula grisea* Fr. and *R. puellaris* Fr., *Tricholoma pessundatum* (S.Ito et Imai) Sing., *Xerocomus spadiceus* (Fr.) Quél—current name *Boletus ferrugineus* Schaeff. and *X. versicolor* E.-J. Gilbert—current name *Hortiboletus rubellus* (Krombh.) Simonini, Vizzini & Gelardi (Table 2) (Species Fungorum 2015).

Each fruit body was separated into cap (with skin) and stipe in order to examine the distribution of ^{137}Cs and ^{40}K between the morphological parts of the mushrooms (Table 2). The individual cap and stipe samples were sliced into pieces using a disposable plastic knife and pooled for each site ($n = 7$ to 10 individuals per pool)—with composite samples representing each species, sampling location, and time of collection (Table 2). Subsequently, the mushroom samples were dried in plastic shelves of a commercial electric dryer (model: Ultra FD1000 dehydrator, Ezidri, Australia) at 65 °C to constant mass. Dried fungal materials were pulverized in a porcelain mortar that was cleaned using a laboratory brush, deionized water, and detergent and further rinsed with distilled water and dried in an electrically heated laboratory dryer at 105 °C. The samples were kept in sealed polyethylene bags under dry conditions.

Topsoil (0–10 cm layer) samples from the Minya Konka region were dark soil and topsoil samples (layers of different length) from Yunnan were red earths. They were examined under the same conditions as mushrooms and data were presented on dry matter content (Table 1).

Activity concentrations of ^{137}Cs and ^{40}K were determined using a gamma spectrometer with coaxial HPGe detector with a relative efficiency of 18% and a resolution of 1.9 keV at 1.332 MeV (with associated electronics) (Zalewska and Saniewski 2011). The equipment was calibrated using a multi-isotope standard, and the method was fully validated. The reference solution, “Standard solution of gamma emitting

Fig. 1 Localization of the sampling sites (for details see Tables 1 and 2)



isotopes, code BW/Z-62/27/07” produced at IBJ-Świerk near Otwock in Poland, was used for preparing reference samples for equipment calibration. The same geometry of cylindrical dishes with 40 mm diameter (as applied for environmental samples) was used for reference samples during equipment calibration. Values of ¹³⁷Cs and ⁴⁰K cap to stipe concentration quotients (index Q_{c/s}) were also calculated.

The laboratory involved was subjected to routine checks to ensure high standards of analytical quality and analytical control and participated successfully in the inter-comparison exercises organized by IAEA-MEL Monaco (IAEA-414, Irish and North Sea Fish) to confirm the reliability and accuracy of the method (Zalewska and Saniewski 2011). Repeated analysis gave values of ¹³⁷Cs, 5.06 ± 0.64 Bq kg⁻¹ d.b. and ⁴⁰K, 474.5 ± 19.3 Bq kg⁻¹ d.b., while the estimated target values were equal to 5.18 ± 0.10 Bq kg⁻¹ d.b. for ¹³⁷Cs and 481 ± 16 Bq kg⁻¹ d.b. for ⁴⁰K. In the gamma spectrometry measurements, the limit of quantification was calculated using GENIE 2000 as a Minimum Detectable Activity (MDA) as

defined by Curie (1968). All numerical data gained were recalculated for dehydrated fungal material (at 105 °C) and all data were decay corrected back to the time of sampling.

Results and discussion

¹³⁷Cs and ⁴⁰K activity concentrations in topsoil Activity concentrations of ¹³⁷Cs in topsoil (dark soil, 0–10 cm layer) collected from the stands of *Cortinarius collinitus* in Minya Konka was in the range 41 ± 1–79 ± 2 and was an order of magnitude less for topsoil layers (0–5 and 0–10 cm) from two sites in Yunnan (Table 1). The upper layer (0–10 cm) of soils from the locations in Yunnan was evidently less polluted with ¹³⁷Cs compared to Minya Konka.

Results on a weaker contamination with ¹³⁷Cs in topsoil in this study correspond well with a few data available for soils from a region situated around 1000 km west of the locations in Yunnan. Namely, soils (sample size n = 26) from the eastern

Table 1 Activity concentrations of ¹³⁷Cs and ⁴⁰K (Bq kg⁻¹ dry matter ± a counting uncertainty) in forest topsoil

Site	Month and year	Elevation (m a.s.l.)	Topsoil layer (cm)	Bq kg ⁻¹ d.m.	
				¹³⁷ Cs	⁴⁰ K
Minya Konka	July, 2012	3000	0–10	79 ± 2	280 ± 16
Minya Konka	July, 2012	3000	0–10	41 ± 1	500 ± 20
Yunnan, Changning	October, 2016	1950	0–1	2.8 ± 0.8	270 ± 24
			1–5	7.5 ± 0.7	340 ± 19
			5–10	0.5 ± 0.4	320 ± 16
Yunnan, Mengman	October, 2016	908	0–1	0.7 ± 0.5	160 ± 16
			1–5	4.9 ± 0.6	170 ± 16
			5–10	3.3 ± 0.3	150 ± 14
			10–25	< 0.5	160 ± 12

a.s.l. above sea level

part of Kumaun Himalaya (west of Nepal) in India at an elevation of around 2000 m a.s.l. showed activity concentrations of ^{137}Cs at 2.8 ± 2.2 (range 0.4–8.2) Bq kg^{-1} (Ramola et al. 2011), which were at the same order of magnitude as those in Yunnan (Table 1). Weather condition (primarily wet deposition) has a great effect on removing of airborne pollutants from the atmosphere. ^{137}Cs from aboveground nuclear detonations and global circulation in the stratosphere can re-enter the lower atmosphere and further precipitate on the earth's surface by wet precipitation (Longmore 1982), and this was noted for fallout from the Chernobyl accident (Smith 1994; Strzelecki et al. 1993). A “hot spot” type contamination as has been evidenced for a forested land affected by ^{137}Cs deposited from the Chernobyl accident release can also be an example (Mietelski et al. 2010). In a study by DeWayne et al. (1999), ^{137}Cs become trapped at greater than background activity concentrations in glacier ice during the 1940s–1960s and also in 1998 in the Nangpai Gosum Glacier, which is located 25 km west northwest of Mount Everest in the Himalayas of Nepal.

The magnitude and difference in forest topsoil contamination with ^{137}Cs between the Minya Konka and Yunnan sites seem to be related largely to substantial differences in climatic conditions because of different elevation and geographical location. The subalpine region in Minya Konka, because of its cold conditions, is more sensitive to contamination by airborne persistent compounds transported at higher altitudes in a global atmospheric circulation pattern where they can be trapped by cold temperature and wet precipitation (Falandysz et al. 2014).

It is well documented, that the Minya Konka region has a mean annual temperature of 4.2 °C, with a minimum mean value in January of –4.6 °C and a maximum mean value in July of 12.5 °C, while the mean annual precipitation was 1947.4 mm in 1988–2010 (Wu et al. 2013). On a contrary, Yunnan Province primarily has a subtropical monsoon climate and is more influenced from the Pacific and Indian oceans and it has temperate summers and mild to warm winters, except for the subtropical region of Xishuangbanna in the south, where it is warm, and also the plateau region of Shangri-La in the northwest, where temperatures are moderate.

The Province of Yunnan has a mean annual temperature of 16.3 °C, with minimum mean values in ranges from 8 to 17 °C in January and 21 to 27 °C in July, while the mean annual precipitation is 1105.12 mm in most regions and more than 1600 mm in the south (Luo et al. 2016). According to Quin et al. (2015), no distinct change in annual precipitation rate was noted in southwestern China including Yunnan-Guizhou Plateau during 1961–2000 while there were significant changes for monthly precipitation overall, with increasing trends for maximum precipitation, rainy day intensity, and annual precipitation in the first half of the year in 1961–2000. Some recent modeling revealed that in Yunnan “the annual average temperature had been increasing, the annual precipitation was

decreasing in the east, northeast, south and west of the province, and particularly, there was an obvious decreasing trend of precipitation in the rainy (May–October) season” (Ren et al. 2017).

Data on the environmental impact of the aboveground nuclear detonations and following the Chernobyl accident were sparse from China, but the impact of the Chernobyl accident was considered negligible, e.g., in the region of the city of Xi'an in the central region of China (Pang et al. 1989). Japan's Fukushima Dai-ichi nuclear accident was considered as having little or no impact on the environmental radiation levels in the region of the Xi'an in Shaanxi Province in the central part of China, and without impact on the environment and food chain from the farmlands of Sichuan Province in western China (Liu et al. 2013; Shuai et al. 2016). Fukushima's radioactive plume arrived via global atmospheric circulation also to the southeastern fringe of the Tibetan plateau in the region of Minya Konka and to the northern part of the Yungui plateau; this was detected in the Guiyang region in Guizhou province in March 24–31, 2011. The Guiyang region also received a radioactive plume in the second, the regional scale event, on April 7–14, 2011, when air masses moved at lower altitudes from eastern Asia (Wan et al. 2014). Nevertheless, no data on the surface contamination with $^{134/137}\text{Cs}$ (Bq per m^2) are available for Minya Konka, Yunnan, or elsewhere in southwest China.

As found in this study, the degree of pollution with ^{137}Cs of the upper layer of red soil (topsoil) in the Changning and Mengman sites in southwestern Yunnan was largely similar ($< 10 \text{ Bq kg}^{-1}$ dry matter (d.m.)), while some differences were observed for the interim soil layers. The uppermost organic (0–1 cm) layer in the Changning and Mengman sites showed on a smaller activity concentration of ^{137}Cs than the interim layers of 2–5 cm (Changning) and of 2–5 to 6–10 cm (Mengman), where ^{137}Cs activity concentrations were greater but further decreased with depth (Table 1). In the case of ^{40}K , forest topsoil in the Changning site was twice as high in this nuclide than topsoil from the Mengman site, while activity concentrations of ^{40}K were in practice almost constant between the layers.

It is known that airborne ^{137}Cs when deposited on forest soil becomes initially trapped in the uppermost “organic” layer (~ 0–10 cm layer) and further, but very slowly migrates down in a soil profile (Fesenko et al. 2001; Letho et al. 2013; Mietelski et al. 2010; Yoshida and Muramatsu 1994). Downward trends of ^{137}Cs differ, depending on many conditions such as the soil itself, topography, vegetation, fungi, etc. (Letho et al. 2013). Nevertheless, a downward trend of ^{137}Cs migration in red soils of southwestern Yunnan (Table 1) can be considered to some degree as similar to the rate of a downward migration as observed for this nuclide in forest soil elsewhere, but this was not studied in detail in this work.

A small fraction of deposited ^{137}Cs can, because of a pores in the forest soil, migrate down a soil profile quickly and not be adsorbed by a layer rich in humus (organic) (Teramage et al. 2014). This can have consequences for efficiency of ^{137}Cs pick-up (also radioactive ^{134}Cs) from soil substrata by mycelium and its bio-concentration in fruit bodies by certain mushrooms. All isotopes of Cs use the same pathway for uptake that exists for natural and non-radioactive isotopes of Cs (^{133}Cs) (Tsukada et al. 1998). Mushrooms, both saprobic and mycorrhizal, take up mineral constituents from the substrate where the mycelium lives—typically from litter, soil, soil solution, and decaying organic matter (Falandysz and Treu 2017).

^{137}Cs and ^{40}K activity concentrations in mushrooms

Yunnan Province in China is the major supplier of wild growing mushrooms both for the domestic market and for export. Due to a high biodiversity and an abundance of species, there is also a great tradition for foraging and eating mushrooms—ranging from the subtropical region of Xishuangbanna up to the Tibetan region of Shangri-La and the Pudacuo National Park in Diqing in the northwest of Yunnan (Falandysz et al. 2016b and 2017). The subalpine region on the east slope of the Gongga Shan Mountain in the area of the Hailuoguo National Park is also diverse in species of mushrooms, while the forest (jungle) there is barely accessible because of dangerous slopes, rocks, dense vegetation, and other mountain hazards. Hence, edible mushrooms from the Hailuoguo National Park are collected only by some locals there and in rather small quantity.

It was expected that the deposition of airborne ^{137}Cs in the subalpine area of Minya Konka from global fallout, and with absence of local and regional sources of emission, should be better reflected in mushrooms and topsoil from there, compared to mushrooms and topsoil from the neighboring northern, central, and southern regions of Yunnan Province. Available data on radioactivity levels in mushrooms from some main producing countries such as China are considered as insufficient (Falandysz et al. 2015a, b, 2016a and 2017).

Activity concentrations of ^{137}Cs in mushrooms collected across of Yunnan ranged from 4.9 ± 1.3 to $83 \pm 3 \text{ Bq kg}^{-1}$ d.b. in the caps and from 3.9 ± 1.3 to $37 \pm 3 \text{ Bq kg}^{-1}$ d.b. in the stipes (Fig. 2). Only in the case of a few samples, the ^{137}Cs activity concentrations were below the limit of detection: in four samples of the caps ($< 4.4 \text{ Bq kg}^{-1}$ d.b.) and three samples of stipes ($< 3.8 \text{ Bq kg}^{-1}$ d.b.). Activity concentrations of ^{137}Cs in mushrooms collected from the subalpine area of Minya Konka were clearly higher and ranged from 62 ± 6 to $280 \pm 150 \text{ Bq kg}^{-1}$ d.b. in the caps and from 32 ± 9 to $400 \pm 72 \text{ Bq kg}^{-1}$ d.b. in the stipes (Table 2). No activity from ^{134}Cs was detected at the time of the measurements (summer 2015) in any of the mushroom samples investigated in this study.

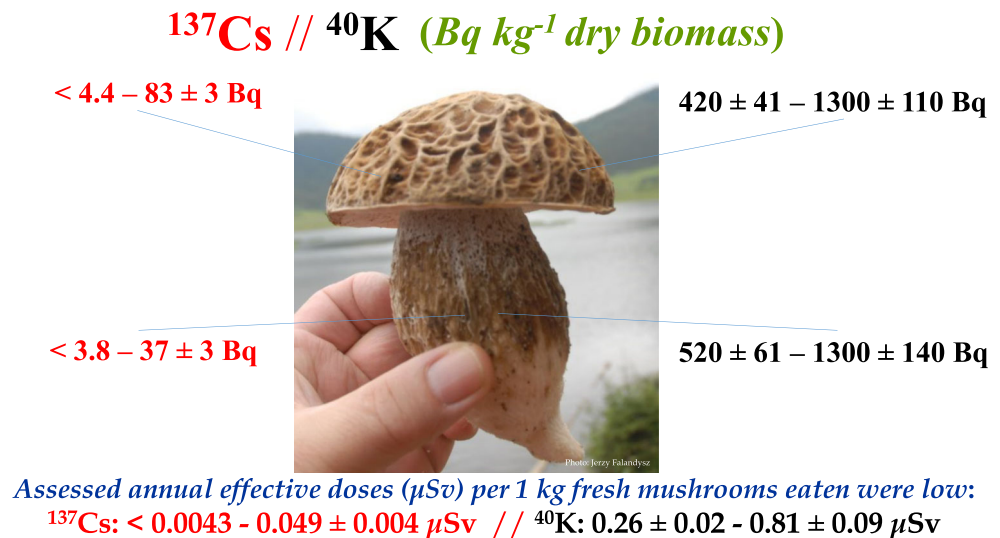
The activity concentrations of ^{137}Cs in the samples of *L. atrostipitatum*, *L. chromapes*, *L. extremiorientale*, *L. griseum*, and *L. rugosiceps* from Yunnan region were roughly similar ($< 4.4\text{--}12 \pm 1 \text{ Bq kg}^{-1}$ d.b. in the caps and $< 3.2\text{--}11 \pm 2 \text{ Bq kg}^{-1}$ d.b. in stipes). An exception was *L. rugosiceps* from Weixi in Diqing where activity concentrations of ^{137}Cs were $38 \pm 3 \text{ Bq kg}^{-1}$ d.b. (caps) and $19 \pm 1 \text{ Bq kg}^{-1}$ d.b. (stipes) (Table 2). The highest activity concentrations of ^{137}Cs equal to $83 \pm 3 \text{ Bq kg}^{-1}$ d.b. in caps and to $37 \pm 3 \text{ Bq kg}^{-1}$ d.b. in stipes were found in the sample of *L. versipelle* from Pudacuo in Diqing. Both the Weixi and Pudacuo sites in Diqing region are located on the Yungui plateau in the northwest of Yunnan. A higher activity concentration of ^{137}Cs in *L. rugosiceps* and *L. versipelle* from the Diqing region could be related to the specific location of the sites rather than a possible higher capacity of *L. versipelle* for contamination, but this was not tested in this study. In a review by Duff and Ramsey (2008), no information is provided on the capacity of *Leccinum* spp. for contamination with ^{137}Cs . A major reason for a species-specific difference in susceptibility to contamination with radiocaesium in mushrooms is related to the status of stable Cs (^{133}Cs), which is better accumulated by certain species of mushrooms but less by other species under the same field conditions (Falandysz and Borovička 2013; Yoshida et al. 2000). As mentioned, specific meteorological conditions, e.g., heavy rainfall, can concentrate the radioactive fallout into localized areas (hot spots) (Smith 1994; Strzelecki et al. 1993), and if this happens in forested areas, it results in much more intense radiation accumulated in mushrooms there (Mietelski et al. 2010; Strandberg 2004).

The activity concentrations of ^{137}Cs in the samples of *L. scabrum* and *L. variicolor* from the subalpine region of Minya Konka were roughly similar $180 \pm 10\text{--}220 \pm 110 \text{ Bq kg}^{-1}$ d.b. in the caps and $120 \pm 8\text{--}180 \pm 24 \text{ Bq kg}^{-1}$ d.b. in stipes and were much higher when compared to *Leccinum* mushrooms from Yunnan Province in this study (Table 1). Minya Konka in the eastern Tibetan plateau is situated north of Yunnan province and northeast of Diqing region (Fig. 1). Diqing region of Yunnan is different from other regions of the province because of a colder climate and higher elevation and the climate of Minya Konka is also widely different.

The *Cortinarius* spp. and *Russula* spp. from the subalpine area of Minya Konka both showed a higher concentration activity of ^{137}Cs than mushrooms sampled in Yunnan, and *Cortinarius bovinus* with ^{137}Cs activity level at $280 \pm 150 \text{ Bq kg}^{-1}$ d.b. in the caps and at $400 \pm 72 \text{ Bq kg}^{-1}$ d.b. in the stipes was the most contaminated species. It is known that among mushrooms of the genus *Cortinarius*, some can much better accumulate radiocaesium in fruit bodies than others (Bakken and Olsen 1990; Zalewska et al. 2016).

Tricholoma matsutake is most famous and expensive among the gourmet mushrooms of Yunnan. One pooled

Fig. 2 Minimum and maximum values of activity concentrations of ^{137}Cs and ^{40}K and of assessed annual effective doses (μSv) per 1 kg fresh mushrooms consumed in Yunnan



sample of ten caps of *T. matsutake* from the Shangri-La area (Diqing region) on the Yungui plateau collected less than 1 year before the Fukushima Dai-ichi nuclear power plant accident on March 11, 2011, showed a low concentration activity of ^{137}Cs , i.e., at $14 \pm 3 \text{ Bq kg}^{-1}$ d.b. (^{134}Cs undetected). A pooled sample of ten caps of *T. matsutake* collected from the Pudacuo area in the Diqing region 1 year after the Fukushima accident showed the same degree of contamination with ^{137}Cs (^{134}Cs undetected) as the pre-Fukushima sample (Table 1). Two other pooled samples of the caps of *T. matsutake* collected from central region of Yunnan showed ^{137}Cs in $8.5 \pm 1.6 \text{ Bq kg}^{-1}$ d.b. in 2012 and in $19 \pm 2 \text{ Bq kg}^{-1}$ d.b. in 2013; therefore, activity concentrations are relatively low and in accordance with data for this species from Diqing region. This result implies that the radioactive plume from the Fukushima release, which arrived via global atmospheric circulation to the northern part of the Yungui plateau, as has been documented by Wan et al. (2014), was in practice without effect in that area. This also applies to the radioactive plume in the second, regional scale event, on April 7–14, 2011, which arrived in the region of Guiyang when air masses moved at lower altitude from eastern Asia (Wan et al. 2014).

Xerocomus rubellus (former name *X. versicolor*) from the Yuxi region, which is located more or less in the center of Yunnan, did not show detectable activity from ^{137}Cs (in the caps $< 3.9 \text{ Bq kg}^{-1}$ d.b.). The species *B. ferrugineus* (earlier called *X. spadiceus*) showed activity concentrations of ^{137}Cs at 14 ± 3 to $15 \pm 1 \text{ Bq kg}^{-1}$ d.b. in the caps of fruitbodies from the northwestern sites in Yunnan and at < 3.3 to $8.2 \pm 2.1 \text{ Bq kg}^{-1}$ d.b. at the more southern locations (Table 1). From the food contamination point of view, mushrooms (assumed moisture content at 90%) both from Yunnan and Minya Konka were below the new regulatory limit of 100 Bq kg^{-1} fresh weight for vegetables in Japan after the Fukushima accident (effective from April 1, 2012) (Merz et al. 2015).

^{137}Cs was usually better sequestered in caps than in stipes (index $Q_{\text{C/S}}$) of fruit bodies. The median value of the index $Q_{\text{C/S}}$ for ^{137}Cs sequestered in fruit bodies of *Leccinum* spp. from Yunnan was 1.3 ± 1.2 (range 0.5–2.2), and for *Leccinum* spp. from Minya Konka was in the range 1.2–1.5. The index $Q_{\text{C/S}}$ for ^{137}Cs in *Tylopilus* spp. was in the range 1.0–13, in *Tricholoma matsutake* was 1.7–2.6 and 2.6 in *Cortinarius collinitus*, while < 1 was in *Cortinarius bovinus*, *Xerocomus* spp., and *Russula* spp.

The activity concentrations of ^{137}Cs in mushrooms from Yunnan in this study and in limited samples of mushrooms collected in Yunnan after the Fukushima accident and examined so far were usually low, i.e., $< 10 \text{ Bq kg}^{-1}$ d.b. (Falandysz et al. 2015a, b, 2016a and 2017; Tuo et al. 2014; Wang et al. 2015). These results were much lower when compared to reported activity concentrations of ^{137}Cs in mushrooms foraged in eastern, central, and western Europe after the Chernobyl catastrophe—as reviewed by Duff and Ramsey (2008) and others (Falandysz and Borovička 2013; Cocchi et al. 2017; Grodzinskaya et al. 2013; Kalač 2001). Even mushrooms collected in 2004 and 2005 at a far distance from Chernobyl, e.g., from the Mediterranean, the Aegean, Marmara, the Black Sea, and from the central and eastern Anatolia regions of Turkey, usually showed ^{137}Cs at $> 10 \text{ Bq kg}^{-1}$ d.b., i.e., in seven species values ranged between 15 ± 1 and $109 \pm 6 \text{ Bq kg}^{-1}$ d.b., while in four species, they were as low as between 2.4 ± 0.3 and $7.6 \pm 0.8 \text{ Bq kg}^{-1}$ d.b. (^{134}Cs was not detected) (Turhan et al. 2007).

Radioactive potassium (^{40}K) is a natural and long-lived isotope of potassium (K), which is the most abundant metallic element in fruit bodies of mushrooms. For example, K was efficiently bio-concentrated by mushrooms and occurred at levels ranging from $30,000 \pm 4000$ to $72,000 \pm 7000 \text{ mg kg}^{-1}$ d.b. (total range 24,000–87,000 mg kg^{-1} d.b.) in the annual collections of fruit body caps of mycorrhizal *Paxillus involutus* (Batsch) Fr., and it

Table 2 Activity concentrations of ¹³⁷Cs and ⁴⁰K (Bq kg⁻¹ dry biomass ± a counting uncertainty) in mushrooms from the Minya Konka (Gongga Shan Mt) in the Sichuan Province and across of the Yunnan Province, China

Location, species name, and year of collection	Altitude (m a.s.l.)	n	¹³⁷ Cs		⁴⁰ K	
			Caps	Stipes	Caps	Stipes
Sichuan Province						
<i>Cortinarius bovinus</i> Fr.						
Minya Konka, 2012	3480	(> 10)	280 ± 150 ^a	400 ± 72	WD	WD
<i>Cortinarius collinitus</i> Fr.						
Minya Konka, 2012	3000	(> 10)	84 ± 20	32 ± 9	2300 ± 1000	2300 ± 630
<i>Leccinum scabrum</i> (Bull.) Gray						
Minya Konka, 2012	2900–3000	(12)	180 ± 10	120 ± 8	2000 ± 310	1900 ± 330
<i>Leccinum varicolor</i> Watling						
Minya Konka, 2012	3000	(6)	220 ± 150	180 ± 24	1700 ± 440	1700 ± 830
<i>Russula grisea</i> Fr.						
Minya Konka, 2012	3600	(> 10)	98 ± 24	110 ± 25	3600 ± 1300	2700 ± 1200
<i>Russula puellaris</i> Fr.						
Minya Konka, 2012	3000	(11)	62 ± 6	70 ± 15	1500 ± 310	3800 ± 930
Yunnan Province						
<i>Leccinum atrostipitatum</i> Smith et Watling						
Pudacuo, Diqing, 2012	3500	(7)	8.2 ± 1.2	10 ± 1	1100 ± 81	990 ± 97
<i>Leccinum chromapes</i> (Forst.) Sing						
Fumin, Kunming, 2011	~ 1800	(10)	6.4 ± 1.4	9.4 ± 1.4	1300 ± 97	690 ± 78
Kunming city, 2011	1892	(10)	5.3 ± 1.3	11 ± 2	950 ± 89	1100 ± 130
Jiangchuan, Yuxi, 2012	~ 1600	(7)	8.7 ± 1.7	8.1 ± 2.1	1200 ± 120	1300 ± 140
<i>Leccinum extremorientale</i> (L.Vass.) Singer						
Nanhua, Chuxiong, 2013	2245	(10)	6.8 ± 1.1	5.6 ± 1.0	1100 ± 81	720 ± 66
<i>Leccinum griseum</i> (Quél.) Sing						
Kunming city, 2011	1892	(7)	16 ± 2	19 ± 2	1300 ± 110	700 ± 87
Wuding, Chuxiong, 2011	~ 2300	(10)	8.1 ± 1.3	9.4 ± 1.8	1200 ± 92	810 ± 110
<i>Leccinum rugosiceps</i> (Peck) Sing						
Huize, Qujing, 2011	~ 3600	(10)	11 ± 2	11 ± 2	980 ± 120	690 ± 96
Fumin, Kunming, 2011	~ 1800	(10)	17 ± 2	8.1 ± 1.7	770 ± 110	660 ± 100
Pu'er City, 2011	~ 1400	(10)	12 ± 1	15 ± 1	1200 ± 77	780 ± 94
Yimen, Yuxi, 2011	~ 1600	(10)	7.6 ± 1.9	9.4 ± 2.0	1200 ± 130	900 ± 130
Yimen, Yuxi, 2012	~ 1600	(7)	5.4 ± 1.3	4.8 ± 1.2	980 ± 82	530 ± 77
Anning, Kunming, 2012	~ 1800	(10)	6.3 ± 1.1	5.3 ± 1.1	880 ± 70	750 ± 70
Shilin, Kunming, 2012	~ 1800	(8)	8.7 ± 1.4	5.9 ± 1.3	1000 ± 82	700 ± 82
Shiping, Honghe, 2012	1745	(10)	9.1 ± 1.6	< 3.2	910 ± 100	750 ± 83
Midu, Dali, 2012	~ 1700	(10)	4.9 ± 1.3	11 ± 1	910 ± 94	460 ± 63
Weixi, Diqing, 2012	2540	(7)	38 ± 3	19 ± 1	1200 ± 160	690 ± 70
Yuanmou, Chuxiong, 2012	1772	(7)	< 4.4	7.1 ± 1.5	810 ± 120	780 ± 94
<i>Leccinum versipelle</i> (Fr.) Snell.						
Pudacuo, Diqing, 2012	3500	(7)	83 ± 3	37 ± 3	1100 ± 130	710 ± 120
<i>Tricholoma matsutake</i> (S. Ito et Imai) Sing.						
Shangri-la, Diqing, 2010	3400	(10)	14 ± 3	WD	1600 ± 180	WD
Pudacuo, Diqing, 2012	3500	(10)	14 ± 3	WD	960 ± 110	WD
Yanshan, Wenshan, 2012	~ 1700	(10)	8.5 ± 1.6	5.1 ± 1.3	1400 ± 98	1200 ± 88
Jiangchuan, Yuxi, 2013	~ 1600	(20)	19 ± 2	7.4 ± 1.8	1900 ± 140	1500 ± 130
<i>Tylopilus felleus</i> (Bull.:Fr.) Karst						
Hongta region, Yuxi, 2013	~ 1600	(10)	9.9 ± 1.6	< 5.2	1400 ± 100	1300 ± 140

Table 2 (continued)

Location, species name, and year of collection	Altitude (m a.s.l.)	n	¹³⁷ Cs		⁴⁰ K	
			Caps	Stipes	Caps	Stipes
Zezhou, Qujing, 2013 <i>Tylopinus nigerrimus</i> (Heim) Hongo & Endo	~ 2000	(10)	4.6 ± 1.1	< 4.0	1100 ± 75	1100 ± 110
Pudacuo, Diqing, 2012 <i>Tylopilus plumbeoviolaceoides</i> T.H. Li, B. Song & Y.H. Shen	3500	(10)	5.9 ± 1.2	5.5 ± 1.4	1100 ± 82	910 ± 88
Shilin, Kunming, 2012	~ 1800	(10)	9.0 ± 1.5	8.7 ± 1.6	1000 ± 91	1300 ± 110
Zezhou, Qujing, 2013 <i>Tylopilus roseolus</i> (Chiu) Tai.	1898	(10)	8.9 ± 1.3	6.8 ± 1.2	1000 ± 77	1100 ± 78
Shiping, Honghe, 2012	2000	(8)	2.8 ± 0.9	< 3.6	940 ± 81	940 ± 98
Gejiu, Honghe, 2012	2000	(9)	12 ± 2	9.8 ± 1.7	960 ± 130	790 ± 110
<i>Xerocomus spadiceus</i> (Fr.) Quél; current name <i>Boletus ferrugineus</i> Schaeff						
Wuding, Chuxiong, 2011	~ 1800	(10)	< 3.7	< 3.8	1200 ± 120	1000 ± 130
Kunming city, 2011	1942	(8)	< 3.3	< 3.2	1100 ± 99	930 ± 100
Pudacuo, Diqing, 2012	3500	(10)	14 ± 3	WD	960 ± 110	WD
Lanping, Nujiang, 2012	~ 1200	(7)	15 ± 1	20 ± 1	420 ± 41	520 ± 61
Yimen, Yuxi, 2012	~ 1600	(9)	8.2 ± 2.1	12 ± 2	880 ± 130	710 ± 110
Shilin, Kunming, 2012	~ 1800	(9)	5.6 ± 1.4	3.9 ± 1.3	730 ± 63	690 ± 63
<i>Xerocomus versicolor</i> E.-J. Gilbert; current name <i>Hortiboletus rubellus</i> (Krombh.) Šutara						
Dayingjie, Yuxi, 2012	~ 1600	(10)	< 3.9	WD	810 ± 86	WD

WD without data

ranged from 26,000 ± 4000 to 57,000 ± 13,000 mg kg⁻¹ d.b. (total range 17,000–78,000 mg kg⁻¹ d.b.) in the caps of the saprotrophic species *Macrolepiota procera* (Scop.) Singer (⁴⁰K contributes at 0.0119% to total K) (Brzostowski et al. 2011; Gucia et al. 2012).

When compared to ¹³⁷Cs in this study, ⁴⁰K was better accumulated in caps than stipes of the fruit bodies of *Leccinum* mushrooms from Yunnan, i.e., the median value of index Q_{C/S} for ⁴⁰K was 1.4 (1.4 ± 0.3; range 0.86–2.0) and in *Xerocomus* mushrooms was 1.2 (1.1 ± 0.2; range 0.81–1.2). For mushrooms from Minya Konka and *Russula* spp. and *Tylopilus* spp. from Yunnan, the values of index Q_{C/S} for ⁴⁰K were 1.0, and for *Tricholoma matsutake* was 1.1–1.2. Those values seem typical for different species of mushrooms and did indicate on different fate of ¹³⁷Cs and ⁴⁰K in fruit bodies of mushrooms (Falandysz and Borovička 2013; Falandysz et al. 2016a and 2017).

There are few data published on the activity concentrations of ¹³⁷Cs in mushrooms foraged in Yunnan and no previous data on the same in mushrooms from Minya Konka and the eastern fringe of the Tibetan plateau. In one of our previous studies, it was shown that the activity concentrations of ¹³⁷Cs in sclerotia of the fungus *Wolfiporia extensa* across Yunnan in 2012 were low, i.e., at < 1.4 to 7.2 ± 1.1 Bq kg⁻¹ d.b. (¹³⁴Cs undetected) (Wang et al. 2015). Also, the pantropical mushroom *Macrocybe gigantea* foraged recently in the wild or

cultivated in Yunnan shows low radioactivity of the radiocaesium isotopes—¹³⁴Cs was undetected and ¹³⁷Cs concentrations were in the range from 6.8 ± 1.3 to < 7.0 Bq kg⁻¹ d.b. in the caps and from < 4.8 to 7.9 ± 1.7 Bq kg⁻¹ d.b. in the stipes (Falandysz et al. 2015b). Contamination with ¹³⁷Cs of *Boletus edulis* from the region of Yuxi in central part of Yunnan was between 4.7 ± 1.3 and 10 ± 1 Bq kg⁻¹ d.b. in 2011–2014, and low concentration activities were also measured in *Cantharellus cibarius* and *Cantharellus minor* in 2013, e.g., they were 1.2 ± 0.5 and < 1.2 Bq kg⁻¹ d.b. (Falandysz et al. 2015a, 2016a and 2017). Contamination with ¹³⁷Cs of 16 species (30 individuals) of forest mushrooms in the Mangshi region in southwest Yunnan in 2012–2013 was between 0.45 ± 0.19 and 21 ± 1 Bq kg⁻¹ d.b., while it was substantially higher in three individuals of *Gomphus floccosus* (Schv.) Sing [current name *Turbinellus floccosus* (Schwein.) Earle ex Giachini & Castellano], i.e., between 150 ± 9 and 340 ± 22 Bq kg⁻¹ d.b. (Tuo et al. 2014).

Mushrooms from Yunnan collected in 2010–2014 and examined in this and other studies were evidently less contaminated with ¹³⁷Cs when compared to mushrooms collected from Minya Konka (Table 2) (Falandysz et al. 2015a, b, 2016a and 2017; Tuo et al. 2014; Wang et al. 2015). There are no data published on contamination with ¹³⁷Cs of mushrooms from Minya Konka in the pre-Chernobyl period (up to April 26, 1986), which could reflect without any doubt an

impact from global radioactive fallout because of the nuclear detonations. Nevertheless, the effects of the Chernobyl and Fukushima accidents were considered negligible in China (Fesenko et al. 2001; Liu et al. 2013; Pang et al. 1989; Wan et al. 2014). Hence, the activity concentrations of ^{137}Cs in soils and mushrooms in Minya Konka can be a result of fallout from the aboveground nuclear detonations.

^{137}Cs from the atmospheric fallout after the aboveground nuclear detonations was found in mushrooms from background areas in Europe (also in USA), while its activity concentrations in Europe were smaller than they were after the Chernobyl accident (Bem et al. 1990; Eckl et al. 1986; Grüter 1964; Johnson and Nayfield 1970). For example, the pre-Chernobyl mushrooms collected in Rogóžno in Poland (500 km west of Chernobyl) in 1984 and 1985 showed a contamination with ^{137}Cs from the global atmospheric fallout due to nuclear weapon detonations at levels of 40–45 Bq kg⁻¹ d.b. in *Leccinum scabrum*, 100–170 Bq kg⁻¹ d.b. in *Russula ochroleuca* and 46–320 Bq kg⁻¹ d.b. in three other species; however, they were much more contaminated later as a result of the Chernobyl accident (Bem et al. 1990).

Higher deposition of ^{137}Cs from fallout resulted in greater contamination of soil substrata and mushrooms. The activity concentration of ^{137}Cs in the surface (0–10 cm) layer of forest soil in Minya Konka was $41 \pm 1-79 \pm 2$ Bq kg⁻¹ dry matter (d.m.) in 2012 (Table 1). Hence, if considering hypothetically no deposition of ^{137}Cs (half-life of 30.05 years) from the Chernobyl fallout in Minya Konka (unlikely) or a small to moderate deposition (possible), i.e., from < 10 up to 20% of the total load of ^{137}Cs in soil substrata after Chernobyl, mushrooms there in ~ 1984–1985 could be approximately contaminated with ^{137}Cs at 100 ~ 700 Bq kg⁻¹ d.b. This scenario seems to reflect an enhanced deposition of ^{137}Cs in the Minya Konka region (also in Yunnan) from global fallout due to the Chernobyl accident and the nuclear detonations but not because of the accident in Fukushima. This may also apply to mushrooms growing in Yunnan. It is worth mentioning that ~ 32% of the ^{137}Cs concentration activity accumulated in mushrooms of the genus *Cortinarius* and from 39 to 46% in *Boletus edulis* from the Reggio Emilia in Italy (region affected by fallout from Chernobyl) collected in 1992–1994 was from the pre-Chernobyl fallout and respectively to that ~ 68% and 54% to 61% was from the Chernobyl fallout (Cocchi et al. 2017; Zalewska et al. 2016).

The activity concentrations of ^{40}K were detected in each sample of mushrooms examined in this study and the caps often were richer in this element than the stipes (Table 2). The range of ^{40}K in the pooled samples of the caps per species and location in Yunnan was between 730 ± 63 and 1300 ± 110 Bq kg⁻¹ d.b. (an exception was the value of 420 ± 41 Bq kg⁻¹ d.b. in the sample of *X. spadiceus* collected near Lanping in the region of Nujiang), and in stipes, the range was between 690 ± 63 and 1300 ± 140 Bq kg⁻¹ d.b. (again

only 520 ± 61 Bq kg⁻¹ d.b. for *X. spadiceus* in Lanping). Hence, the activity concentrations of ^{40}K exceed around 100-fold the values of ^{137}Cs in the *Leccinum* and *Xerocomus* mushrooms from Yunnan (Table 2).

Potassium is a major bio-metal of mushrooms (at around 3% d.b. for numerous species of soil mushrooms) and natural ^{40}K constitutes a small part of total K and are absorbed from a substrate and sequestered in fruiting bodies (Falandysz and Borovička 2013; Kojta and Falandysz 2016). Because of a high abundance of K in mushrooms can be interesting to evaluate activity concentration from artificial radionuclides accumulated in fruiting bodies against a natural ^{40}K as well as for risk evaluation (Wang et al. 2015). Mushrooms from the region of Minya Konka showed activity concentrations of ^{40}K in the range from 1500 ± 310 to 3600 ± 1300 Bq kg⁻¹ d.b. in caps and from 1700 ± 830 to 3800 ± 930 Bq kg⁻¹ d.b. in stipes; therefore, these values are higher than the ones determined in mushrooms from Yunnan in this study, i.e., with range from 770 ± 110 to 1900 ± 140 Bq kg⁻¹ d.b. in caps and from 520 ± 61 to 1500 ± 130 Bq kg⁻¹ d.b. in stipes (Table 2). A reason for a higher abundance of ^{40}K (and so also stable K) in mushrooms from Minya Konka when compared to mushrooms collected across Yunnan can be simply related to an abundance of K in topsoil, which therefore favors the Minya Konka dark forest soil (Table 1). On the other hand, in light of data presented in Table 1, the weathered, latosols, lateritic red earths, and red and yellow earths of Yunnan can be considered as a good resource of K contained in the rocky geochemical background there and this potassium is not easily leachable by the process of weathering.

A species-specific accumulation of some elements is known for certain mushrooms and examples documented for mushrooms from the wild are the elements Ag, As, Cd, Fe, Hg, Rb, Se, or V (Borovička et al. 2010; Falandysz and Borovička 2013; Falandysz and Rizal 2016; Falandysz et al. 2007; Gaścecka et al. 2017; Horyna and Řanda 1988; Krasínska and Falandysz 2015 and 2016; Lepp et al. 1987), but this accumulation can also be site specific because of particular geogenic characteristics or because of anthropogenic (emission and deposition) influences. Absorption and accumulation of certain elements (K, P, Mg, Cu, Zn) can be more or less regulated under typical soil substrata conditions by species (Falandysz and Borovička 2013). Data on the accumulation of the stable isotope of Cs (^{133}Cs) in mushrooms are few (Řanda and Kučera 2004), and they showed species-specific differences in content of this metallic element among the species. Mushrooms do not discriminate between stable caesium and radiocaesium—there was a high correlation for ^{133}Cs and ^{137}Cs sequestered in the flesh of fruit bodies (Tsukada et al. 1998).

Effective radiation doses To evaluate a possible risk arising from the radioactivity for the people in Yunnan eating

Table 3 Annual effective radiation dose (μSv) for the internal exposure of ^{137}Cs and ^{40}K in mushrooms of the genus *Leccinum* and *Russula* from the Minya Konka region in Sichuan Province and *Leccinum* and *Xerocomus* from the Yunnan Province, China

Location, mushroom, and year of collection	Annual effective radiation dose (μSv) ^c			
	^{137}Cs		^{40}K	
	Fruiting bodies		Fruiting bodies	
	Caps	Stipes	Caps	Stipes
Sichuan Province				
<i>Leccinum scabrum</i> (Bull.) Gray				
Minya Konka, 2012	0.23 ± 0.03	0.16 ± 0.01	1.3 ± 0.2	1.2 ± 0.2
<i>Leccinum variicolor</i> Watling				
Minya Konka, 2012	0.29 ± 0.20	0.23 ± 0.03	1.1 ± 0.3	1.1 ± 0.5
<i>Russula grisea</i> Fr.				
Minya Konka, 2012	0.13 ± 0.03	0.14 ± 0.03	2.2 ± 0.8	1.7 ± 0.7
<i>Russula puellaris</i> Fr.				
Minya Konka, 2012	0.081 ± 0.008	0.091 ± 0.020	0.93 ± 0.19	2.4 ± 0.6
Yunnan Province				
<i>Leccinum atrostipitatum</i> Smith et Watling				
Pudacuo, Diqing; 2012	0.011 ± 0.002 ^b	0.013 ± 0.001	0.68 ± 0.05	0.61 ± 0.06
<i>Leccinum chromapes</i> (Forst.) Sing				
Fumin, Kunming; 2011	0.0083 ± 0.0018	0.012 ± 0.002	0.81 ± 0.06	0.43 ± 0.05
Kunming City; 2011	0.0069 ± 0.0017	0.014 ± 0.003	0.59 ± 0.05	0.68 ± 0.08
Jiangchuan, Yuxi; 2012	0.011 ± 0.002	0.010 ± 0.003	0.74 ± 0.07	0.81 ± 0.09
<i>Leccinum extremorientale</i> (L.Vass.) Singer				
Nanhua, Chuxiong; 2013	0.0088 ± 0.0014	0.0073 ± 0.0013	0.68 ± 0.05	0.45 ± 0.04
<i>Leccinum griseum</i> (Quél.) Sing				
Kunming City; 2011	0.021 ± 0.003	0.025 ± 0.003	0.81 ± 0.07	0.43 ± 0.05
Wuding, Chuxiong; 2011	0.010 ± 0.002	0.012 ± 0.002	0.74 ± 0.06	0.50 ± 0.07
<i>Leccinum rugosiceps</i> (Peck) Sing				
Huize, Qujing; 2011	0.014 ± 0.003	0.014 ± 0.003	0.61 ± 0.07	0.43 ± 0.06
Fumin, Kunming; 2011	0.022 ± 0.003	0.010 ± 0.002	0.48 ± 0.07	0.41 ± 0.06
Pu'er City; 2011	0.016 ± 0.001	0.019 ± 0.001	0.74 ± 0.05	0.53 ± 0.05
Yimen, Yuxi; 2011	0.010 ± 0.002	0.012 ± 0.003	0.74 ± 0.08	0.56 ± 0.08
Yimen, Yuxi; 2012	0.0070 ± 0.0017	0.0062 ± 0.0016	0.61 ± 0.05	0.33 ± 0.05
Anning, Kunming; 2012	0.0082 ± 0.0014	0.0069 ± 0.0014	0.55 ± 0.04	0.46 ± 0.04
Shilin, Kunming; 2012	0.011 ± 0.002	0.0077 ± 0.0017	0.62 ± 0.05	0.43 ± 0.05
Shiping, Honghe; 2012	0.012 ± 0.002	< 0.0042	0.56 ± 0.06	0.46 ± 0.05
Midu, Dalil; 2012	0.0064 ± 0.0017	0.014 ± 0.001	0.56 ± 0.06	0.28 ± 0.04
Weixi, Diqing; 2012	0.049 ± 0.004	0.025 ± 0.001	0.74 ± 0.10	0.43 ± 0.04
Yuanmou, Chuxiong; 2012	< 0.0057	0.0092 ± 0.0019	0.50 ± 0.07	0.48 ± 0.06
<i>Leccinum versipelle</i> (Fr.) Snell.				
Pudacuo, Diqing; 2012	0.11 ± 0.00	0.048 ± 0.004	0.68 ± 0.08	0.44 ± 0.07
<i>Xerocomus spadiceus</i> (Fr.) Quél.; <i>Boletus ferrugineus</i> Schaeff				
Wuding, Chuxiong; 2011	< 0.0048	< 0.005	0.74 ± 0.07	0.62 ± 0.08
Kunming City; 2011	< 0.0043	< 0.004	0.68 ± 0.06	0.58 ± 0.06
Pudacuo, Diqing; 2012	0.018 ± 0.003	WD	0.59 ± 0.07	WD
Lanping, Nujiang; 2012	0.019 ± 0.001	0.026 ± 0.001	0.26 ± 0.02	0.32 ± 0.04
Yimen, Yuxi; 2012	0.011 ± 0.003	0.016 ± 0.003	0.55 ± 0.08	0.44 ± 0.07
Shilin, Kunming; 2012	0.0073 ± 0.0018	0.0051 ± 0.0017	0.45 ± 0.04	0.43 ± 0.04
<i>Xerocomus versicolor</i> E.-J. Gilbert; current name <i>Hortiboletus rubellus</i> (Krombh.) Šutara				
Dayingjie, Yuxi; 2012	< 0.0051	WD	0.50 ± 0.05	WD

WD without data

^a Assumed that moisture content of fruiting bodies is at consensus value of 90% and the annual consumption rate of fresh mushrooms of the genus *Leccinum*, *Russula* or *Xerocomus* is 1000 g per capita

^b ±Measurement uncertainty

^c The dose conversion factors for ^{137}Cs and ^{40}K were 1.3×10^{-8} and 6.2×10^{-9} Sv Bq⁻¹, respectively (Gasó et al. 2000)

mushrooms, the annual effective dose from internal exposure to ^{137}Cs and ^{40}K from mushroom meals has been assessed. The nuclide ^{137}Cs leaches out considerably from the flesh when mushrooms are blanched (parboiled) (Daillant et al.

2013; Skibniewska and Smoczyński 1999). The stable alkali elements such as Cs, K, or Rb and leach out similarly into the aqueous phase during the blanching of mushrooms, and also leach numerous other metallic elements (Drewnowska et al.

2017a and b; Falandysz and Drewnowska 2017). The aqueous solution from blanched mushrooms is usually discarded. Hence, in practice, blanching highly reduces the annual radiation effective dose resulting from internal exposure to ¹³⁷Cs in consumed mushrooms. Also, frying of fresh mushrooms with vegetable oil decreases the nuclide ¹³⁷Cs content in cooked products because of leaching out of the ¹³⁷Cs (Steinhauser et al. 2014).

In Yunnan, some mushrooms, e.g., *Macrocybe gigantea*, are well blanched, before being used as a soup. In southwest China, the mushrooms are sometimes boiled together with vegetables and other ingredients, and the “soup” may be consumed (poured into a bowl of rice). In Yunnan, mushrooms of the genera *Boletus*, *Leccinum*, and *Xerocomus* and others with pores are generally cooked using a wok (Falandysz and Borovička 2013). Cooking in a wok, because of its specific cooking conditions and procedures, will probably not lead to a significant (as high as blanching) reduction of ¹³⁷Cs (also K, Cs, Rb, Li) in a mushroom meal but this was not examined in this study. No original data are known about the impact of cooking using a wok on the fate of the alkali elements contained in cooked mushrooms. Hence, when assessing the annual effective dose from internal exposure to ¹³⁷Cs and ⁴⁰K when eating meals of *Leccinum* and *Xerocomus* by consumers in Yunnan, leaching out of both nuclides was not considered in the calculations. The wild growing edible mushrooms are a popular food item in Yunnan; hence, the annual rate of consumption was assessed as 1 kg per capita but regionally this could be over 20 kg (Zhang et al. 2010).

The assessed figures of the annual effective radiation dose for internal exposure to ¹³⁷Cs and ⁴⁰K for mushrooms from the Yunnan and Minya Konka examined in this study were calculated using the formula (1) (ICRP 1993) and were presented in Table 3 and Fig. 2.

$$E_1 = C_1 d_1 (x \times 0.1) \tag{1}$$

where

- E_1 the annual effective dose from isotope ingestion of different mushroom species
- C_1 activity concentration of isotope in mushroom (Bq kg⁻¹ d.b.)
- d_1 isotope dose coefficient (1.3 × 10⁻⁸ Sv Bq⁻¹ for ¹³⁷Cs; 6.2 × 10⁻⁹ Sv Bq⁻¹ for ⁴⁰K)
- (x × 0.1) annual mushroom consumption per capita (kg d.b. year⁻¹) based on the assumption that water content of fruitbodies is at 90%
- x annual mushroom consumption per capita (kg fresh mushrooms year⁻¹)

The annual effective radiation dose figures due to ¹³⁷Cs in mushrooms, depending on morphological part, species, and

location in Yunnan, range from <0.0043 to 0.049 ± 0.004 μSv and for ⁴⁰K range from 0.26 ± 0.02 to 0.81 ± 0.09 μSv, and in Minya Konka from 0.013 ± 0.001 to 0.29 ± 0.20 μSv for ¹³⁷Cs and from 0.93 ± 0.19 to 2.4 ± 0.6 μSv for ⁴⁰K. If considering a maximal figure for mushroom consumption by some locals in Yunnan, the figures above have to be multiplied by 20–30. Both figures obtained for the annual effective radiation dose for ¹³⁷Cs and ⁴⁰K contained in mushrooms in Yunnan and Minya Konka are very low. The effective dose from ⁴⁰K contained in mushrooms from Yunnan and Minya Konka were an order of magnitude greater than from ¹³⁷Cs.

Conclusions

A higher radioactive contamination of forest topsoil and mushrooms from the Alpine region of southwestern China, when compared to neighboring areas at lower elevation, e.g., Yunnan Province, can be attributed to difference in climate that is substantially colder in the subalpine area of Minya Konka, a finding which can be stimulating for further research there. Nevertheless, an overall contamination with ¹³⁷Cs of forest topsoil and mushrooms from the Alpine region of southwestern China and neighboring areas at lower elevation and assessed the annual effective dose from ¹³⁷Cs ingestion of different mushroom species there can be considered as low or very low.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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