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^{137}Cs and ^{40}K activity concentrations in edible wild mushrooms from China regions during the 2014–2016 period

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Abstract:
Introduction. Contamination by radiocaesium of edible wild mushrooms after major nuclear accidents is a long-lasting process in some regions of the world. Following greater awareness of radioactive pollution in Asia, particularly after the Fukushima accident, this study investigated the radioactivity of ^{137}Cs and ^{40}K contamination in edible wild mushrooms in China.
Study objects and methods. The objects of the research were edible wild mushrooms collected during 2014 to 2016, from the Inner Mongolian and Yunnan regions of China. To obtain an insight into any environmental impacts to distant regions of mainland Asia, the mushrooms were analyzed for ^{137}Cs activity. In parallel, the natural activity of ^{40}K was also determined and used to estimate the content of total K. The topsoil underneath the mushrooms was also investigated from a few sites in Bayanhushu in Inner Mongolia in 2015.
Results and discussion. The results showed that in 4 to 6 mushrooming seasons after the accident, mushrooms from both regions were only slightly contaminated with ^{137}Cs, which implied negligible consequences. The activity concentrations of ^{137}Cs in dried caps and whole mushrooms in 63 of 70 lots from 26 locations were well below 20 Bq kg^{-1} dry weight. Two species (*Lactarius hygrophoroides* L. and *Lactarius volemus* L.), from Jiulongchi in Yuxi prefecture showed higher ^{137}Cs activities, from 130 ± 5 to 210 ± 13 Bq kg^{-1} dw in the caps. ^{40}K activities of mushrooms were around two- to three-fold higher. A composite sample of topsoil (0–10 cm layer) from the Bayanhushu site (altitude 920 m a.s.l.) in Inner Mongolia showed ^{137}Cs activity concentration at a low level of 6.8 ± 0.7 Bq kg^{-1} dw, but it was relatively rich in potassium (^{40}K of 595 ± 41 Bq kg^{-1} and total K of 17000 ± 1000 mg kg^{-1} dw).
Conclusion. Wild mushrooms from the Yunnan and Inner Mongolia lands only slightly affected with radioactivity from artificial ^{137}Cs. Lack of ^{134}Cs showed negligible impact from Fukushima fallout. Ionizing radiation dose from ^{137}Cs in potential meals was a fraction of ^{40}K radioactivity. The associated dietary exposure to ionizing irradiation from ^{137}Cs and ^{40}K contained in mushrooms from the regions studied was considered negligible and low, respectively. Mushroom species examined in this study are a potentially good source of dietary potassium.

Keywords: Asia, forest, fungi, pollution, soil, radioactivity, radiocaesium, wild food

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INTRODUCTION

Radiocaesium ($^{134/137}$Cs), if not mention the short-lived radioactive ^{131}I ($t_{0.5}$ = 8.02 days), is the main mass and a long-term source of the toxic radiation, polluting the Earth in the past from the nuclear weapon explosions and nuclear power plant accidents [1, 2].

Macromycetes (fungi) can accumulate various elements in their fruiting bodies, including radioactive isotopes (^{134}Cs, ^{137}Cs, ^{40}K, ^{210}Po, ^{210}Pb, ^{238}Pu, $^{239+240}$Pu, ^{90}Sr, ^{230}Th, ^{232}Th, ^{234}U, ^{238}U) emitting radiation of various toxicities [3–9]. Many wild fungi are effective accumulators of artificial radioactive cesium, which circulates in forest ecosystems for years in contaminated areas and can cause a potential health hazard from ingestion of the mushrooms [2, 10–14].

Radiocaesium (^{137}Cs) is an artificial and long-lived ($t_{0.5}$ = 30.1 years) nuclide, which appeared in mushrooms after global fallout from nuclear weapons detonations in the atmosphere. High levels of radioactivity reappeared following the collapse of the Chernobyl nuclear power plant in 1986, including massive levels of ^{134}Cs and ^{137}Cs emissions [15]. The consequent radioactive fallout caused a long-lasting and substantial contamination with ^{137}Cs of forest ecosystems including mushrooms in regions surrounding the collapsed plant, especially in the Ukraine, Belarus and Russia, as well as elsewhere in Europe [16–23].

As in Chernobyl, a similar accident occurred in Japan in March 2011, where, following a major earthquake, a 15-meter tsunami disabled the power supply and cooling systems of three Fukushima Daiichi nuclear power plant reactors. All three cores largely melted in the first three days, caused radioactive contamination of the environment on a large scale, including high ^{137}Cs pollution of fungi growing in the region [24–26].

The nuclear accidents caused long-term psychosocial consequences on exposed individuals. One of the consequences was that big game and domesticated ruminants that eat contaminated mushrooms could be also heavily loaded with ^{137}Cs [27–29]. In humans, mushrooms can be also the most important exposure route to ^{137}Cs when there is elevated consumption of wild species [30]. As mentioned, contamination by ^{137}Cs after the Chernobyl accident as well as atomic weapon testing is a long-lasting process in some mushroom species even collected relatively away from this source [12–14].

The contribution of the ^{137}Cs fallout from the Chernobyl accident to ecosystems in distant places like the Japanese islands was considered small compared to the previous global fallout [31]. The Chernobyl fallout had also some impacts on continental Asia. In China, soils (layer 0–10 cm) sampled from 56 sites in the Inner Mongolia province in 1982–1987 showed ^{137}Cs mean activity concentration of 13.6 ± 6.6 Bq kg^{-1} dry weight (dw) (from 5.8 ± 4.4 to 23.4 ± 13.4 Bq kg^{-1} dw) [32]. Soil from Yunnan province was also contaminated, showing activity of 6.2 ± 5.4 Bq kg^{-1} dw (from 1.9 ± 0.3 to 31.6 ± 0.8 Bq kg^{-1} dw) in 1982–1987 [33].

The accident in the Fukushima nuclear power plant caused a high alert on a direct and indirect radioactive pollution consequences regarding to exposed staff and local residents. It affected public health and foods safety in Japan, as well as continental Asia from serious accidental discharge and included studies on the consequence to various types of environmental media including soils, vegetation and wild growing mushrooms [25, 34–46].

Edible mushrooms collected from the wild are common foodstuffs in Yunnan, a land diverse in climate, soil, forest types and landscape topography and with a high biodiversity of mushroom species [47, 48]. Certain species are conditionally edible or medicinal mushrooms, e.g. *Caloboletus calopus* (Pers.) Vizzini or *Tricholoma sejunctum* (Fr. ex Sow.) Quél. Inner Mongolia has an area of 1 183 000 km^2 (457 000 sq mi) with a landscape made up largely of meadows with an abundance of saprobic mushrooms. This region is poor in ectomycorrhizal mushrooms, a result of the limited wooded areas, apart from the thickets along the Huang He River [49].

To get greater awareness of radioactive pollution in Asia, particularly after the Fukushima accident, this study investigated the radioactivity contamination with ^{137}Cs and ^{40}K of edible wild mushrooms from the Inner Mongolian and Yunnan provinces of China. The activity concentrations of ^{137}Cs and ^{40}K were studied for the first time in wild mushrooms (five species) from Inner Mongolia and also in more than 26 species, including taxa without previous data on ^{137}Cs, from Yunnan, collected during 2014–2016.

STUDY OBJECTS AND METHODS

Mushroom and topsoil samples. Mushrooms were collected from the Inner Mongolia province (approximate distance from Fukushima Daiichi power plant site is 2500 km). They all represented saprobic species and included *Agaricus arvensis* Schaeff, *Calocybe gambosa* (Fr.) Donk, *Calvatia gigantea* (Batsch) Lloyd, *Macrolepiota excoriata* (Schaeff.) Wasser and *Lepista personata* (Fr.:Fr) Sing. The 26 species collected from Yunnan province (distance from Fukushima is in the range of 3500 to 4500 km) included *Auricularia delicata* (Fr.) Henn, *Baorangia bicolor* (Kuntze), *Boletus bainiugan* Dentinger, *Boletus ferrugineus* Schaeff., *Hemileccinum impolitum* (Fr.) Šutara, *Boletus reticulatus* Schaeff., *Butyriboletus roseoflavus*, *Boletus tomentipes* Earle, *Caloboletus calopus* (previous name *Boletus calopus* Fr.), *Neoboletus brunneissimus* (W.F. Chiu), *Retiboletus griseus* (Frost), *Rubroboletus sinicus* (W.F. Chiu), *Sutorius magnificus* (W.F. Chiu), *Sutorius obscureumbrinus* (Hongo), *Laccaria vinaceoavellanea* Hongo, *Lactarius deliciosus* (L.:Fr.) Gray, *Lactarius hatsudake* Tanaka, *Lactarius hygrophoroides* Berk. & M.A. Curtis, *Lactarius volemus* Fr., *Lentinula edodes* (Berk.) Pegler, *Leccinum rugosiceps* (Peck) Singer, *Morchella esculenta* Pers., *Russula compacta* Frost and *Tricholoma sejunctum*. The *L. edodes* samples were taken from cultivars from the Wuding in Chuxiong and Longyang in Baoshan from Yunnan, while solely composite samples were from Baise in Guangxi province and the Northeast of China.

Soil samples were collected in parallel as two pooled samples of topsoil (0–10 cm layer) beneath the fruiting bodies of *A. arvensis* from grassy stands in the Bayanhushu site in Inner Mongolia. Details of the geographical locations of the sampling sites from which mushrooms and topsoil were collected are given in Fig. 1 and Table 1.

Preparation of materials. To examine the distribution of ^{137}Cs and ^{40}K and total K between the morphological parts, individual fruiting bodies were rinsed and separated into caps (with skin) and stipes, but some were examined as whole (Table 1). Before drying, the fungal materials were sliced into pieces using a ceramic knife and pooled to create composite

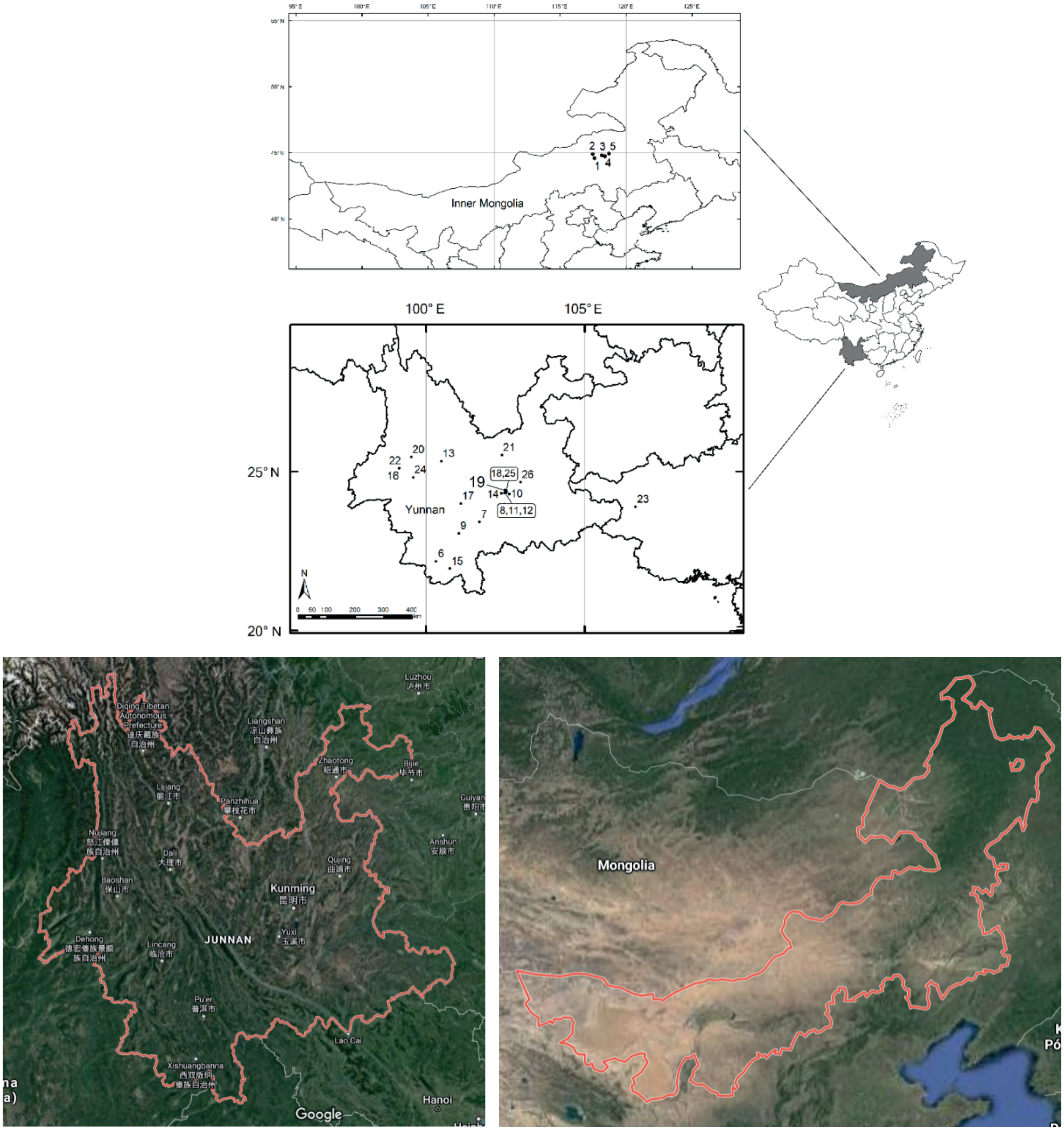

Figure 1 Localization of the sampling sites of mushrooms from the Inner Mongolia and Yunnan provinces in China

samples representing each species, sampling location and time of collection. Mushroom parts were dried at 65°C to constant mass (Ultra FD1000 dehydrator, Ezidri, Australia), finely powdered in a porcelain mortar, passed through an 80-mesh sieve, and stored in screw sealed plastic (low density polyethylene) bags under dry conditions.

Two pooled samples of topsoil (0–10 cm layer; 150 g whole weight each) were cleaned from any visible pebbles, leaves and twigs, soil samples, air dried under clean condition, ground (porcelain mortar), sieved (2 mm mesh plastic sieve), and stored in sealed polyethylene bags.

Directly before analysis, the mushroom and soil materials were prophylactically deep frozen and lyophilized (Labconco Freeze Dry System, Kansas City, MO, USA) for three days to ensure full dehydration.

Instrumental analysis. The analytical methodology applied has been presented in detail before [43, 67, 68] but a summarized description is given below. In brief, activity concentrations of ^{137}Cs, ^{134}Cs and ^{40}K were measured using a γ-spectrometer with a coaxial HPGe detector with a relative efficiency of 18% and a resolution of 1.9 keV at 1.332 MeV of ^{60}Co (with associated electronics) (Detector GC 1819 7500 SL, Canberra Packard, Poland, Warsaw). The measurements of the fungal materials in this study were preceded by

Table 1 ^{137}Cs and ^{40}K activity concentration (± an instrumental counting error) and estimated K in mushrooms collected from the provinces of China

				^{137}Cs, Bq kg^{-1} dw		^{40}K, Bq kg^{-1} dw		K, g kg^{-1} dw	
Province and species	Location	Year	n#	Caps	Stipes	Caps	Stipes	Caps	Stipes
Inner Mongolia province	Xilin Gol League								
Agaricus arvensis	West Ujimqin [1]*	2015	80	< 8.7	19 ± 4	2100 ± 240	1700 ± 250	72 ± 8	58 ± 8
A. arvensis	Bayanhushu [2]	2015	60	7.2 ± 1.7	7.6 ± 1.7	875 ± 140	1100 ± 140	30 ± 1	37 ± 5
A. arvensis	Bayanhushu [2]	2014	60	< 4.1	< 7.1	1500 ± 190	1100 ± 180	51 ± 6	37 ± 6
Calocybe gambosa	Jinhe [3]	2015	14	9.7 ± 1.7	12 ± 2	1250 ± 100	1200 ± 120	43 ± 3	41 ± 4
Calvatia gigantea	Bayanhushu [2]	2015	4	(10 ± 2)		(1400 ± 170)		(41 ± 5)	
Macrolepiota excoriata	Bayanhushu [2]	2015	2	15 ± 4	< 23	1600 ± 320	1400 ± 620	55 ± 11	48 ± 21
Lepista personata	Baiyinhua [4]	2015	10	< 8.7	19 ± 4	1400 ± 93	1300 ± 110	48 ± 3	44 ± 4
L. personata	Jinshan [5]	2015	10	6.4 ± 1.4	< 4.1	1200 ± 100	1200 ± 110	41 ± 3	41 ± 4
Yunnan province									
Auricularia delicate	Meng'a, Xishuangbanna [6]	2016	7	(< 1.4)		(540 ± 61)		(16 ± 2)	
Baorangia bicolor	Mojiang, Pu'er [7]	2015	5	4.9 ± 4.7	ND	1000 ± 200	ND	29 ± 6	ND
B. bicolor	Yuxi [8]	2015	11	(< 3.6)		(900 ± 100)		(26 ± 3)	
Boletus bainiugan	Ning'er, Pu'er [9]	2016	5	< 2.8	2.7 ± 0.9	870 ± 88	520 ± 68	25 ± 3	15 ± 2
B. bainiugan	Jiuxi, Yuxi [10]	2015	17	6.1 ± 1.2	6.6 ± 1.1	ND	ND	ND	ND
B. bainiugan	Dayingjie, Yuxi [11]	2015	12	< 2.9	ND	810 ± 76	ND	24 ± 2	ND
B. bainiugan	Ning'er, Pu'er [9]	2016	30	5.3 ± 1.1	< 2.5	780 ± 89	690 ± 66	27 ± 3	24 ± 2
Boletus ferrugineus	Midu, Dali [13]	2016	10	17 ± 1	13 ± 1	730 ± 85	600 ± 74	21 ± 2	18 ± 2
Boletus impolitus	Jiuxi, Yuxi [10]	2016	2	41 ± 3	9.5 ± 1.8	1000 ± 130	910 ± 120	29 ± 4	27 ± 3
Boletus reticulatus	Jiuxi, Yuxi [10]	2015	1	21 ± 6	< 3.1	1500 ± 440	2000 ± 850	44 ± 13	59 ± 25
Boletus speciosus	Yuxi [8]	2015	7	(5.0 ± 1.1)		(720 ± 74)		(21 ± 2)	
Boletus tomentipes	Yuxi [8]	2015	12	(69 ± 4)		(1300 ± 210)		(38 ± 6)	
B. tomentipes	Hongta, Yuxi [12]	2015	7	35 ± 9	< 19	4000 ± 680	1800 ± 520	120 ± 20	53 ± 15
Caloboletus calopus	Jiuxi,Yuxi [10]	2015	12	< 4.2	ND	960 ± 110	ND	33 ± 4	ND
C. calopus	Hongta, Yuxi [12]	2015	10	9.8 ± 1.8	ND	1000 ± 110	ND	29 ± 3	ND
C. calopus	Midu, Dali [13]	2015	11	7.2 ± 1.3	3.2 ± 1.2	640 ± 95	380 ± 78	19 ± 3	11 ± 2
Neoboletus brunneissimus	Yuxi [8]	2015	11	(< 3.6)		(1000 ± 95)		(29 ± 3)	
N. brunneissimus	Midu, Dali [13]	2015	9	5.7 ± 1.3	9.6 ± 1.5	940 ± 87	960 ± 91	28 ± 3	28 ± 3
Retiboletus griseus	Yuxi [8]	2015	10	(4.3 ± 1.4)		(1400 ± 94)		41 ± 3	
R. griseus	Luohe, Yuxi [14]	2016	7	9.7 ± 2.7	< 5.4	1300 ± 250	950 ± 140	38 ± 7	28 ± 4
R. griseus	Midu, Dali [13]	2015	14	9.4 ± 1.3	< 2.6	1100 ± 81	940 ± 73	32 ± 2	28 ± 2
Rubroboletus sinicus	Jiuxi, Yuxi [13]	2015	9	< 6.2	13 ± 2	1100 ± 160	750 ± 140	37 ± 5	26 ± 5
R. sinicus	Yuxi [8]	2015	11	< 4.9	ND	1100 ± 140	ND	33 ± 3	ND
R. sinicus	Jiuxi, Yuxi [10]	2015	9	2.4 ± 0.3	ND	1000 ± 90	ND	32 ± 4	ND
Sutorius magnificus	Dayingjie, Yuxi [11]	2016	7	18 ± 2	45 ± 3	1300 ± 120	1000 ± 120	38 ± 3	29 ± 3
Sutorius obscureumbrinus	Yuxi [8]	2015	12	(3.9 ± 3.7)		(1200 ± 130)		(35 ± 4)	
S. obscureumbrinus	Gasa, Xishuangbanna [15]	2016	16	< 2.7	3.0 ± 0.7	1300 ± 100	975 ± 74	45 ± 4	33 ± 3
Laccaria vinaceoavellanea	Baoshan city, Baoshan [16]	2016	7	(< 3.2)		(1200 ± 93)		(35 ± 3)	
Lactarius deliciosus	Zhengyuan, Pu'er [17]	2014	5	< 5.3	< 10	800 ± 150	1100 ± 290	23 ± 4	32 ± 8
L. deliciosus	Lianhuachi, Yuxi [18]	2016	20	8.1 ± 1.6	17 ± 2	580 ± 110	720 ± 140	17 ± 3	21 ± 4
Lactarius hatsudake	Lianhuachi, Yuxi [18]	2016	10	6.2 ± 1.3	15 ± 3	830 ± 80	710 ± 210	24 ± 2	21 ± 6
L. hatsudake	Lianhuachi, Yuxi [18]	2016	4	12 ± 3	20 ± 5	1000 ± 160	1100 ± 350	29 ± 5	32 ± 10
Lactarius hygrophroides	Lianhuachi, Yuxi [18]	2016	2	< 19	ND	1500 ± 64	ND	44 ± 2	ND
L. hygrophroides	Lianhuachi, Yuxi [18]	2016	6	< 5.0	29 ± 7	1200 ± 140	1400 ± 500	35 ± 4	41 ± 15
L. hygrophroides	Jiulongchi, Yuxi [19]	2016	9	130 ± 5	60 ± 5	920 ± 150	1300 ± 260	27 ± 4	38 ± 8
Lactarius volemus	Jiulongchi, Yuxi [19]	2016	17	210 ± 13	67 ± 7	1000 ± 99	760 ± 97	30 ± 23	22 ± 3
L. volemus	Yongping, Dali [20]	2016	8	< 3.5	6.1 ± 1.6	920 ± 100	830 ± 102	31 ± 3	28 ± 3
Lentinus edodes	Wuding, Chuxiong [21]	2015	70	5.2 ± 1.4	12 ± 3	810 ± 110	910 ± 270	24 ± 3	27 ± 8
L. edodes	Longyang, Baoshan [22]	2015	100	12 ± 2	22 ± 4	1200 ± 140	1100 ± 240	35 ± 4	32 ± 7
Lentinula edodes	Northeast of China	2016	30+	5.3 ± 1.4	4.5 ± 1.2	880 ± 110	640 ± 88	26 ± 3	19 ± 3
L. edodes	Baise, Guangxi province [23]	2016	30+	6.9 ± 1.7	< 3.6	790 ± 110	690 ± 82	23 ± 3	20 ± 2
Leccinum rugosiceps	Ning'er, Pu'er [9]	2016	30	6.3 ± 1.1	4.0 ± 0.8	815 ± 84	781 ± 90	27 ± 3	27 ± 3
Morchella esculenta	Midu, Dali [13]	2016	30	(< 3.4)		(1200 ± 140)		(35 ± 4)	
Russula compacta	Midu, Dali [13]	2016	5	(4.6 ± 1.0)		(940 ± 80)		(28 ± 2)	
Boletus sp.	Baoshan city, Baoshan [16]	2016	5	8.3 ± 1.4	9.3 ± 1.5	ND	ND	ND	ND
Boletus sp.	Midu, Dali [13]	2016	7	5.2 ± 1.2		1000 ± 83		29 ± 2	
Boletus sp.	Midu, Dali [13]	2016	6	5.9 ± 1.2		1200 ± 92		35 ± 3	
Boletus sp.	Baoshan city, Baoshan [16]	2016	9	9.0 ± 1.2		690 ± 78		20 ± 2	

Continuation of Table 1

Province and species	Location	Year	n#	^{137}Cs, Bq kg^{-1} dw Caps	^{137}Cs, Bq kg^{-1} dw Stipes	^{40}K, Bq kg^{-1} dw Caps	^{40}K, Bq kg^{-1} dw Stipes	K, g kg^{-1} dw Caps	K, g kg^{-1} dw Stipes
Boletus sp.	Baoshan city, Baoshan [16]	2016	5	< 2.7	3.0 ± 0.7	1300 ± 100	975 ± 74	39 ± 3	29 ± 2
Boletus sp.	Midu, Dali [13]	2016	6	7.7 ± 1.7		1100 ± 130		32 ± 4	
Boletus sp.	Changning, Baoshan [24]	2016	5	5.7 ± 1.4		860 ± 98		25 ± 3	
Boletus sp.	Baoshan city, Baoshan [16]	2016	7	9.6 ± 1.4		760 ± 96		22 ± 3	
Boletus sp.	Baoshan city, Baoshan [16]	2016	6	< 4.1		780 ± 110		23 ± 3	
Boletus sp.	Changning, Baoshan [24]	2016	7	9.6 ± 2.2		1100 ± 150		32 ± 4	
Boletus sp.	Baoshan city, Baoshan [16]	2016	5	7.9 ± 1.4		790 ± 100		23 ± 3	
Boletus sp.	Midu, Dali [13]	2016	6	6.0 ± 1.5		1100 ± 120		32 ± 3	
Boletus sp.	Changning, Baoshan [24]	2016	6	4.4 ± 0.9		960 ± 73		28 ± 2	
Boletus sp.	Changning, Baoshan [24]	2016	5	7.4 ±1.4		810 ± 93		24 ± 3	
Boletus sp.	Changning, Baoshan [24]	2016	7	18 ± 2		990 ± 97		29 ± 3	
Tricholoma sejunctum	Liqi, Yuxi [25]	2016	14	7.7 ± 2.0	6.3 ± 2.0	1400 ± 140	1700 ± 170	41 ± 4	50 ± 5
T. sejunctum	Yiwanshui, Yuxi [26]	2016	20	9.0 ± 1.4	23 ± 1	1400 ± 92	1200 ± 79	41 ± 3	35 ± 2
T. sejunctum	Lianhuachi, Yuxi [18]	2016	5	20 ± 3	15 ± 4	2000 ± 270	1900 ± 340	59 ± 8	56 ± 10

*ID of the sampling site (see also in Fig. 1); #Quantity of specimens (fruit bodies) in a pool; ND – no data

background measurement (time 80 000 s) and counting time was similar (> 22 h).

The instrument was calibrated using a multi-isotope standard by validated methodology. The reference solution (Standard solution of gamma emitting isotopes, code BW/Z-63/48/16), obtained from the IBJ-Świerk near Otwock in Poland, was used to prepare reference samples for equipment calibration. The radionuclides used in the reference solution during equipment calibration were ^{241}Am (1.2%), ^{109}Cd (2.1%), ^{57}Co (0.80%), ^{51}Cr (1.55%), ^{113}Sn (2.0%), ^{85}Sr (1.2%), ^{137}Cs (1.5%), ^{54}Mn (1.55%), ^{65}Zn (1.2%) and ^{60}Co (0.8%). The same geometry of cylindrical dishes with a 40-mm diameter was used for the analysis of the fungal material extracts as well as for the reference samples during equipment calibration organized by IAEA-RML-2018-01. Detailed results of the intercalibration are available in the publication [50].

Minimum detectable activity was determined by the Currie method. This method is based on two basic parameters: (a) critical level, which is defined as a level below which the detection signal cannot be reliably recognized and (b) detection limit specifying the smallest signal that can be quantitatively reliable. The measurement results obtained were recalculated for dehydrated materials and decay corrected back to the time of collection. Total potassium content was calculated from the original ^{40}K activity concentration data (using mean value of 29.32 Bq g^{-1}) in natural K, which is in the range from 27.33 to 31.31 Bq g^{-1} of K (percentage abundance of ^{40}K atoms in natural K is 0.0117%) [51].

RESULTS AND DISCUSSION

^{137}Cs and ^{134}Cs in mushrooms and soil. All species collected from Inner Mongolia in this study were saprobic. ^{134}Cs activity was not detected in any of the study samples. It was possibly due to the negligible impact from the Fukushima's fallout in 2011 as wells as a relatively short half-life of this isotope ($t_{0.5}$ = 2.1 years) and small impacts from the Chernobyl's fallout in 1986 and preceding, the nuclear weapons detonations in the atmosphere.

The values of the activity concentration of ^{137}Cs in caps and stipes of the fruiting bodies of *Agaricus arvensis*, *Calocybe gambosa*, *Lepista personata* and *Macrolepiota excoriata* and in the whole fruiting bodies of *C. gigantea* were in the range from < 4.1 to 19 ± 4 Bq kg^{-1} dw (Table 1). There is no prior data for these species from regions of Asia other than Inner Mongolia [44, 53, 54]. The low levels of ^{137}Cs contamination in the studied mushrooms from the Inner Mongolian region reflects low activities of this nuclide in local soils as well as a lower potential of these species to bio-accumulate this nuclide.

In this study, a composite sample of the upper (0–10 cm) layer of soil collected in parallel with *A. arvensis* from the Bayanhushu site (altitude 920 m a.s.l.) showed ^{137}Cs activity concentration of 6.8 ± 0.7 Bq kg^{-1} dw. This result obtained for the sample from 2015 is around 2 to 4-fold lower than earlier results cited for topsoils collected in Inner Mongolia in 1982–1987, and is close to the activity values reported in 1–5 cm layer of forest topsoils sampled from the Changning and Mengman sites in Yunnan in 2016 (4.9 ± 0.6 and 7.5 ± 0.7 Bq kg^{-1} dw) [53].

Because of colder weather in the mountains, soil and the mushrooms can be specifically affected with radiocaesium, which is scavenged from the contaminated plumes by wet precipitation [53–55]. Forest topsoil collected at 3000 m above sea level from the Minya Konka (Gongga Shan) mountain in Sichuan province of China in 2012 showed ^{137}Cs at level from 41 ± 1 to 79 ± 2 Bq kg^{-1} dw. This result is well in excess of what has been noted in topsoil from Inner Mongolia in this study or other studies of soils from China [32, 33, 53].

As given in Table 1, the determined activity concentrations of ^{137}Cs in fruiting bodies of the saprobic and perhaps a little parasitic species of *Auricularia delicate*, the caps and stipes of fruiting bodies of the saprobic decomposer *Lentinula edodes*, the saprobic *Morchella esculenta* as well as over 20 species of mycorrhizal mushrooms collected in Yunnan were low and roughly in the range of values noted in mushrooms from Inner Mongolia.

The only exception was individuals of *Lactarius hygrophoroides* collected from the region of Jiulongchi in Yuxi prefecture in central Yunnan in the summer of 2016. They showed activity concentrations of ^{137}Cs from 130 ± 5 to 210 ± 13 Bq kg dw^{-1} in caps and from 60 ± 5 to 67 ± 7 Bq kg dw^{-1} in stipes (Table 1). These relatively high levels of ^{137}Cs activity in *L. hygrophoroides* from the Jiulongchi site were in the range of activities determined previously in several species of ectomycorrhizal mushrooms collected at 2900–3600 m above sea level from the Minya Konka summit in 2012 [53].

Many other species of mushrooms collected from the prefecture of Yuxi and across other regions from Yunnan and elsewhere in China (Zhangzhou in the Fujian province) in 2010–2018 were substantially less contaminated than *L. hygrophoroides* from the Jiulongchi site or even mushrooms from the subalpine regions on the eastern slope of the Minya Konka summit [12, 16, 42, 44, 47, 52, 53, 56]. The exception was *Turbinellus floccosus* (Schwein.) Earle ex Giachini & Castellano [previous name *Gomphus floccosus* (Schw.) Singer] collected from the region of Mangshi (98°24' E, 24°22' N) in the western part of Yunnan during August 2012 to July 2013, which showed a ^{137}Cs activity concentration of 212 (148–339) Bq kg^{-1} dw in the whole fruiting bodies [44, 57].

Elevated activity concentrations of ^{137}Cs in *L. hygrophoroides* from the Jiulongchi site in this study can possibly be explained by weather conditions (episodic rain) scavenging nuclides from the radioactive plume after the Fukushima (Japan) nuclear power plant accident in early 2011.

The radioactive incident took place in Tongchuan, Shaanxi Province, south of the central region of Inner Mongolia (approximate distance from the sampling sites mushrooms there is 1200 km). Some ^{137}Cs from a measuring instrument (lead ball – a major component of a nuclear scale) when dismantling a cement factory has gone missing. In a later investigation, radioactivity from ^{137}Cs was found at a steel refinery in Shaanxi's Fuping county. Possibly, a lead ball with scrap metal was melted down into the steel [58]. Information on possible, if any, ground pollution in the region from this accident is not available.

A recent (2021) study showed that the activity concentration of ^{137}Cs in 66 out of 68 of wild mushrooms (17 species) collected from the northeast regions of China in 2017–2020 ranged from < 0.6 to 26 Bq kg^{-1} dw (data rounded), and only in single *Lactarius deliciosus* and *Lepista nuda* (Bull.) Cooke specimens collected in 2020, was 46 ± 3 Bq kg^{-1} dw and 130 ± 9 Bq kg^{-1} dw, respectively [59].

The maximum activity concentration of ^{137}Cs noted in *L. nuda* in the above mentioned study was close to values determined in *Lactarius hygrophroides* and *Lactarius volemus* from Jiulongchi, Yuxi (Yunnan) (Table 1), while the results are not very comparable due to only two single specimens examined by Wang *et al.* [59].

The radiocaesium contamination of land, the oceans and biota, including edible wild growing mushrooms has thus far, occurred in three main waves. The first one arose from the nuclear weapons detonations in the atmosphere in the period from 1945 to 1980 and resulted in wide-spread aerial diffusion of radiocaesium and other nuclides including ^{14}C, ^{137}Cs, ^{90}Sr, $^{239–240}$Pu, ^{241}Am and ^{3}H [60]. With time, the resulting depositions of longer lasting ^{137}Cs affected every region of the world [1, 60].

Data on radiocaesium in mushrooms for the period before 1986 is scarce [10–13, 42, 61]. Fifteen years before the Chernobyl accident, a solely fruiting body of *Tricholoma terreum* collected from the Czech Republic in 1971 showed ^{137}Cs at a level of 40 Bq kg^{-1} dw [61]. Additional historical data on ^{137}Cs in mushrooms was recorded in 1984, in Poland for the Poison Pax (*Paxillus involutus*), which showed ^{137}Cs at a level of 2700 Bq kg^{-1} dw, with lower levels noted for the King Bolete (*Boletus edulis*) (95 and 104 Bq kg^{-1} dw) and Slippery Jack, *Suillus luteus* (125 and 150 Bq kg^{-1} dw) collected in 1984 and 1985, respectively [10].

Data on the radiocaesium concentration activities accumulated in wild mushrooms growing in Asia from the period before the Chernobyl accident are absent in the available literature. Effectively, there is also nothing published on radiocaesium in wild mushrooms from mainland Asia in the period between the Chernobyl and Fukushima incidents.

The Chernobyl emission of radioactivity caused an extreme and long-lasting radiocaesium pollution of wild growing mushrooms in the regions of Europe, and particularly in the neighbor areas collapsed nuclear power plant [12, 16, 17, 62–65]. Japanese researchers have published a large volume of data on artificial radioactivity accumulated in wild mushrooms growing in the country, both from the post-Chernobyl and post-Fukushima emissions, which have recently been evaluated by Komatsu *et al.* and Prand-Stritzko and Steinhauser [25, 66]. The activity in these wild mushrooms collected in the period up to March 2011 was largely from accumulated radiocaesium (^{137}Cs) due to the global fallout from nuclear weapons detonations, with a small proportion being attributed to the Chernobyl emissions [54]. The more recent emissions from the Fukushima incident changed the pattern of radionuclide contamination of wild mushrooms in Japan. However, as shown in this study (Table 1) and in a few other reports, the emissions could have only a small impact on mainland Asia or elsewhere [44, 53, 68–69].

^{40}K and K in mushrooms and soil. The topsoil from the Bayanhushu site showed ^{40}K activity concentration of 595 ± 41 Bq kg^{-1} dw and total K content of 17 000 ± 1000 mg kg^{-1} dw, which were higher than previously determined in topsoils sampled from several forested areas in Yunnan (150 ± 14 to 340 ± 19 Bq kg^{-1} dw) [53].

In the study by Zhang *et al.*, the means of ^{40}K activity concentrations in topsoils (0–10 cm) in Inner Mongolia and Yunnan in 1982–1987 were 755 (866–1066 Bq kg^{-1} dw) and 487 Bq kg^{-1} dw (149–1010 Bq kg^{-1} dw), respectively [70]. In another national survey performed during 1983–1990, the area-weighted mean and the point-weighted mean of ^{40}K were 655.6 and 624.6 Bq kg^{-1} dw, respectively, for soils in Inner Mongolia, while the two values for soils from Yunnan were 532.0 and 518.6 Bq kg^{-1} dw, respectively [71].

The activity concentrations of ^{40}K in mushrooms from Inner Mongolia were in the range of 875 ± 140 to 1600 ± 320 Bq kg^{-1} dw in caps and from 1100 ± 180 to 1400 ± 620 Bq kg^{-1} dw in stipes (Table 1). In the case of mushrooms from Yunnan, *A. delicate* (ear-like jelly fungus), which grows on wood, they had a lower activity concentration of ^{40}K (540 ± 61 Bq kg^{-1} dw) than *L. edodes* (Table 1), which also grows on wood. The *L. edodes* showed activities in the range of 790 ± 110 to 1200 ± 140 Bq kg^{-1} dw in the caps, which are culinary valued, and from 640 ± 88 to 1100 ± 240 Bq kg^{-1} dw in the stipes, which are largely discarded. This species collected from Yunnan and examined by other authors, demonstrated the mean value of ^{40}K activity concentration to be 629 Bq kg^{-1} dw (from 396 to 1010 Bq kg^{-1} dw; n = 11) [44]. ^{40}K values in the caps of terrestrial mushrooms from Yunnan were from 580 ± 110 Bq kg^{-1} dw in *L. deliciosus* to 4000 ± 680 Bq kg^{-1} dw in *Boletus tomentipes*, while stipes showed activities from 380 ± 78 Bq kg^{-1} dw in *L. deliciosus* to 1900 ± 340 Bq kg^{-1} dw in *Tricholoma sejunctum*.

Potassium (total K) is the major metallic element in mushrooms and occurs in dried fungal materials in quantities of up to several percent, while the natural nuclide ^{40}K forms only a small proportion (makes up 0.012%) of the total. Hence, mushrooms collected from areas that are only mildly affected by ^{137}Cs depositions or mushrooms without a high species-specific ability to bioconcentrate this nuclide, e.g. like some species from the genus *Cortinarius*, contained natural ^{40}K in high excess relative to ^{137}Cs (Table 1) [12].

The amounts of K in the caps, stipes, or whole fruiting bodies of the species in this study were in the range 16 000 to 120 000 mg kg^{-1} dw (1.6 to 12 g kg^{-1} dw). Potassium is indispensable for mushrooms, for the uptake and osmotic regulation of water in the cytoplasm of cells and is a co-factor in certain enzymes [72]. However, the same species, i.e. *A. arvensis*, *Boletus bainiugan*, *Retiboletus griseus*, *Rubroboletus sinicus*, *Caloboletus calopus*, *L. hygrophoroides*, *L. edodes* and *T. sejunctum* collected from different sites could differ around twofold in the content of K (Table 1).

The daily adequate intake of K for adults is 2300 mg for females and 3400 mg for males [73]. Thus, the mushroom species examined in this study and assuming absorption rate at around 90% could be considered as potentially good sources of dietary potassium, especially when stir-fried with oil, which is a common culinary technique in SW China [67].

Potential risk from ionizing radiation doses. In this study, a total of 70 lots of several species of edible mushrooms collected from 26 locations in Yunnan were examined and in 63 lots, the contamination with ^{137}Cs of the caps or the whole mushrooms was well below 20 Bq kg^{-1} dw (Table 1). There were three of 70 lots that were more contaminated with ^{137}Cs than the others. Those lots were the gilled mushroom *B. tomentipes* (of 69 ± 4 Bq kg^{-1} dw), caps of the lamellar mushroom *L. hygrophoroides* (130 ± 5 Bq kg^{-1} dw), and caps of lamellar *L. volemus* (210 ± 13 Bq kg^{-1} dw) (Table 1). Assuming that the moisture content in fruiting bodies is 90%, the estimated ^{137}Cs activities in these three species were 6.9, 13, and 21 Bq kg^{-1} on a wet weight basis. Therefore, these amounts were much lower than the maximum permitted levels for import of mushrooms from third countries [specific 13 countries affected by the Chernobyl's radioactive fallout for which the regulation applies] to the European Union (600 Bq kg^{-1}) [74].

In Yunnan, the main way to cook mushrooms is stir-frying in vegetable oil in a wok pan [75]. It is interesting that stir-fried mushroom meals showed about 2 to 5-fold higher activity concentrations of ^{137}Cs than the raw mushrooms on a whole weight (wet) basis [67, 68].

Therefore, a 100-g portion of stir-fried *L. volemus* caps from the most contaminated lot in this study could include from 4.2 to 10.5 Bq of ^{137}Cs (equivalent to ionizing radiation dose from 56×10^{-3} to 140×10^{-3} μSv *per capita* or 0.49×10^{-3} to 2.35×10^{-3} μSv per kg body mass; 60 kg body mass). These estimates are low, taking into account the risk associated with the doses of ionizing radiation received by consumers in Yunnan, even if stir-fried mushrooms are consumed daily for longer periods during the mushrooming season.

In comparison, the natural ^{40}K nuclide contained in mushrooms (Table 1) introduces much higher doses of ionizing radiation than ^{137}Cs for locals in Inner Mongolia and Yunnan provinces but is not considered as a hazardous nuclide for consumers due to homeostasis of K in human body.

CONCLUSION

The activity concentrations of ^{137}Cs in lamellar mushrooms from the Inner Mongolia province of China and the local soil were low. ^{137}Cs contamination of the lamellar and gilled mushrooms from Yunnan province in China was also low, i.e. well below one tenth of statutory limits, and mushroom meals there can be considered as a negligible source of ^{137}Cs for their consumers.

In view of the results from this study, the accident in the Fukushima nuclear power plant had little or negligible effect on radioactive contamination of edible and medicinal fungi in the regions of China. Natural nuclide ^{40}K contained in mushrooms is not considered as hazardous for mushroom meal consumers. Wild mushrooms can be considered as a good source of dietary potassium for consumers.

CONTRIBUTION

Michał Saniewski: resources, methodology, investigation, validation, data curation and analysis, writing – review & editing. Jerzy Falandysz: conceptualization, resources, investigation, formal analysis, data curation, graphics, supervision, writing – original draft, writing – review & editing. Tamara Zalewska: resources, methodology, investigation, validation, data curation and analysis.

CONFLICT OF INTEREST

The authors declare no conflict of interests regarding the publication of this article.

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