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^{137}Cs in mushrooms from Croatia sampled 15–30 years after Chernobyl

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ABSTRACT

The aim of this study was to select species with higher potential to accumulate ^{137}Cs among the available mushroom species, by determining the activity concentrations of ^{137}Cs in mushrooms collected along north and north-western part of Croatia. A total of 55 samples of 14 different species were analyzed and the potential of mycorrhizal and saprotrophic species to accumulate ^{137}Cs was compared. A wide range of the dry weight activity concentrations of ^{137}Cs was detected, ranging from 0.95 to 1210 Bq/kg (154 Bq/kg mean value; 52.3 Bq/kg geometric mean) in mycorrhizal and 1.05–36.8 Bq/kg (8.90 Bq/kg mean value; 5.49 Bq/kg geometric mean) in saprotrophic species. Statistical analyses showed that mycorrhizal species accumulate significantly higher concentrations of ^{137}Cs and thus could perform better as long-term bioindicators of environmental pollution by radiocaesium then saprotrophic species. The comparison of *Boletus* sp. and *Hydnum repandum* (both mycorrhizal species commonly found in Croatia) showed, in general order of magnitude, higher accumulation in *Hydnum repandum.* Clearly, mushrooms, especially mycorrhizal species, can be used as significant indicators even decades after the occurrence of any serious ^{137}Cs contamination event. However, as a wide range of values indicates that various parameters may influence the total uptake of the ^{137}Cs into the mushroom fruit bodies, it is necessary to emphasize that ^{137}Cs activity detected in a single mushroom sample is very site-specific.

1. Introduction

Monitoring of anthropogenic radionuclide pollution of the environment is of high importance, particularly if related to nuclear weapons testing and accidents at nuclear power-plant facilities. Search for the most appropriate bioindicating organisms in the specific geographic area and for a specific radionuclide has been carried out extensively, especially after the Chernobyl nuclear accident in 1986, with emphasis on radiocaesium. Along with ^{90}Sr, ^{137}Cs is the most significant long-lived radionuclide produced in those types of incidents. The accumulation of radiocaesium in different mushroom species is widely studied (Byrne, 1988; Kalač, 2001; Baeza et al., 2004; Dighton et al., 2008; Kioupi et al., 2015; Zalewska et al., 2016). The focus of most of the studies is radioactive concentration in mushroom fruit bodies along the specific geographic area and the dose estimation for the population due to their ingestion. A large portion of the pre-Chernobyl ^{137}Cs detected in fungi (Dighton and Horrill, 1988; Byrne, 1988; Giovani et al., 1990) indicates that fungi could be used as indicators of radiocaesium presence in the environment long time after the contamination. The aim of this work is to identify ^{137}Cs accumulators among the available mushroom species from the north and north-western part of Croatia, regardless of their edibility.

Generally, a wide range of ^{137}Cs concentrations in fungal fruit bodies was observed in most of the studies, not always following the level of contamination of the sampling sites (Olsen, 1994; Kioupi et al., 2015). Olsen reported more than 50 times higher (in some cases up to 100 times) radiocaesium concentrations in mycorrhizal fungal fruit bodies than in some other vascular plants sampled on the same site. It is obvious that the fungi differ in their potential to accumulate Cs (Clint et al., 1991). A thorough investigation of each transfer step in the process is essential (Clint and Dighton, 1992; Dupré de Boulois et al., 2008). Numerous factors influence ^{137}Cs uptake by mushrooms, such as distribution and density of fungal mycelia (Giovani et al., 1990; Kammerer et al., 1994), soil or substrate with its characteristics which also vary in depth (such as soil organic matter content and pH) (Guillitte et al., 1994; Yoshida and Muramatsu, 1994; Rühm et al., 1997), forest type and fruit body location (Grueter, 1964; Andolina and Guillitte, 1990; Vinichuk and Johanson, 2003) or trophic status (saprotrophic, parasitic or mycorrhizal). Often, a higher ^{137}Cs concentration is detected in mycorrhizal mushrooms, if compared to saprotrophic or parasitic ones (Guillitte et al., 1994; Kammerer et al., 1994; Yoshida and Muramatsu, 1994; Gillet and Crout, 2000). Saprotrophes grow on organic matter while parasitic mushrooms grow attached to other species in a non-symbiotic relationship. Mycorrhizal species, on the

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other hand, form a close symbiotic relationship with their host plant through underground mycorrhiza. Therefore, it is reasonable to expect for them to retrieve more cesium via their mycorrhizal association with plant roots. Various species, both saprotrophic (S) and mycorrhizal (all of them ectomycorrhizal) (M), collected during the years 2012 and 2016 from differently contaminated parts of north and north-western Croatia, were analyzed by gamma-spectrometry to determine the ^{137}Cs mass activity concentrations. In order to obtain information about the contamination level of the sampling sites, soil samples from the same areas were collected and analyzed.

Due to a large range of ^{137}Cs activities found in mushrooms within the same group, especially mycorrhizal, the comparison between two very common ectomycorrhizal fungi – *Boletus* sp. and *Hydnum repandum* was made. *Boletus* mushrooms express high affinity for Cs (Heinrich, 1993; Kammerer et al., 1994; Toal et al., 2002; Vinichuk and Johanson, 2003; Řanda and Kučera, 2004), while some studies declare *Hydnum repandum* as one of the greatest Cs accumulators among mushrooms (Heinrich, 1993; Kammerer et al., 1994; García et al., 2015). As emphasized in previous studies (Mietelski et al., 1994; Shutov et al., 1996; Skuterud et al., 1997; Kalač, 2001), it should be indicated that in case of elevated ^{137}Cs activity in mushrooms, the annual dose due to their consumption should not be neglected.

2. Materials and methods

2.1. Mushrooms and soils sampling and sample preparation

A total of 55 samples of 14 different mushroom species were collected during 2012 and 2016. In 2012, the samples were collected, mainly randomly, from the three broader areas: 1) North-western Croatia (NWC) covering the area of about 4000 km^2, 2) Gorski Kotar area including surrounding areas and a part of Istria (GK) covering the space of about 4000 km^2 and 3) Banovina (B) covering the space of about 1000 km^2. Additional samples were collected in 2016, from the same locations - Banovina area and a smaller part of Gorski Kotar in vicinity of Vrbovsko (GKV) which covers an area of about 10 km^2. Both saprotrophic and mycorrhizal mushrooms were collected. The largest number of mycorrhizal species belonged to the genus *Boletus* (10 of *B. aestivalis* (Paulet) Fr., 8 *B. edulis* Bull., 2 *B. erythropus* Pers.) and a small number to other species – 2 samples of *Tricholoma portentosum* (Fr.) Quel., 3 *Lactarius* (1 *L. deterrimus* Groger, 1 *L. piperatus* (L.) Pers. and 1 *L. vellereus* (Fr.) Fr.), 2 *Leccinum griseum* (Quel.) Singer samples, 1 sample of *Russula cyanoxantha* (Schaeff.) Fr. and 1 of *Hydnum repandum* L. Saprotrophic species collected were as follows: *Agaricus campestris* L. (4), *Macrolepiota procera* (Scop.) Singer (7), *Clitocybe* (3 of *C. inversa* (Scop.) Quel., 4 of *C. nebularis* (Batsch) P.Kumm. species) and *Armillaria mellea* (Vahl) P. Kumm. (8). The number of individuals making one sample varied depending on their availability on each sampling site. The whole fruit bodies of mushrooms were collected and the samples were prepared from their stems and caps. The mushrooms were cleaned from any adhering debris of foreign material (plant, soil) by a plastic knife and dried at 50 °C until constant weight was reached, then ground and homogenized before being placed into cylindrical counting vessels of 125 cm^3. The mass of the dry mushroom samples packed into the given geometry ranged from 10 g up to 130 g.

Additionally, to compare two very common mycorrhizal fungi – *Boletus* sp. and *Hydnum repandum,* ^{137}Cs activity concentrations in fresh weight of mushrooms from Gorski Kotar area collected in 2001 and 2006 are included in the study. The stems and caps of these mushrooms were cleaned, cut and placed into the identical cylindrical counting vessels (125 cm^3). The mass of the fresh mushroom samples packed into the given geometry ranged from about 100 g up to 120 g.

Mushroom sampling sites were placed in vicinity of locations wherefrom soil samples in the NWC (39 samples) and GK areas (53 samples) were collected in the period 2000–2010. Considering that soil samples from these two areas were not collected along with mushrooms, the care was taken to collect mushrooms grown at same type of soils that were previously sampled in the vicinity. Soils from B (14 samples) and GKV (7 samples) areas were sampled along with mushrooms during the summer 2016. Each bulk soil sample was collected from the surface to the depth of 10 cm of open vertical soil profile. The soil was dried at 105 °C to a constant weight and homogenized before being placed into counting vessels of identical geometry (125 cm^3). The mass of the soil samples ranged between 100 and 180 g.

Table 1
^{137}Cs activity concentrations in dry weight mushroom tissue for the mushrooms collected in 2012 and 2016 (ref. date 1st of July 2016).

Species (Scientific name)	Location[a]	Year of collection	^{137}Cs activity (Bq/kg) dw
Mycorrhizal species (M)			
Boletus aestivalis	NWC	2012	33.2 ± 2.22
Boletus aestivalis	NWC	2012	15.9 ± 1.10
Boletus aestivalis	NWC	2012	16.3 ± 1.08
Boletus aestivalis	NWC	2012	64.8 ± 4.08
Boletus edulis	NWC	2012	22.9 ± 1.58
Boletus edulis	NWC	2012	41.9 ± 2.82
Tricholoma portentosum	NWC	2012	63.8 ± 3.97
Tricholoma portentosum	NWC	2012	48.8 ± 3.03
Lactarius deterrimus	NWC	2012	9.80 ± 0.75
Boletus aestivalis	GK	2012	1210 ± 73
Boletus aestivalis	GK	2012	240 ± 14.6
Boletus aestivalis	GK	2012	24.1 ± 1.80
Boletus aestivalis	GK	2012	12.8 ± 1.01
Boletus edulis	GK	2012	168 ± 10.3
Boletus edulis	GK	2012	170 ± 10.6
Boletus edulis	GK	2012	705 ± 42.6
Boletus edulis	GK	2012	308 ± 18.8
Boletus edulis	GK	2012	266 ± 16.1
Boletus edulis	GK	2012	79.9 ± 4.90
Boletus erythropus	GK	2012	355 ± 21.5
Boletus aestivalis	B	2012	27.7 ± 1.77
Boletus erythropus	B	2012	312 ± 19.0
Boletus aestivalis	B	2016	46.3 ± 2.92
Leccinum griseum	B	2016	52.2 ± 3.29
Leccinum griseum	B	2016	8.66 ± 0.59
Lactarius piperatus	B	2016	0.95 ± 0.36
Russula cyanoxantha	B	2016	7.75 ± 0.53
Lactarius vellereus	GKV	2016	5.11 ± 0.39
Hydnum repandum	GKV	2016	151 ± 9.11
Saprotrophic species (S)			
Agaricus campestris	NWC	2012	3.10 ± 0.62
Agaricus campestris	NWC	2012	4.46 ± 0.49
Agaricus campestris	NWC	2012	1.05 ± 0.29
Macrolepiota procera	NWC	2012	4.11 ± 0.52
Macrolepiota procera	NWC	2012	1.74 ± 0.28
Macrolepiota procera	NWC	2012	11.6 ± 0.83
Clitocybe inversa	NWC	2012	2.22 ± 0.48
Clitocybe inversa	NWC	2012	5.21 ± 0.70
Clitocybe inversa	NWC	2012	14.6 ± 0.98
Clitocybe nebularis	NWC	2012	6.07 ± 0.62
Armillaria mellea	NWC	2012	3.39 ± 0.41
Armillaria mellea	NWC	2012	1.13 ± 0.32
Armillaria mellea	NWC	2012	10.9 ± 0.82
Armillaria mellea	NWC	2012	10.3 ± 0.76
Agaricus campestris	GK	2012	8.00 ± 1.12
Macrolepiota procera	GK	2012	30.6 ± 0.65
Macrolepiota procera	GK	2012	1.59 ± 0.44
Macrolepiota procera	GK	2012	5.91 ± 0.51
Clitocybe nebularis	GK	2012	36.8 ± 2.50
Clitocybe nebularis	GK	2012	30.3 ± 2.07
Armillaria mellea	GK	2012	2.76 ± 0.53
Armillaria mellea	GK	2012	5.77 ± 0.62
Macrolepiota procera	B	2012	2.10 ± 0.41
Armillaria mellea	B	2012	16.4 ± 1.12
Clitocybe nebularis	GKV	2016	2.57 ± 0.37
Armillaria mellea	GKV	2016	8.92 ± 0.76

[a] NWC – North-western Croatia; GK – expanded Gorski Kotar area; B – Banovina; GKV - Vrbovsko (in Gorski Kotar area).

Table 2
^{137}Cs activity concentrations (Bq/kg) in soils collected in period 2000–2010 from GK and NWC areas, and in soils collected in 2016 from B and GKV areas. (ref. date 1st of July 2016 for all samples), with statistical parameters.*

LOCATION	Geom. mean ± GSD	Mean ± SD	Range	Mean ± SD (log(x))	LSM (log(x))	SE_{LSM} (log(x))	Sign. level
NWC (n = 39)	17.5 ± 50.8	26.8 ± 19.9	1.67–72.8	2.86 ± 1.10	2.86[a]	0.16	***
GK (n = 53)	69.0 ± 282	93.7 ± 68.8	1.43–322	4.23 ± 0.92	4.23[c]	0.14	P < 0.001
GKV (n = 7)	68.6 ± 391	77.2 ± 48.6	44.1–184	4.23 ± 0.48	4.23[bc]	0.37	
B (n = 14)	28.7 ± 105	42.6 ± 32.2	2.9–103	3.36 ± 1.08	3.36[ab]	0.26	

[a,b,c] - Values with different superscript within the same column differ significantly (P < 0.05).
*** - Statistical significance with P value less than 0.001.
* Abbreviations are as explained in section 2.3.

Table 3
^{137}Cs activity concentrations (Bq/kg) in dry weight of mycorrhizal (M) and saprotrophic (S) mushrooms collected in summer of 2012 and 2016, separated by location of collection. (ref. date: 1st of July of 2016. for all samples).

LOCATION	Trophic status	n	Geom. mean ± GSD	Mean ± SD	Range
NWC	M	9	29.4 ± 111	35.3 ± 20.8	9.80–64.8
	S	14	4.20 ± 8.32	5.70 ± 4.38	1.05–14.6
GK	M	11	173 ± 1300	322 ± 351	12.8–1210
	S	8	8.94 ± 26.3	15.2 ± 14.6	1.59–36.8
GKV	M	2	27.8 ± 715	77.9 ± 103	5.11–151
	S	2	4.79 ± 20.4	5.75 ± 4.49	2.57–8.92
B	M	7	20.1 ± 99.8	65.1 ± 111	0.95–312
	S	2	5.87 ± 35.5	9.26 ± 10.1	2.10–16.4

2.2. γ –spectrometric measurements

Activity concentrations of ^{137}Cs were determined by gamma spectrometry, by the HPGe semiconductor detector systems. Standard Electrode Coaxial Ge Detector (SEGe) (resolution: 1.76 keV at 1332 keV, relative efficiency: 25.4%) was used for the measurements of the soil samples and mushroom samples collected in 2001 and 2006, while a broad energy detector (BEGe) (resolution: 1.95 keV at 1332 keV, relative efficiency: 48%) was used for mushroom samples collected in 2012 and 2016. The spectra were analyzed by Genie 2000 software. The counting time for soil samples and fresh mushroom samples (from 2001 and 2006) was 80,000 s, while for dry mushroom samples (collected in 2012 and 2016) it ranged from 80,000 to 200,000 s, depending on the sample quantity (mass), which ranged from 10 g up to 130 g. ^{137}Cs activity concentrations were calculated from the 661.6 keV peak. The SEGe detector system was calibrated using gamma mixed standards supplied by Ecker & Ziegler (Analytics USA). BEGe detector system was calibrated mathematically with the use of Canberra's LabSOCS software. The Laboratory for radioecology (LRE) of Ruđer Bošković Institute (RBI) is accredited by the Croatian Accreditation Agency for gamma-spectrometric measurements (HRN EN ISO/IEC 17025:2007). Therefore, the efficiency of the systems is regularly checked during inter-comparison calculations, while the precision and accuracy of the systems are additionally checked by the simultaneous measurement of IAEA reference materials. In case of mathematical calibrations, combined uncertainty budget (k = 1) includes net peak area uncertainties extracted by the software during the analysis, and the efficiency uncertainty derived and imported by the software. For standard calibrations, the measured uncertainty budget includes net peak area uncertainty, efficiency uncertainty and background fluctuation uncertainty.

2.3. Statistical analysis

All calculations (preliminary, descriptive and inferential statistical analyses) were performed with R (R Core Team, 2014.). The log-normal distributions of the ^{137}Cs activity concentrations were determined in both the fungi and soil, so the log transformation of the original records was performed prior to the inferential statistical analysis (log base was set to 10). Along with the descriptive statistics reported on the original scale, we also reported geometric means (Geom. mean) and geometric standard deviations (GSD) as well as means and standard deviations (SD) of the log transformations (log(x)), since these transformations were a prerequisite for conduction of parametric statistical tests. Inferential statistical analysis related to the examination of impacts of trophic status and location on the activity concentration of ^{137}Cs in fungi was conducted with a full two-way ANOVA model for the unbalanced design with R package “car” (Fox and Weisberg, 2011). Least-squares means (LSM) a.k.a predicted marginal means (PMM), which in essence represent estimates that would have been observed if the data had arisen from a balanced experiment, and their standard errors (SE_{LSM}), were obtained with R package “lsmeans” (Lenth, 2016). The impact of location on the ^{137}Cs activity concentrations in soil was examined with one-way ANOVA and additionally with its' non-parametric counterpart, Kruskal-Wallis test. Due to the great consistency of the obtained results, only those obtained with ANOVA were reported in the paper. After obtaining a significant effect for a factor in ANOVA-s, we carried out Tukey HSD (Honestly Significant Difference) test for simultaneous multiple comparisons of the means with R package “multcomp” (Hothorn et al., 2008).

3. Results and discussion

All the ^{137}Cs dry weight activity concentrations for the mushrooms collected in 2012 and 2016 are presented in Table 1, where scientific

Table 4
^{137}Cs activity concentrations (Bq/kg) in dry mass of mycorrhizal (M) and saprotrophic (S) mushrooms collected in summers 2012 and 2016. (ref. date 1st of July 2016 for all samples), with statistical parameters.*

Trophic status	Geom. mean ± GSD	Mean ± SD	Range	Mean ± SD (log(x))	LSM (log(x))	SE_{LSM} (log(x))	Sign. level
M (n = 32)	52.3 ± 242	154 ± 255	0.95–1210	1.70 ± 3.96	1.61[a]	0.12	***
S (n = 29)	5.49 ± 11.8	8.90 ± 9.70	1.05–36.8	1.00 ± 1.62	0.76[b]	0.14	P < 0.001

[a,b] - Values with different superscript within the same column differ significantly (P < 0.05).
*** - Statistical significance with P value less than 0.001.
* Abbreviations are as explained in section 2.3.

Table 5
^{137}Cs activity concentrations (Bq/kg) in fresh weight of mycorrhizal mushrooms *Boletus* sp. and *Hydnum repandum* collected in past at sampling sites from Gorski Kotar area.

Year	n	Mean ± SD	Geom. mean ± GSD	Range	Source	Ref. date
Boletus sp.						
1999 & 2002	13	22.0 ± 14.8	–	5.10–58.4	Vilić et al., 2005	1st of July 2002
2001	20	24.6 ± 15.3	18.4 ± 55.5	0.70–58.1	this work	1st of July 2001
2006	7	29.4 ± 18.5	24.2 ± 93.6	11.2–59.1	this work	1st of July 2006
2012	3	10.7 ± 10.3	5.43 ± 25.1	0.70–21.4	Šprem et al., 2016	1st of July 2013
2012[a]	11	32.1 ± 35.1	173 ± 1299	1.28–121	this work	1st of July 2016
Hydnum repandum						
1999 & 2002	11	360 ± 281	–	64.0–816	Vilić et al., 2005	1st of July 2002
2001	11	207 ± 94.5	187 ± 1295	94.0–418	this work	1st of July 2001
2006	5	231 ± 167	195 ± 2210	105–516	this work	1st of July 2006
2012	2	132 ± 178	38.9 ± 1417	5.90–258	Šprem et al., 2016	1st of July 2013
2013	4	234 ± 232	138 ± 1880	21.7–562	Šprem et al., 2016	1st of July 2013
2016[a]	1	15.1	15.1	15.1	this work	1st of July 2016

[a] Recalculated activities assuming 90% water content in fresh weight of mushrooms.

Table 6
^{137}Cs activity concentrations (Bq/kg) in fresh weight of *Boletus* sp. and *Hydnum repandum* samples. (ref. date 1st of July 2016 for all samples), with statistical parameters.*

Species	n	Geom. mean ± GSD	Mean ± SD	Range	LSM (log(x))	SE_{LSM} (log(x))	Sign. level
Boletus sp.	41	13.7 ± 37.6	21.1 ± 13.6	0.50–110	2.62[a]	0.17	***
Hydnum repandum	23	111 ± 578	159 ± 120	5.49–524	4.71[b]	0.23	$P < 0.001$

[a,b] - Values with different superscript within the same column differ significantly ($P < 0.05$).
*** - Statistical significance with P value less than 0.001.
* Abbreviations are as explained in section 2.3.

names of the species, locations and years of collection are specified for each sample. Results are divided into two groups – for mycorrhizal (M) and for saprotrophic (S) mushrooms.

The obtained values of ^{137}Cs activity concentrations in soil samples from the examined areas are presented in Table 2. Determined geometric means of ^{137}Cs activity concentrations evidenced the highest degree of contamination in GK and the lowest in NWC which is in great accordance with the results presented by Barišić et al., (2002) (contamination map of Croatia derived immediately after the Chernobyl accident). It has been found that contamination levels significantly differ between those locations ($P < 0.001$). As expected (following the previous report), the highest discrepancy in soil contamination was detected between NWC and two sampling sites in GK while the B was in-between. Geographically speaking, GK and GKV could be considered as one location. However, since GKV is defined more precisely by simultaneous mushroom and soil sampling, they are demonstrated as separate sampling sites throughout the paper. Aside from these between-location differences, a wide range of the determined ^{137}Cs activity concentrations within the examined areas suggests a considerably different degree of within-area contamination which is in accordance with previous findings of Barišić et al. (2002).

Descriptive statistics (cross tabulation by location and trophic status) of the ^{137}Cs dry weight activity concentrations found in 55 mushroom samples collected in 2012 and 2016 is presented in Table 3.

Table 3 shows that, regardless of the sampling site, mycorrhizal species consistently accumulated considerably higher amount of ^{137}Cs, which was, finally, confirmed by inferential statistical analysis (Table 4). In order to reduce Type I error, a two-way ANOVA method was chosen over multiple t-tests (within sampling sites). Insignificant interaction of trophic status and location, accompanied by significant main effect of the trophic status of the mushroom, evidenced consistency in the direction of the examined effect regardless of the sampling site and its level of contamination. Since the inferential statistical analysis was conducted on the logarithmic data, results obtained on this scale were also reported in the Table.

Mycorrhizal mushrooms accumulated significantly higher ($P < 0.001$) levels of ^{137}Cs than saprotrophic ones. Speaking of the magnitude, approximately two-fold (on the log scale) and ten-fold (the original scale) higher activity concentrations of ^{137}Cs were determined in the mycorrhizal species as compared to saprotrophic ones.

After the detection of heterogeneity of determined ^{137}Cs levels within the mushrooms of the same trophic status, it was decided to apply additional testing of the differences in potential to accumulate ^{137}Cs among the species. Mushrooms from two different genera – *Boletus* sp. and *Hydnum repandum* were selected for this purpose since they are widespread M mushrooms in Croatia. Table 5 presents the data of the ^{137}Cs activity concentrations in *Boletus* sp. and *Hydnum repandum* mushrooms collected in 2001 and 2006 in Gorski Kotar area as well as the other previously published results for the same species of mushrooms from the same location (Vilić et al., 2005; Šprem et al., 2016), all expressed for fresh weight of mushroom tissue. Therefore, the values for the samples of *Boletus* sp. and *Hydnum repandum* sampled in 2012 and 2016 in Gorski Kotar area, added in Table 5, are converted to the ^{137}Cs activity concentration in fresh weight, recalculated assuming 90% water content in fresh weight of mushroom.

Inferential statistical analysis targeted towards elucidating the impact of the genera on the ^{137}Cs accumulation potential was conducted on the records recalculated on the same reference date (1st of July 2016). The results by Vilić et al. are not included in the analysis since the individual results per sample were not available. As the results of descriptive and inferential statistical analysis presented in Table 6 show, the *Hydnum repandum* mushrooms accumulated significantly higher ($P < 0.001$) levels of ^{137}Cs than those of *Boletus* sp.

With regard to the magnitude, approximately two-fold (on the log scale) and ten-fold (the original scale) higher ^{137}Cs activity concentrations were determined in *Hydnum repandum* as compared to the mushroms of the genus *Boletus*. Taking into account these results, *Hydnum repandum* can be considered a more informative species in term of bioaccumulation potential.

4. Conclusions

The results of the study show obvious differences of ^{137}Cs accumulation potential of mycorrhizal and saprotrophic mushrooms

collected a long time after contamination (15–30 years). It is observed that mycorrhizal fungi, in general, accumulate higher concentrations of ^{137}Cs which indicates that they could perform better as bioindicators of ^{137}Cs a long time after contamination. The differences in accumulation ability are observed among the particular species, too. The comparison of two common mycorrhizal species of mushrooms in Croatia, *Boletus* sp. and *Hydnum repandum,* showed, in general order of magnitude, higher concentrations of ^{137}Cs in *Hydnum repandum*. However, the large range of results found among the mycorrhizal species, and even within the same species at the same location, indicates that there are many various parameters which may influence the total uptake of the ^{137}Cs into the mushroom fruit bodies. Therefore, to be able to give the quantitative information of the ^{137}Cs contamination level of the environment based on the activities found in mushrooms (transfer factors) a thorough study has to be undertaken. Taking all the results obtained within this research into account, it can be stated with sufficient certainty that mycorrhizal mushrooms, and especially those of *Hydnum repandum* species are better indicators of the ^{137}Cs presence in the environment a long time after contamination than any saprotrophic species.

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