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Radiocaesium in *Tricholoma* spp. from the Northern Hemisphere in 1971–2016

Jerzy Falandysz [a,*], Michał Saniewski [b], Alwyn R. Fernandes [c], Daniela Meloni [d], Luigi Cocchi [e,f], Dagmara Strumińska-Parulska [g], Tamara Zalewska [b]

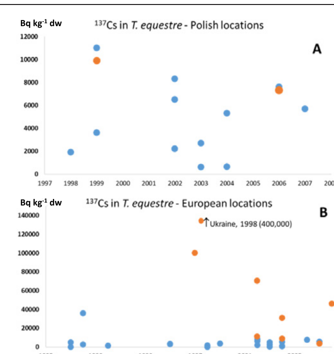
[a] Department of Toxicology, Faculty of Pharmacy, Medical University of Lodz, 1 Muszyńskiego Street, 90-151 Łódź, Poland
[b] Institute of Meteorology and Water Management – Maritime Branch, National Research Institute, 42 Waszyngtona Av., 81-342 Gdynia, Poland
[c] School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK
[d] Istituto Zooprofilattico Sperimentale del Piemonte Liguria e Valle d'Aosta, Via Bologna 148, 10154 Torino, Italy
[e] Gruppo Micologico e Naturalistico R. Franchi, Via D. Piani, 6, I-42100 Reggio Emilia, Italy
[f] Comitato Scientifico Nazionale dell' Associazione Micologica Bresadola, Via A.Volta, 46, I-38100 Trento, Italy
[g] Toxicology and Radiation Protection Laboratory, Faculty of Chemistry, University of Gdańsk, 80-308 Gdańsk, Poland

HIGHLIGHTS

- Published occurrences of ^{134}Cs, ^{137}Cs in twenty four *Tricholoma* spp. are reviewed and discussed.
- The available data may suggest a selective difference in the accumulation of ^{137}Cs for *Tricholoma* spp.
- A ^{137}Cs ecological half-life of between 16 and 17 years in *T. equestre* is suggested.

GRAPHICAL ABSTRACT

Tricholoma equestre **(L.) P. Kumm.**



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ABSTRACT

A considerable amount of data has been published on the accumulation of radiocaesium (^{134}Cs and particularly, ^{137}Cs) in wild fungi since the first anthropogenically influenced releases into the environment due to nuclear weapon testing, usage and subsequently from major accidents at nuclear power plants in Chernobyl (1986) and Fukushima (2011). Wild fungi are particularly susceptible to accumulation of radiocaesium and contamination persists for decades after pollution events. *Macromycetes* (fruiting bodies, popularly called mushrooms) of the edible fungal species are an important part of the human and forest animal food-webs in many global locations. This review discusses published occurrences of ^{134}Cs and ^{137}Cs in twenty four species of *Tricholoma* mushrooms sourced from the Northern Hemisphere over the last five decades, but also includes some recent data from Italy and Poland. *Tricholoma* are an ectomycorrhizal species and the interval for contamination to permeate to lower soils layers which host their mycelial networks, results in a delayed manifestation of radioactivity. Available data from Poland, over similar periods, may suggest species selective differences in accumulation, with some fruiting bodies, e.g. *T. portentosum*, showing lower activity levels relative to others, e.g. *T. equestre*. Species like *T. album*, *T. sulphurescens* and *T. terreum* also show higher accumulation of radiocaesium, but reported observations are few. The uneven spatial distribution of the data combined with a limited number of observations make it difficult to decipher any temporal contamination patterns from the observations in Polish regions. When data from other European sites is included, a similar variability of ^{137}Cs activity is apparent but the more

* Corresponding author.
E-mail address: jerzy.falandysz@gmail.com (J. Falandysz).

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recent Ukrainian data appears to show relatively lower activities. ^{40}K activity in mushrooms which is associated with essential potassium, remains relatively constant. Further monitoring of ^{137}Cs activity in wild mushrooms would help to consolidate these observations.

1. Introduction

The radioactive contamination of foods with natural and anthropogenic nuclides and particularly, artificial nuclides such as ^{134}Cs, ^{137}Cs, ^{90}Sr, ^{239}Pu, ^{240}Pu etc., persists as a continuing hazard to human health due to the long-lived nature of such contamination. The sources of ^{134}Cs and ^{137}Cs nuclide contamination of environmental compartments are recognized and commonly result from atmospheric nuclear weapons testing and use that has subsequently generated global fallout. Additionally, accidents at nuclear installations (power generation or weapon production), leakage from power plants during routine operation or during the handling and storage of waste material (the vast majority of nuclear waste is classified as low or intermediate level), and the industrial use of radioisotopes, generates largely local or regional distributions, which subsequently migrate albeit in substantially weaker amounts to spatially distant regions (Dementyev and Bolsunovsky, 2020; Mietelski, 2010; Prand-Stritzko and Steinhauser, 2018; Steinhauser et al., 2013). Of these sources, the most widespread environmental impacts are usually due to accidents at power plants or from the testing of weapons (Grodzinskaya et al., 2003; Pravalie, 2014; Trappe et al., 2014).

Weather patterns can carry this pollution to distant locations including areas that are used for crop cultivation or where wild food is foraged from woodlands or forests by some populations. As an example, the ^{137}Cs activity concentration in montane soils increases with altitude and the rate of precipitation (Movsisyan et al., 2021), impacting forest fungi in high mountains (Falandysz et al., 2018) including edible species. Some fungi are a popular food in many communities world-wide and wild mushrooms are prized, because of their taste but also because of their scarcity. The fruiting bodies and in particular, the mycelia of ectomycorrhizal fungal species are known to be efficient absorbers and accumulators of radioactive contaminants from forest floors, especially from decaying litter and from the humified (organic) and mineral layers of soil (Elstner et al., 1989).

Radiocaesium, and particularly ^{137}Cs, is a long-lived nuclide, deposited from radioactive fallout, and is known to undergo a biogeochemical cycle in forest ecosystems, where its eco-life in mycelial networks persists for years after the initial pollution (Dighton and Horrill, 1988; Falandysz et al., 2019b). Due to the susceptibility of wild mushrooms to contamination with radiocaesium, they can potentially act as a significant source of radioactivity to consumers (Kiefer et al., 1965; Stijve and Poretti, 1990), but radiation from other nuclides, both artificial and natural, that accumulates in mushrooms should not be neglected (Betti et al., 2017; Daillant et al., 2013; Duff and Ramsey, 2008; Falandysz et al., 2015; Falandysz et al., 2021a; Saniewski et al., 2016; Steinhauser, 2014; Strumińska-Parulska and Falandysz, 2020; Szymańska et al., 2020). In comparison to ^{137}Cs (half-life 30.17 yrs) ^{134}Cs has a much shorter half-life (2.06 years) and is generally used as a tracer of fresh release or deposition of radiocaesium from sources such as nuclear weapon testing or releases from nuclear power plant accidents such as those at Chernobyl (Figs. 1 and 2) and Fukushima, and also in the short-term, to follow the origin of ^{137}Cs. For obvious reasons, there is considerably less data available or discussed for ^{134}Cs.

Over 530 nuclear weapon explosions in the atmosphere (ca 90% in the northern hemisphere) during the period 1945–1980 (banned from 1963), have caused widespread radioactive contamination, especially with ^{14}C but also with substantial amounts of ^{137}Cs and ^{90}Sr (UNSCEAR, 2000). Over time, the resulting fallout can be considered to have spread relatively homogenously over the northern hemisphere. The consequent radiation levels of artificial nuclides (^{137}Cs and ^{90}Sr) accumulated in mushrooms can be substantial (Bem et al., 1990; Dighton and Horrill, 1988; Grütter, 1967; Saniewski et al., 2016; Strumińska-Parulska et al., 2021). More recently, accidents at the nuclear power plants in Chernobyl (1986) Ukraine, and Fukushima (2011), Japan have caused the major non-military sources of airborne ^{137}Cs in history. The steam explosion and open-air reactor core fire at the Chernobyl power plant released radioactivity to the atmosphere for about nine days and caused substantial pollution over large parts of Europe. Both the Chernobyl and Fukushima accidents caused severe pollution of the neighboring land areas (Nakashima et al., 2015; Steinhauser et al., 2014; Vinichuk et al., 2005).

Local weather conditions such as rainfall, fog or snow effectively scavenge many atmospheric pollutants including ^{137}Cs from the lower troposphere and the depositions can result in radioactive hot-spots (Bakken and Olsen, 1990; Mietelski et al., 2010). Local topographical features such as high altitude, colder temperature and humidity also play a role in the level of ^{137}Cs contamination of montane soils (Le Roux et al., 2010; McGee et al., 1992) and the mushrooms that grow in these habitats (Falandysz et al., 2018; Sugijama et al., 1994), but the number of observations is scarce. A specific source of ^{137}Cs in mushrooms was reported (Dementyev and Bolsunovsky, 2020) from the waterborne (caused by flooding) and airborne radioactive discharges from a mining and radiochemical plant of a nuclear facility producing weapons grade plutonium.

2. Materials and methods

The mushrooms examined included specimens collected in the Reggio Emilia Province in Italy (*Tricholoma album* (Schaeff.) P. Kumm., *Tricholoma gausapatum* (Fr.) Quél., *Tricholoma imbricatum* (Fr.) P. Kumm., *Tricholoma lascivum* (Fr.) Gillet., *Tricholoma orirubens* Quél., *Tricholoma saponaceum* Bres., *Tricholoma scalpturatum* (Fr.) Quél., *Tricholoma sulphurescens* Bres., and *Tricholoma* spp. (possibly *Tricholoma salero* (Barla) Sacc. and *Tricholoma terreum*) and Poland (*Tricholoma equestre* (L.) P. Kumm., *Tricholoma saponaceum* (Fr.) P. Kumm., *Tricholoma portentosum* (Fr.) Quél., and *Tricholoma terreum* (Schaeff.) P. Kumm.). Most of the sampling sites from Poland were from northern regions, such as Pomerania, Kuyavian-Pomerania, Warmia-Mazury and Podlasie provinces, but a sampling site was also located more centrally in the Wielkopolska province (Table 1). The locations and year of sample collection are given in detail in Table 1 and the sampling sites (Poland) are also shown in Fig. 1.

The activity concentrations of ^{134}Cs and ^{137}Cs in samples collected in Italy and of ^{134}Cs, ^{137}Cs and ^{40}K in Poland were determined using a validated method of gamma spectrometry with coaxial high purity germanium (HPGe) detectors (Cocchi et al., 2017; Consiglio et al., 1990, Falandysz et al., 2020a, 2020b, 2021b, 2021c, 2021d; Saba and Falandysz, 2020; Zalewska et al., 2016). All numerical results obtained were adjusted for fully dehydrated fungal materials and final results were decay corrected back to the time of collection. Potassium (total K) content was calculated (Table 1) using the mean value of the activity concentration of ^{40}K in natural K which is in the range 27.33 to 31.31 Bq g^{-1} of K (Samat et al., 1997). Additionally, the available records on ^{137}Cs, ^{134}Cs and ^{40}K in *Tricholoma* mushrooms (20 species) that have been reported from other regions of the world from 1971 to 2016 have also been collated, analyzed and discussed here.

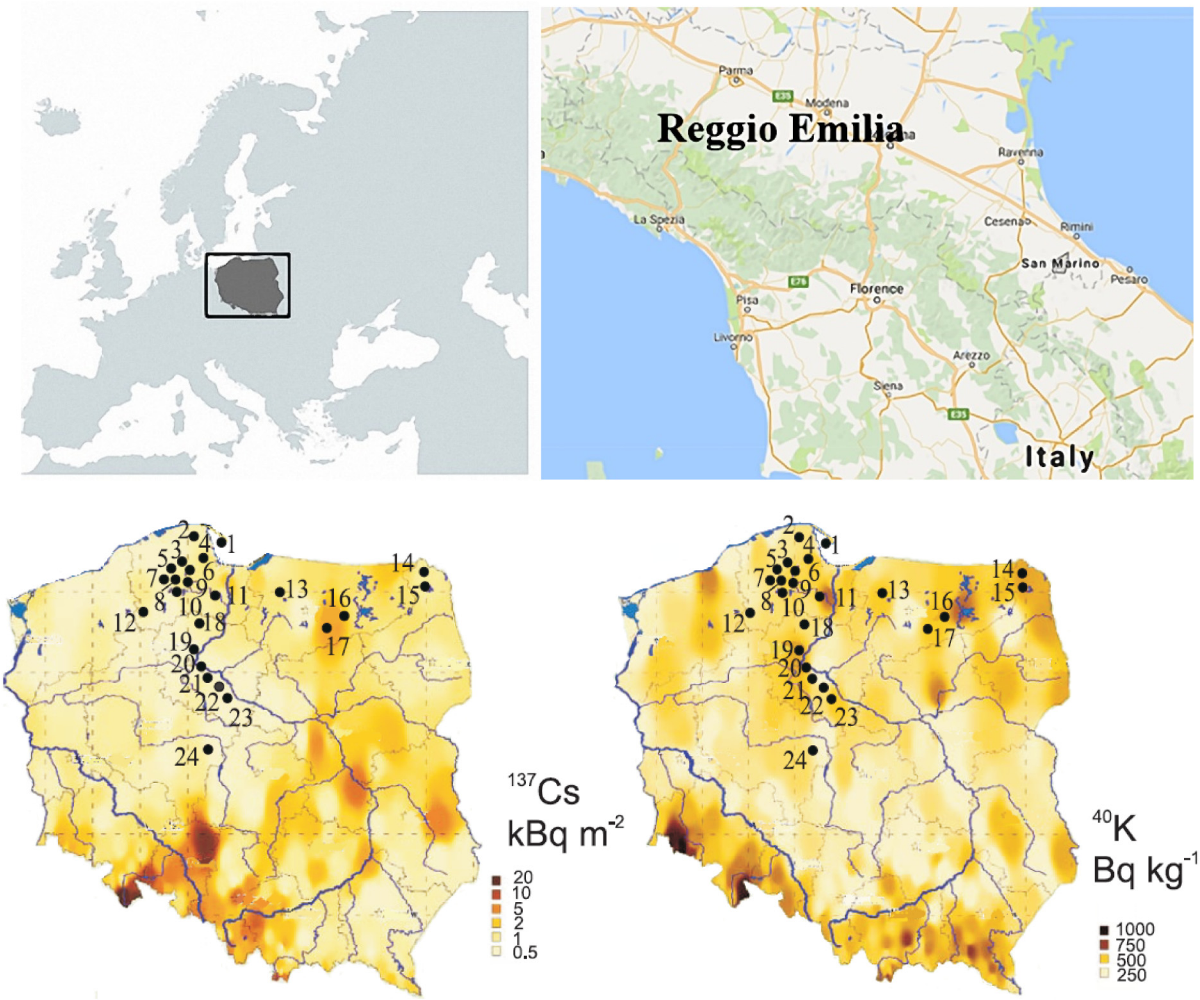

Fig. 1. Localization of the sampling sites of mushrooms in Italy (Reggio Emilia) and Poland (●): 1 – Hel, 2 – Darżlubska Wilderness, 3 – Sierakowice, 4 – Otomin, 5 – Otnoga, 6 – Gołubie Kaszubskie, 7 – Przymuszewo, 8 – Dziemiany, 9 – Wdzydze Landscape Park, 10 – Zaborski Landscape Park, 11 – Pelplin, 12 – Rzecznica, 13 – Morąg, 14 – Augustów Primeval Forest, 15 – Augustów, 16 – Piska Forest, 17 – Lipowiec, 18 – Tuchola Pinewoods, 19 – Tuszynki, 20 – Toruń, 21 – Odolion, 22 – Ciechocinek, 23 – Włocławek, 24 – Turek. In the background the maps of activity of a) ^{137}Cs in kBq m^{-2} and b) ^{40}K in Bq m^{-2} soil of Poland (Isajenko et al., 2012; adapted).

3. Nomenclature

In order to standardize the taxonomic nomenclature, we have used (Table 2) the current names for *Tricholoma* mushrooms according to the updated list of species which are based on molecular genome data in the Index Fungorum database (Index Fungorum 2020), including *T. album* (Schaeff.) P. Kumm., *T. atrosquamosum* Sacc., *T. cingulatum* (Almfelt ex Fr.) Jacobashch, *T. equestre* (L.) P. Kumm., *T. fulvum* (DC.) Bigeard & H. Guill., *T. gausapatum* (Fr.) Quél., *T. imbricatum* (Fr.) P. Kumm., *T. magnivelare* (Peck) Redhead, *T. matsutake* (S. Ito & S. Imai) Singer, *T. orirubens* Quél., *T. pessundatum* (Fr.) Quél., *T. populinum* J.E. Lange, *T. portentosum* (Fr.) Quél., *T. radicans* Hongo, *T. robustum* (Alb. & Schwein.) Ricken, *T. saponaceum* (Fr.) P. Kumm, *T. scalpturatum* (Fr.) Quél., *T. sejunctum* (Sowerby) Quél., *T. atrosquamosum* Sacc., *T. terreum* (Schaeff.) P. Kumm., *T. vaccinum* (Schaeff.) P. Kumm., and *T. virgatum* (Fr.) P. Kumm.

Data on ^{134}Cs, ^{137}Cs and ^{40}K in *Tricholoma* mushrooms worldwide (Table 2) were collated from available literature (Baeza and Guillén, 2004; Baeza et al., 2004; Bakken and Olsen, 1990; Ban-nai et al., 1997; Bazala et al., 2005; Bem et al., 1990; Beregovaya et al., 2012; Calmet et al., 1998; Cadová et al., 2017; Elstner et al., 1989; Falandysz et al. 2018, 2020a and 2020b; Fujii et al., 2014; Garcia et al., 2015; Gry and Andersson, 2014; Grodzinskaya et al., 2003; Gjelsvik, 2008; Kabai et al., 2016; Kammerer et al., 1994; Karadeniz and Yaprak, 2010; Klán et al., 1988; Kuwahara et al., 2005; Lee et al., 2018; Lux et al., 1995; Mietelski et al., 2010; Molzahn et al., 1989; Muramatsu et al., 1991; Nakashima et al., 2015; Orita et al., 2017; Rückert and Diethl, 1987; Rõmmelt et al., 1990; Skibniewska and Smoczynski, 1999; Sugijama et al. 1994 and 2000; Trappe et al., 2014; Tsukada et al., 1998; Tucakovic et al., 2018; Vinichuk et al. 2005 and 2010; Watling et al., 1993; Yamada et al., 2013; Yoshida et al., 1994; Yoshida and Muramatsu 1994a and 1994b).

The ^{134}Cs, ^{137}Cs and ^{40}K concentrations in *Tricholoma* spp. reviewed in Table 2 are presented with the inclusion of information on sampling location, sample size and year of sampling as reported by the cited authors. The majority of the data on ^{134}Cs, ^{137}Cs and ^{40}K was obtained using gamma spectrometry with high-purity-Ge detectors, although some earlier literature also cites the use of gamma spectrometry with NaI-scintillation detectors (Bakken and Olsen, 1990; Bem et al., 1990; Skibniewska and Smoczynski, 1999; Watling et al., 1993).

4. Results

^{137}Cs activity concentrations in dried fruiting bodies of *T. equestre* ranged from 600 to 11,000 Bq kg^{-1} in the mushroom caps and from 250 to 3500 Bq kg^{-1} in the stipes. In the case of the natural isotope ^{40}K, activity concentrations ranged from 840 to 1900 Bq kg^{-1} dw in the caps and from 240 to 1900 Bq kg^{-1} dw in the stipes (Table 1). A lower

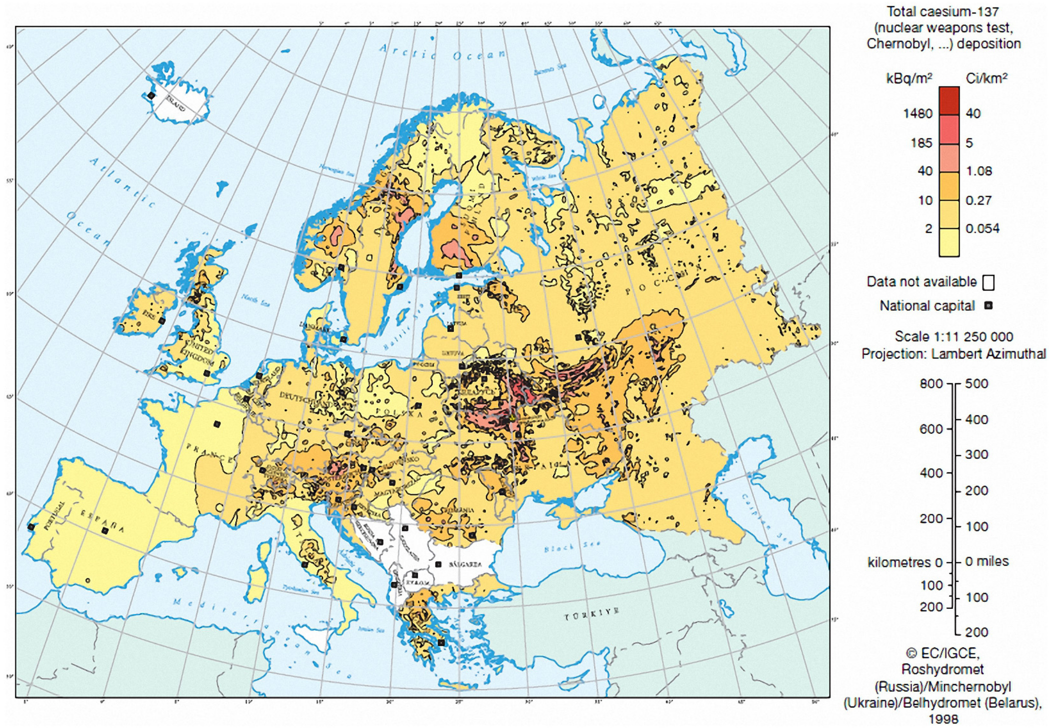

Fig. 2. Surface ground deposition of ^{137}Cs throughout Europe as a result of the Chernobyl accident (IAEA, 2006).

range of ^{137}Cs activity was seen over a similar time period (1998-1999 and 2002; Table 1) in another species, *T. saponaceum*, for which both samples showed (after rounding) an activity of 150 Bq kg^{-1} in dried caps and 69 Bq kg^{-1} in the stipes, while the ^{40}K activity in both samples of caps was 1100 Bq kg^{-1} and ranged from 820 to 825 Bq kg^{-1} in the stipes. In dried fruiting bodies of *T. terreum*, the activity concentration of ^{137}Cs ranged from 630 Bq kg^{-1} dw to 2700 Bq kg^{-1} dw in the caps and from 220 Bq kg^{-1} dw to 1200 Bq kg^{-1} dw in the stipe, with ^{40}K ranging from 1400 Bq kg^{-1} dw to 2300 Bq kg^{-1} dw in the caps and from 1100 Bq kg^{-1} dw to 1600 Bq kg^{-1} dw in the stipes. In *T. portentosum*, the concentration of ^{137}Cs ranged from 6.1 Bq kg^{-1} dw to 1900 Bq kg^{-1}dw in the caps and from 6.9 Bq kg^{-1} dw to 830 Bq kg^{-1} dw in the stipes, while ^{40}K ranged from 1400 Bq kg^{-1} dw to 1800 Bq kg^{-1}dw in the caps and from 880 Bq kg^{-1} dw to 1900 Bq kg^{-1} dw in the stipes (Table 1).

As with a number of other fungi, significantly higher activity of both ^{137}Cs and ^{40} K was recorded in the cap relative to the stipe (Bazala et al., 2005; Cocchi et al., 2017; Zalewska et al., 2016). For ^{137}Cs, the activity in the caps was 2.5 times higher than in the stipes, and in the case of ^{40}K, the ratio was 1.6 (Fig. 3). A number of authors have related quotients from the concentration of an element in cap/stipe/whole fruiting body to concentration level in the soil substrate using bioconcentration factors (BCF; a quotient of the activity concentration of radiocaesium in cap or stipe to activity concentration in the soil beneath the fruiting bodies on a dry to dry weight basis), for radiocaesium, in different species of mushroom and demonstrated that ^{137}Cs activity concentrations in soil can be an influencing factor on the magnitude of the resulting activity observed in the associated mushrooms (Ciuffo et al., 2002; Falandysz et al., 2019b; Karadeniz and Yaprak, 2010). In parallel with the mushrooms, the pooled topsoil (0–10 cm layer; ca 150 g whole weight each, air-dried and sieved) samples collected beneath the fruiting bodies of *T. portentosum* and *T. terreum* at few sites were analyzed in this study. Topsoil for *T. portentosum* from the sites Tuchola Pinewoods (id 18), Tuszynki (id 19) and Włocławek (id 28) showed activity concentrations of ^{137}Cs of 15 ± 1, 9.2 ± 0.7 and 8.4 ± 0.7 Bq kg^{-1} dw (^{40}K of 280 ± 37, 200 ± 29 and 380 ± 35 Bq kg^{-1} dw) respectively. The *T. terreum* topsoils sampled at the Morąg (id 13) and Ciechocinek (id 22) sites showed activities of 59 ± 1 and 19 ± 1 Bq kg^{-1} dw of ^{137}Cs, and 340 ± 15 and 260 ± 11 Bq kg^{-1} dw of ^{40}K, respectively.

Based on the results of ^{137}Cs and ^{40}K for topsoil, BCFs were calculated for the associated mushroom samples. The BCFs for ^{137}Cs and ^{40}K ranged from 0.7 to 140 and from 4.3 to 7.4 respectively for the caps. The corresponding BCFs for the stipes were 1.1 to 62 and from 4.4 to 7.0 respectively. For whole mushrooms from the Tuchola Pinewoods (id 18), the ratio was 54 for ^{137}Cs and 4.9 for ^{40}K.

5. Spatial distribution

Although Poland was affected by global fallout from weapons testing from the middle of the last century, the distance from sources, time lapse and weather patterns have led to a more diffuse distribution of this contamination. In contrast, the proximity of Eastern Poland to the Chernobyl nuclear power plant and the projected radioactive fallout from plumes in the aftermath of accident and discharge, have resulted in high levels of local radioactive depositions in some areas over Northeastern, Central-eastern and Central-southern regions of Poland (Fig. 1). The resulting contamination of the Northeastern part of the country, including remote and protected areas such as forests and national parks is reflected in the results obtained from the *T. equestre* mushrooms in this study (Table 1). A single result for *T. equestre* from the Rogóźno site in the central-eastern region of the country showed 6700 Bq kg^{-1} dw of ^{137}Cs in 1988 (Bem et al., 1990), but there is no other data for other *Tricholoma* spp. from this site for comparison purpose (Table 2). The highest activity of ^{137}Cs was observed in caps and stipes of the mushrooms collected in the Augustów region, Augustów Primeval Forest and Turek. For samples of *T. portentosum* collected from Lipowice (location id 17 in Fig. 1), the activities of ^{137}Cs in the caps and stipes were 420 ± 9 Bq kg^{-1}dw and 190 ± 5 Bq kg^{-1} dw. The caps of fruiting bodies usually show higher activity concentration of ^{137}Cs relative to the stipes and is often reported as the quotient of cap to stipe activity (Qc/s). The Qc/s of 1^{37}Cs for *T. equestre* was 2.8 ± 0.5 (median 2.9) in this study (Table 1). The ^{137}Cs and ^{40}K activity concentrations respectively in the whole fruiting bodies can be calculated based on the original

Table 1
Activity concentrations of radiocaesium and ^{40}K (Bq kg^{-1} dw; mean value ± measurement uncertainty) and estimated concentration of total K (mg kg^{-1} dw) in fruiting bodies of *Tricholoma* mushrooms collected in Italy and Poland (all data rounded to show only two significant figures if different from zero).

Species, location, quantity of fruiting bodies in a composite sample and year of collection		^{137}Cs (Bq kg^{-1} dw)		^{40}K (Bq kg^{-1} dw)		K (mg kg^{-1} dw)	
		Caps	Stipes	Caps	Stipes	Caps	Stipes
		(Whole fruit bodies)		(Whole fruit bodies)		(Whole fruit bodies)	
Italy							
Tricholoma album (Schaeff.) P. Kumm.							
Italy, Reggio Emilia [1]*	X. 1994	32,000 (^{137}Cs)//185 (^{134}Cs)					
Italy, Reggio Emilia [1]	XI. 1994	1500//0.10					
Tricholoma gausapatum (Fr.) Quél.							
Italy, Reggio Emilia [1]	1994	1700//45					
Tricholoma imbricatum (Fr.) P. Kumm.							
Italy, Reggio Emilia [1]	1992	560//20					
Tricholoma lascivum (Fr.) Gillet.							
Italy, Reggio Emilia [1]	1992	4300//170					
Tricholoma orirubens Quél.							
Italy, Reggio Emilia [1]	1992	0.10//0.10					
Italy, Reggio Emilia [1]	1994	150//0.10					
Tricholoma saponaceum Bres.							
Italy, Reggio Emilia [1]	1993	220//0.10					
Tricholoma scalpturatum (Fr.) Quél.							
Italy, Reggio Emilia [1]	1994	1200//0.10					
Tricholoma sulphurescens Bres.							
Italy, Reggio Emilia [1]	1992	45,000//1300					
Tricholoma spp.							
Italy, Reggio Emilia [1]*	1992	130//0.10					
Italy, Reggio Emilia [1]**	1992	350//0.10					
Notes: *Possibly *Tricholoma salero* (Barla) Sacc.; **Possibly *T. terreum*							
Poland							
Tricholoma equestre (L.) P. Kumm							
(9)* Wdzydze Landscape Park [15]**	1998	1900 ± 26	630 ± 51	840 ± 140	< 760	27 ± 4	< 23
(15) Augustów [9]	1999	11,000 ± 97	3500 ± 63	1100 ± 110	270 ± 170	36 ± 4	8.6 ± 5.6
(14) Augustów Primeval Forest [16]	1999	9900 ± 83	3400 ± 32	1200 ± 100	430 ± 99	39 ± 3	14 ± 3
(14) Augustów Primeval Forest [15]	2006	7300 ± 55	2600 ± 21	1600 ± 92	1300 ± 83	51 ± 3	41 ± 3
(20) Kobylarnia near Bydgoszcz [53]	1999	3600 ± 33	1400 ± 14	1100 ± 98	730 ± 88	35 ± 3	23 ± 3
(5) Otnoga [13]	2002	6500 ± 53	1600 ± 20	1200 ± 97	590 ± 120	39 ± 3	19 ± 4
(24) Turek [13]	2002	8300 ± 68	2900 ± 47	950 ± 96	240 ± 150	30 ± 3	7.7 ± 5.0
(12) Rzecznica [10]	2002	2200 ± 23	1100 ± 15	1900 ± 12	1900 ± 150	62 ± 1	59 ± 5
(3) Sierakowice [7]	2003	600 ± 7	390 ± 8	1300 ± 81	1200 ± 140	43 ± 3	39 ± 5
(8) Dziemiany [15]	2003	2700 ± 25	1200 ± 15	1500 ± 100	1200 ± 15	48 ± 3	39 ± 1
(1) Hel [15]	2004	630 ± 55	250 ± 22	1500 ± 110	700 ± 91	47 ± 3	22 ± 3
(21/22) Odolin/Ciechocinek [15]	2004	5300 ± 100	1700 ± 32	1100 ± 95	620 ± 80	35 ± 3	20 ± 3
(4) Otomin [15]	2006	7600 ± 150	2300 ± 74	1300 ± 110	1200 ± 270	41 ± 3	39 ± 9
(6) Głołubie Kaszubskie [6]	2007	5700 ± 47	1700 ± 35	1300 ± 100	WD	41 ± 3	WD
Tricholoma portentosum (Fr.) Quél.							
(10) Zaborski Landscape Park [12]	1998	690 ± 15	300 ± 21	1800 ± 160	1300 ± 760	57 ± 5	42 ± 24
(13) Morąg [22]	1998	34 ± 3	25 ± 3	1400 ± 120	880 ± 100	45 ± 4	28 ± 3
(17) Lipowiec [17]	2000	420 ± 9	190 ± 5	1600 ± 100	1300 ± 88	53 ± 3	43 ± 3
(11) Pomerania, Mysinek [43]	2000	(660 ± 14)		(1400 ± 100)		(44 ± 3)	
(18) Tuchola Pinewoods [4]	2000	(800 ± 18)		(1400 ± 190)		(44 ± 6)	
(7) Zaborski Landscape Park, Przymuszewo [28]	2002	(1900 ± 34)		(830 ± 18)		(27 ± 1)	
(14) Augustów Primeval Forest [23]	2006	1600 ± 28	590 ± 11	1600 ± 82	1200 ± 77	51 ± 3	40 ± 3
(19) Tuszynki [15]	2006	230 ± 5.7	100 ± 5	1500 ± 100	1400 ± 180	47 ± 3	44 ± 6
(23) Włocławek [13]	2006	6.1 ± 1.4	9.4 ± 1.5	1600 ± 88	1800 ± 90	53 ± 3	58 ± 3
(23) Włocławek [15]	2006	19 ± 2	6.9 ± 1.5	1600 ± 87	1900 ± 99	50 ± 3	61 ± 3
Tricholoma saponaceum (Fr.) P. Kumm							
(13) Morąg [15]	1998-1999	150 ± 4	69 ± 3	1100 ± 84	820 ± 110	36 ± 3	26 ± 4
(2) Darżlubska Wilderness [15]	2002	150 ± 4	69 ± 3	1100 ± 84	825 ± 110	36 ± 3	26 ± 4
Tricholoma terreum (Schaeff.) P. Kumm.							
(13) Morąg [14]	1998	630 ± 12	240 ± 5	1900 ± 57	1600 ± 58	61 ± 2	51 ± 2
(9) Wdzydze Landscape Park [20]	1998	1700 ± 29	860 ± 16	1400 ± 46	1100 ± 44	46 ± 1	35 ± 1
(20) Kobylarnia near Bydgoszcz [59]	1999	900 ± 16	390 ± 7	1600 ± 49	1300 ± 40	53 ± 2	41 ± 1
(16) Piska Primeval Forest [22]	2002	1100 ± 19	720 ± 13	1500 ± 45	1200 ± 42	48 ± 1	40 ± 1
(12) Rzecznica [15]	2003	780 ± 14	220 ± 5	2300 ± 72	1300 ± 50	74 ± 2	42 ± 2
(22) Ciechocinek [13]	2004	2700 ± 45	1200 ± 20	1400 ± 43	1100 ± 39	45 ± 1	36 ± 1

Notes: *(Sampling site id number); **[Quantity of fruiting bodies in a composite sample; if 1 it means that only a sole fruitbody was examined]; WD (without data).

measurement data and taking into account the mean share of the biomass of the caps and stipes (percentage by mass) in the whole fruiting bodies - both fresh and dehydrated, but this was not measured in this study.

Higher levels were noted for *T. terreum* from the Piska Forest location (location id 16), with ^{137}Cs activities of 1100 ± 19 Bq kg^{-1} dw and 720 ± 13 Bq kg^{-1} dw in the caps and stipes respectively. Temporal observations for samples of *T. equestre* collected in the Augustów Primeval Forest showed ^{137}Cs activity of 9900 ± 83 Bq kg^{-1} dw and 3400 ± 32 Bq kg^{-1} dw (caps and stipes respectively) in the year 1999, which appears to have declined to 7300 ± 55 Bq kg^{-1} dw and 2600 ± 21 Bq kg^{-1} dw (caps and stipes respectively), by 2006 (Fig. 4). These comparative levels of activity for samples of the same species from the same location suggest a ^{137}Cs ecological half-life of between 16 and 17 years in *T.*

Table 2
The literature data review on ^{137}Cs, ^{134}Cs and ^{40}K activity concentrations (Bq kg^{-1} dw; mean value ± measurement uncertainty and range where applicable) in *Tricholoma* mushrooms worldwide (adapted from the sources cited; all data rounded to show only two significant figures if different from zero).

Species, place, year and number of fruiting bodies (in parentheses) examined	^{137}Cs	^{134}Cs	^{40}K	Reference
Tricholoma album (Schaeff.) P. Kumm.				
Italy, Reggio Emilia, X, 1994 (1)*	32,000	985	WD	Own study
Italy, Reggio Emilia, XI, 1994 (1)	1500	0.10	WD	Own study
Norway, *Jotunheimen Mt., 1988 (7)*	330 ± 120			Bakken and Olsen, 1990
Norway, south-central, 1990-2002	1900 – 34,000			Gjelsvik, 2008
Scotland, Rhosesmor, 1987 (1)	BDL			Watling et al., 1993
Japan, Rokkaso-mura, Aomori, prefecture 1992 (1)	63	BDL		Tsukada et al., 1998
Tricholoma atrosquamosum Sacc.				
Scotland, Powmill, 1987 (1)	730			Watling et al., 1993
Noto Peninsula, Japan, 2007 (1)	4100 ± 14		2200 ± 42	Fujii et al., 2014
Tricholoma cingulatum (Almfelt ex Fr.) Jacobashch				
Scotland, Saline, 1987 (1)	350			Watling et al., 1993
Scotland, Saline, 1989 (1)	250			Watling et al., 1993
Tricholoma equestre (L.) P. Kumm.				
Ukraine, Polis'ke, Chernobyl zone, Kyiv region, 1998	400,000			Beregovaya et al., 2012
Ukraine, near city of Ivankiv, Ivankiv district, Kyiv region, 2002	11,000			Beregovaya et al., 2012
Ukraine, Fenevychi, Ivankiv district, Kyiv region, 2002	70,500			Beregovaya et al., 2012
Ukraine, Lutizh, Vyshgorod district, Kyiv region, 2004	9000			Beregovaya et al., 2012
Ukraine, Zamostia, Manevychi district, Volyn' region, 2004	31,000			Beregovaya et al., 2012
Ukraine, Smolyn, Kozelets district, Chernigiv district, 2007	3700			Beregovaya et al., 2012
Ukraine, Sukholuchchia, Vyshgorod district, Kyiv region, 2008	46,000			Beregovaya et al., 2012
Ukraine, Ovruch district, 1996-1998 (1)	100,000			Vinichuk et al., 2005
Lithuania, 1995	3200 ± 200	27 ± 2	1700 ± 200	Calmet et al., 1998
Lithuania, 1995	3400 ± 200	25 ± 2	1800 ± 90	Calmet et al., 1998
Poland, Rogóźno, 51°23′12 N 22°58′12 E, 1988 (1)	6700		2900	Bem et al., 1990
Poland, Olsztyn, 1990 (1)	1300$^{\#}$ ($^{134/137}$Cs)			Skibniewska and Smoczynski, 1999
Poland, Wdzydze Landscape Park, 1998 (15)	1900 ± 26^{C}//630 ± 51^{S}		840 ± 140^{C}//< 760^{S}	Own study
Poland, Augustów, 1999 (9)	11,000 ± 97//3500 ± 63		1100 ± 110//270 ± 170	Own study
Poland, Augustów Primeval Forest, 1999 (16)	9900 ± 83//3400 ± 32		1200 ± 100//430 ± 99	Own study
Poland, Kobylarnia near Bydgoszcz, 1999 (53)	3600 ± 33//1400 ± 14		1100 ± 98//730 ± 88	Own study
Poland, Otnoga, 2002 (13)	6500 ± 53//1600 ± 20		1200 ± 97//590 ± 120	Own study
Poland, Turek, 2002 (13)	8300 ± 68//2900 ± 47		950 ± 96//240 ± 150	Own study
Poland, Rzecznica, 2002 (10)	2200 ± 23//1100 ± 15		1900 ± 12//1900 ± 150	Own study
Poland, Sierakowice, 2003 (7)	600 ± 7//390 ± 8		1300 ± 81//1200 ± 140	Own study
Poland, Dziemiany, 2003 (15)	2700 ± 25//1200 ± 15		1500 ± 100//1200 ± 15	Own study
Poland, Hel, 2004 (15)	630 ± 55//250 ± 22		1500 ± 110//700 ± 91	Own study
Poland, Odolin/Ciechocinek, 2004 (15)	5300 ± 100//1700 ± 32		1100 ± 95//620 ± 80	Own study
Poland, Aleksandrów Kujawski, 2004 (1)	1200 ± 6//170 ± 12		1700 ± 140//1500 ± 250	Bazala et al., 2005
Poland, Augustów Primeval Forest, 2006 (15)	7300 ± 55//2600 ± 21		1600 ± 92//1300 ± 83	Own study
Poland, Otomin, 2006 (15)	7600 ± 150//2300 ± 74		1300 ± 110//1200 ± 270	Own study
Poland, Głołubie Kaszubskie, 2007 (6)	7600 ± 150//1700 ± 35		1300 ± 100//WD	Own study
Finland, Kirkkonummi, 1998 (1)	250			Gry and Andersson, 2014
Sweden, Järniåsa, 1988 (1)	36,000			Gry and Andersson, 2014
Sweden, east coast of central part, 2003 (1)	5200			Vinichuk et al., 2010
Germany, Southern Bavaria, 1987 (3)	1400–8400$^{\#}$			Kammerer et al., 1994
Germany, Upper Hessen, 1987 (1)	180$^{\#}$			Molzahn et al., 1989
Germany, South Bavaria, 1987-1989 (1)	2700$^{\#}$ ($^{134/137}$Cs)			Rõmmelt et al., 1990
Spain, Muñoveros (1)	35 ± 1		1300 ± 33	Baeza et al., 2004; Baeza and Guillén, 2004
Japan, Ibaraki prefecture, 1990 (1)	3100	< 65	1800	Yoshida and Muramatsu, 1994a; Yoshida et al., 1994
Japan, Rokkaso-mura, Aomori, prefecture 1992 (1)	250	1.5		Tsukada et al., 1998
Japan, Yamanashi prefecture, 1996 (1)	3300$^{\#}$	< 39$^{\#}$		Sugiyama et al., 2000
Japan, Yamanashi prefecture, 1996 (1)	7800$^{\#}$	< 100$^{\#}$		Sugiyama et al., 2000
Japan, Mt. Fuji, Yamanashi, 1998 (1)	7900		2500	Kuwahara et al., 2005
Japan, Fukushima, Kawauchi village, 2015 (5)	2000$^{\#}$ (1500–3000)	500$^{\#}$ (300–600)		Orita et al., 2017
USA, Soda Fork, 2011-2012 (1)	240 ± 8	4.2 ± 3.5		Trappe et al., 2014
Tricholoma fulvum (DC.) Bigeard & H. Guill				

Table 2 (*continued*)

Species, place, year and number of fruiting bodies (in parentheses) examined	^{137}Cs	^{134}Cs	^{40}K	Reference
Czech R., Bohemia, Kvilda, 2014 (6)	3800 ± 30		1500 ± 120	Cadová et al., 2017
Norway, *Jotunheimen Mt., 1988* (5)	89 ± 29			Bakken and Olsen, 1990
Tricholoma gausapatum (Fr.) Quél.				
Italy, Reggio Emilia, X, 1994 (1)	1700	45		Own study
Tricholoma imbricatum (Fr.) P. Kumm.				
Italy, Reggio Emilia, 1992 (1)	560	20		Own study
Norway, *Jotunheimen Mt., 1988* (3)	3.6 ± 1.0			Bakken and Olsen, 1990
Tricholoma lascivum (Fr.) Gillet				
Italy, Reggio Emilia, 1992 (1)	4300	170		Own study
Tricholoma magnivelare (Peck) Redhead				
USA, Long Beach, 2011-2012 (1)	8.8 ± 0.6	1.6 ± 0.9		Trappe et al., 2014
Tricholoma matsutake (S. Ito & S. Imai) Singer				
China, 1993-1994 (1)	20		1400	Ban-nai et al., 1997
China, Yunnan, Shangri-La, Diqing, 2010 (10)	23 ± 3		1300 ± 160	Falandysz et al., 2020a
China, Yunnan, 2010 - 2013 (4 (50) caps	8.5 ± 1.5–19 ± 2		960 ± 110–1900 ± 140	Falandysz et al., 2018
China, Yunnan, 2012 - 2013 (2 (30) stipes	5.1 ± 1.3–7.4 ± 1.8		1200 ± 98–1500 ± 130	Falandysz et al., 2018
China, Yunnan, Yuxi, Jiangchuan, 2013 (11)	9.6 ± 1.9//9.6 ± 1.9		1300 ± 160//930 ± 110	Falandysz et al., 2020a
S. Korea, 2016 (1)	12 ± 1[#]		1600 ± 130	Lee et al., 2018
Japan, Ohita, 1989 (1)	39	< 10	1500	Muramatsu et al., 1991
Japan, Hiroshima, 1989 (1)	57	< 15	830	Muramatsu et al., 1991
Japan, 1989-1990 (3)	100 ± 76	< 11 ± 8	1200 ± 300	Yoshida and Muramatsu, 1994a
Japan, Hiroshima,1990 (1)	210	< 8	1100	Yoshida et al., 1994
Japan, 1993-1994 (4)	39 - 310		830–1500	Ban-nai et al., 1997
Japan, Fukushima, Kawauchi village, 2013 (6)	3000[M#] (1800–12,000)	1400[M#] (700–4900)		Nakashima et al., 2015
Tricholoma orirubens Quél.				
Italy, Reggio Emilia, X, 1992 (1)	0.10	0.10		Own study
Italy, Reggio Emilia, X, 1994 (1)	150	0.10		Own study
Tricholoma pardinum (Pers.) Quél.				
Ukraine, Fenevychi, Ivankiv district, Kyiv region, 2002				Beregovaya et al., 2012
Tricholoma pessundatum (Fr.) Quél.				
Norway, *Jotunheimen Mt., 1988* (3)	7.4 ± 3.4			Bakken and Olsen, 1990
Spain, Muñoveros (1)	120 ± 2		1100 ± 21	Baeza et al., 2004; Baeza and Guillén, 2004
Tricholoma populinum J.E. Lange				
Ukraine, Kiev Region, 1993 (1)	BDL	BDL		Grodzinskaya et al., 2003
Tricholoma portentosum (Fr.) Quél.				
Ukraine, Smolyn, Kozelets district, Chernigiv district, 2007	9100			Beregovaya et al., 2012
Ukraine, Fenevychi, Ivankiv district, Kyiv region, 2008	13,500			Beregovaya et al., 2012
Ukraine. Sukholuchchia, Vyshgorod district, Kyiv region, 2008	3000			Beregovaya et al., 2012
Ukraine, Smolyn, Kozelets district, Chernigiv district	930			Beregovaya et al., 2012
Ukraine. Mizhrichen'ske forestry, Chernigiv district	8200			Beregovaya et al., 2012
Ukraine, Chernobyl, 30 km zone, 1992 (1)	4100	245	980	Lux et al., 1995
Ukraine, Ovruch district, 1996-1998 (4)	20,000 (12,000–29,000)			Vinichuk et al., 2005
Poland, Zaborski Landscape Park, 1998 (12)	690 ± 15//300 ± 21		1800 ± 160//1300 ± 760	Own study
Poland, Morąg, 1988 (22)	34 ± 3//25 ± 3		1400 ± 120//880 ± 100	Own study
Poland, Lipowiec, 2000 (17)	420 ± 9//190 ± 5		1600 ± 100//1300 ± 88	Own study
Poland, Pomerania, Mysinek, 2000 (43)	660 ± 14		1400 ± 100	Own study
Poland, Tuchola Pinewoods, 2000 (4)	800 ± 18		1400 ± 190	Own study
Poland, Zaborski Landscape Park, Przymuszewo, 2002 (28)	1900 ± 34		830 ± 18	Own study
Poland, Aleksandrów Kujawski, 2004 (1)	110 ± 8//45 ± 6		1900 ± 240[C]//1700 ± 270[S]	Bazala et al., 2005
Poland, Augustów Primeval Forest, 2006 (23)	1600 ± 28//590 ± 11		1600 ± 82//1200 ± 77	Own study
Poland, Tuszynki, 2006 (15)	230 ± 6//100 ± 5		1500 ± 100//1400 ± 180	Own study
Poland, Włocławek, 2006 (13)	6.1 ± 1.4//9.4 ± 1.5		1600 ± 88//1800 ± 90	Own study
Poland, Włocławek, 2006 (15)	19 ± 2//6.9 ± 1.5		1600 ± 87//1900 ± 99	Own study
Hungary, 1989 (1)	250	44	1700	Vaszari et al., 1992
Sweden, Järniåsa, 1988 (1)	36,000			Gry and Andersson, 2014
Germany, Upper Hessen, 1987 (1)	180			Molzahn et al., 1989
Croatia, N and NW, 2012 (1)	64 ± 4			Tucakovic et al., 2018
Croatia, N and NW, 2012 (1)	49 ± 3			Tucakovic et al., 2018

(continued on next page)

Table 2 (*continued*)

Species, place, year and number of fruiting bodies (in parentheses) examined	^{137}Cs	^{134}Cs	^{40}K	Reference
Spain, Galicia, 2010 (5)	160 ± 160 (12 - 350)			Garcia et al., 2015
Japan, Mt. Fuji in Yamanashi, 1800 m asl, 1989-90 (1)	120	BDL		Sugijama et al., 1994
Japan, Kofu, Nirasaki, 1989-90 (1)	130	BDL		Sugijama et al., 1994
Japan, Iwate prefecture, 1990 (1)	420	< 11	1700	Yoshida and Muramatsu, 1994a
Japan, Aomori prefecture, 1991 (1)	400	< 9	1800	Yoshida and Muramatsu, 1994b
Japan, Mt. Fuji in Yamanashi, 2300 m asl, 1996 (1)	3400#	< 150#		Sugiyama et al., 2000
Japan, Mt. Fuji in Yamanashi, 1800 m asl, 1996 (1)	830#	< 130#		Sugiyama et al., 2000
Japan, Yamanashi prefecture, 1996 (1)	44#	< 24#		Sugiyama et al., 2000
Japan, Mt. Fuji in Yamanashi, 1998 (1)	2000		2300	Kuwahara et al., 2005
Tricholoma radicans Hongo				
Japan, Noto Peninsula, 2007 (1)	< 11		1200 ± 47	Fujii et al., 2014
Tricholoma robustum (Alb. & Schwein.) Ricken				
Japan, Rokkaso-mura, Aomori, prefecture 1992 (1)	200	BDL		Tsukada et al., 1998
Japan, Rokkaso-mura, Aomori, prefecture 1992 (1)	94	BDL		Tsukada et al., 1998
Tricholoma saponaceum (Fr.) P. Kumm				
Ukraine, Klavdievo-Tarasovo, Borodianka district, Kyiv region, 2007	6400			Beregovaya et al., 2012
Ukraine, Mizhrichen'ske forestry, Chernigiv district, 2008	1500			Beregovaya et al., 2012
Poland, Morąg, 1998-1999 (15)	150 ± 4//69 ± 3		1100 ± 84//820 ± 110	Own study
Poland, Darżlubska Wilderness, 2002 (15)	150 ± 4//69 ± 3		1100 ± 84//825 ± 110	Own study
Norway, *Jotunheimen Mt., 1988* (3)	5.0 ± 2.2			Bakken and Olsen, 1990
Japan, Aomori, 1992	4.0	BDL		Tsukada et al., 1998
Japan, Mt. Fuji in Yamanashi, 1998 (1)	1800		2100	Kuwahara et al., 2005
Japan, Saitama, Chichibu, 2011 (1)	230	160		Yamada et al., 2013
Tricholoma scalpturatum (Fr.) Quél.	1200//0.10			Own study
Italy, Reggio Emilia, 1994 (1)				
Germany, Baden, 1986 (1)	38#	< 17#		Rückert and Diethl, 1987
Germany, Baden, 1986 (1)	33#	< 21#		Rückert and Diethl, 1987
Tricholoma sejunctum (Sowerby) Quél.				
China, Yuxi, Liqi, 2016 (14)	7.7 ± 2.0//6.3 ± 2.0		1400 ± 140//1700 ± 170	Falandysz et al., 2020b
China, Yuxi, Yiwanshui, 2016 (20)	9.0 ± 1.4//23 ± 1		1400 ± 92//1200 ± 79	Falandysz et al., 2020b
China, Yuxi, Lianhuachi, 2016 (5)	20 ± 3//15 ± 4		2000 ± 270//1900 ± 340	Falandysz et al., 2020b
Japan, Mt. Fuji in Yamanashi, 1800 m asl, 1996 (1)	210#	< 56#		Sugiyama et al., 2000
Japan, Yamanashi prefecture, 1996 (1)	540#	< 79#		Sugiyama et al., 2000
Japan, Mt. Fuji in Yamanashi, 1998 (1)	1800		1800	Kuwahara et al., 2005
Tricholoma sulphurescens Bres.				
Italy, Reggio Emilia, 1993 (1)	45,000	1800		Own study
Tricholoma terreum (Schaeff.) P. Kumm.				
Poland, Morąg, 1998 (14)	630 ± 12//240 ± 5		1900 ± 57//1600 ± 58	Own study
Poland. Wdzydze Landscape Park, 1998 (20)	1700 ± 29//860 ± 16		1400 ± 46//1100 ± 44	Own study
Poland, Kobylarnia near Bydgoszcz, 1999 (59)	900 ± 16//390 ± 7		1600 ± 49//1300 ± 40	Own study
Poland, Piska Primeval Forest, 1999 (22)	1100 ± 19//720 ± 13		1500 ± 45//1200 ± 42	Own study
Poland, Rzecznica, 2003 (15)	780 ± 14//220 ± 5		2300 ± 72//1300 ± 50	Own study
Poland, Ciechocinek, 2004 (13)	2700 ± 45//1200 ± 20		1400 ± 43//1100 ± 39	Own study
Poland, Lambinowice forest, 2007 (1)	10,000 ± 520	3400 ± 510		Mietelski et al., 2010
Czech Republic, 1971 (1)	40			Klán et al., 1988
Hungary, 1989 (1)	69	4	1200	Vaszari et al., 1992
Hungary, 1990 (1)	710	89	2200	Vaszari et al., 1992
Turkey, Uruzral, 2002 (1)	8 ± 1		1900 ± 50	Karadeniz and Yaprak, 2010
Turkey, Yaka, 2002 (1)	5 ± 1		820 ± 29	Karadeniz and Yaprak, 2010
Germany, Schneizlreuth/Oberjettenberg, 2005 (1)	21,000#		2300#	Kabai et al., 2016
Germany, Siegenburg, 2010 (1)	4500#		1500#	Kabai et al., 2016
Germany, Aufham, 2015 (1)	6400#		2000#	Kabai et al., 2016
Germany, Schneizlreuth/Oberjettenberg, 2015 (1)	21,000#		1300#	Kabai et al., 2016
Spain, Muñoveros (1)	49 ± 1		1700 ± 25	Baeza et al., 2004; Baeza and Guillén, 2004
Japan, Ibaraki prefecture,1990 (1)	600	< 21	2400	Yoshida and Muramatsu, 1994a
Tricholoma vaccinum (Schaeff.) P. Kumm.				
Ukraine, Fenevychi, Ivankiv district, Kyiv region, 2008	9000			Beregovaya et al., 2012
Germany, SW-Bavaria, 1987 (1)	540 ± 120#	140 ± 280#		Elstner et al., 1989
Japan, Mt. Fuji in Yamanashi, 1400 m asl, 1996 (1)	560#	< 89#		Sugiyama et al., 2000
Japan, Mt. Fuji in Yamanashi, 1998 (1)	1600		2900	Kuwahara et al., 2005
Tricholoma virgatum (Fr.) P. Kumm.				
Japan, Ibaraki prefecture, 1991 (1)	< 20	< 2	2000	Yoshida and Muramatsu, 1994b

Table 2 (*continued*)

Species, place, year and number of fruiting bodies (in parentheses) examined	^{137}Cs	^{134}Cs	^{40}K	Reference
Tricholoma spp.				
Possibly *T. salero* (Barla) Sacc., Italy, Reggio Emilia, 1992 (1)	130	0.10		Own study
Possibly *T. terreum*, Italy, Reggio Emilia, 1992 (1)	350	0.10		Own study

Notes: The quantity of fruiting bodies in a sample (in parentheses); #(assuming humidity content at 90%); C//S (cap//stipe); BDL (below detection limit); M (median value); asl (above sea level); References: Baeza and Guillén, 2004; Baeza et al., 2004; Bakken and Olsen, 1990; Ban-nai et al., 1997; Bazala et al., 2005; Bem et al., 1990; Beregovaya et al., 2012; Calmet et al., 1998; Cadová et al., 2017; Elstner et al., 1989; Falandysz et al., 2018, 2020a and 2020b; Fujii et al., 2014; Garcia et al., 2015; Gry and Andersson, 2014; Grodzinskaya et al., 2003; Gjelsvik, 2008; Kabai et al., 2016; Kammerer et al., 1994; Karadeniz and Yaprak, 2010; Klán et al., 1988; Kuwahara et al., 2005; Lee et al., 2018; Lux et al., 1995; Mietelski et al., 2010; Molzahn et al., 1989; Muramatsu et al., 1991; Nakashima et al., 2015; Orita et al., 2017; Rückert and Diethl, 1987; Rõmmelt et al., 1990; Skibniewska and Smoczynski, 1999; Sugijama et al. 1994 and 2000; Trappe et al., 2014; Tsukada et al., 1998; Tucakovic et al., 2018; Vaszari et al., 1992; Vinichuk et al. 2005 and 2010; Watling et al., 1993; Yamada et al., 2013; Yoshida et al., 1994; Yoshida and Muramatsu 1994a and 1994b.

equestre (16 years and 17.2 years calculated individually in caps and stipes, respectively). Although mushrooms accumulate significant amounts of the ^{137}Cs isotope, the activity of this isotope is less than that resulting from the half-life, which may indicate purification of forest floor litter via constant depletion through processes such as bioaccumulation, foraging by animals and humans, and infiltration of a portion of the nuclide down to lower soil layers over time. It is recognized that forest animals such as wild boar and deer consume mushrooms with resulting high levels of ^{137}Cs accumulation in tissues and organs (Steiner and Fielitz, 2009; Steinhauser and Saey, 2016).

For areas which were known for their severity of fallout and deposition from observations of wind directions and projected fallout plumes, such as locations in Northeastern Poland, it is easier to associate the observations of higher observed activity levels (Fig. 1; Isajenko et al., 2012). However, many areas of Poland such as the Pomerania and Kuyavian-Pomeranian provinces, suffered highly uneven levels of fallout and deposition, which resulted in many local or regional hotspots as reflected in the degree of contamination in mushrooms (Falandysz et al. 2019b and 2021c). In these affected regions, such deposition incidents were expected to have a high impact on the forested areas in general, and consequently on their wild fungal species.

Koarashi et al. (2016) noted that radiation risks from radiocaesium in aerial fallout lasts longer in evergreen coniferous forests than in deciduous broad-leaved tree forests. Thus, a dominant tree type may have an effect on prolonged accumulation of ^{137}Cs by forest fungi – an impact similar to that observed in species like *Boletus edulis* whose mycelia penetrate deeper into the soil. The *Tricholoma* spp. are all mycorrhizal species (Falandysz et al., 2021c), of which *T. equestre*, *T. portentosum* and *T. imbricatum* are found in temperate coniferous forest where needle-leaf trees are highly dominant, (e.g. Scots pine *Pinus sylvestris* L. in Poland). Other *Tricholoma* spp. such as *T. album*, *T. orirubens*, *T. saponaceum*, *T. scalpturatum*, *T. sulphurescens* and *T. terreum* grow in forests with mixed, needle- and broadleaf trees, while some, such as *T. lascivum* form particular associations with specific tree species such as the oak (*Quercus*). However, the variability in ^{137}Cs contamination of mushrooms introduced by varying types of tree-cover are likely to be small in comparison to the variability in fall-out and deposition.

These uneven deposition patterns can affect areas at considerable distances (up to a 1000 km) from the source (Bakken and Olsen, 1990; Mietelski et al., 2010) and help to explain the variation in activities (a "dose – effect" like mode) seen in mushrooms in the different sampling locations in Pomerania and Kuyavian-Pomeranian provinces. And although the rate of contaminant transfer from substrate to fruiting body may be similar – as seen by the BCF values – other factors such as the extent of local soil pollution as well as the fruiting stage of the mushroom are important, e.g. button stage fruit bodies generally have higher levels of contamination but there is a dilution effect with growth to a full size (Falandysz et al. 2019a and 2021a) and perhaps more dominant influences on the variability in the levels of observed contamination.

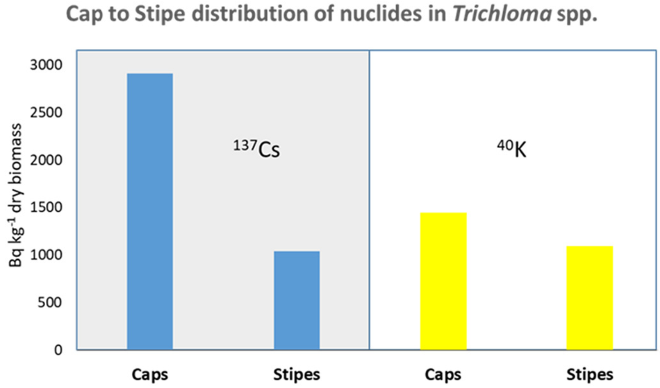

Fig. 3. Cap to stipe distribution of nuclides in *Tricholoma* spp.

6. Radionuclide contamination of *Tricholoma* spp. across the Northern Hemisphere

The uneven distribution of artificial radionuclide contamination that is observed across Poland is also seen in the collated data on nuclides including ^{137}Cs, in *Tricholoma* spp. from several countries in Europe (Table 2).

The majority of the available data is from Europe and East Asia, and reflects the areas where studies have taken place (often as a result of accidental release of radiation), rather than the habitats or areas where *Tricholoma* spp. are consumed. There are fewer reported observations for ^{134}Cs in *Tricholoma* spp., which is not surprising, as this isotope has a relatively shorter physical half-life (2.06 years) and is depleted to a far greater extent than ^{137}Cs during the time taken to permeate to the deeper soil layers where the mycelial networks of *Tricholoma* spp. proliferate. The highest reported ^{134}Cs activity of 3400 Bq kg^{-1}dw (Mietelski et al., 2010), is therefore surprising as it is associated with a sample of *T. terreum* from the Lambinowice forest in Poland in 2007. The site is approximately a 1000 km west of the last known significant release of radiation, 21 years earlier, as a result of the Chernobyl accident in 1986. On the other hand the highest activity of ^{134}Cs in East Asia was reported (Nakashima et al., 2015) for a sample of *T. matsutake*, at 1400 (range 700–4900) Bq kg^{-1}dw. The sample was collected in 2013 from Kawauchi village, Fukushima, which lies in close proximity (less than 15 km, West) to the Fukushima Daiichi plant that suffered a catastrophic release of radiation two years earlier in 2011. However, it is difficult to make direct comparisons between the impacts on fungi from the releases from Chernobyl and Fukushima accidents. The release from Chernobyl was considerably greater, and although the range of volatile nuclides released were similar, the quantity of collective radioactivity estimated to have been release may be up to almost an order of magnitude lower at Fukushima (Steinhauser et al., 2014). More importantly, the prevailing weather conditions and location of Fukushima saw much of the releases dispersed over the proximate Pacific Ocean, compared to Chernobyl which is land-bound. Additionally, the ratio of radiocaesium nuclides (^{134}Cs:^{137}Cs) released was also different for the

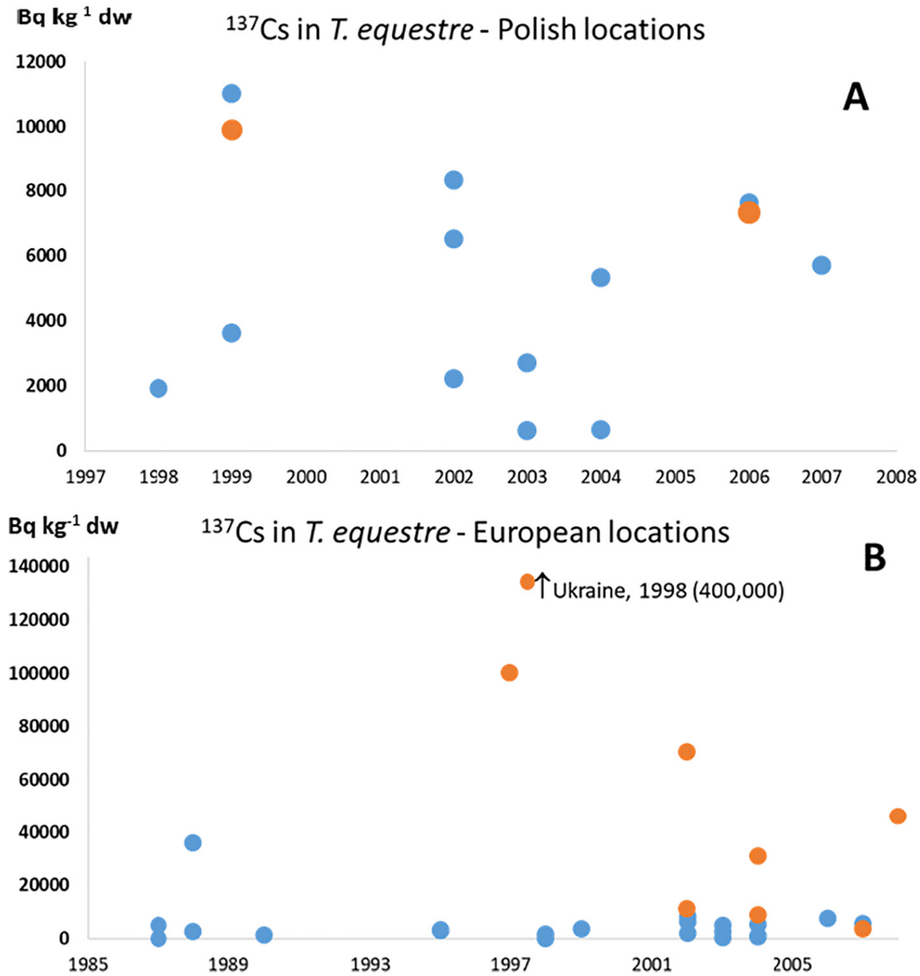

Fig. 4. Temporal variation in ^{137}Cs activity (Bq kg^{-1} dw) in *T. equestre*. A –Locations in Poland, (the Augustów Primeval forest location data are shown by red dots) and B. Europe-wide locations over longer interval. (Ukraine sites are shown as red dots; data for 1998 is off-scale). Note: scales for A and B are different by x10.

two releases with the ratio ^{134}Cs:^{137}Cs, for Chernobyl being approximately half (0.4 - 0.6 compared to 0.98) that of Fukushima (Merz et al., 2015; De Cort et al., 1998; Masson et al., 2011). These dispersion characteristics underline the difficulty of making simple comparisons between the two release events.

A more notable characteristic of Tables 1 and 2, and one that is reasonably predictable, is the relatively smaller variations in the activities of ^{40}K, which is a natural isotope that is directly related to the amounts of nutritionally functional, stable potassium that is required by the fungus for its physiological activities, growth, regulation of water, etc. The activity for all reported ^{40}K observations ranged from 820 to 2900 Bq kg^{-1}dw for all species and all locations (Table 2), suggesting the close association with the physiologically essential potassium levels, (^{40}K constitutes of 0.012% (120 mg kg^{-1}) of the total amount of natural K) which do not appear to vary greatly across the different species. This holds true even across continental divides, with a range of 820–2900 Bq kg^{-1} dw for East Asia and the same range of 820 -2900 Bq kg^{-1} dw for different species from Europe/North Western Asia (Turkey).

The greatest activity concentrations of ^{137}Cs in *Tricholoma* spp. (Table 2) were recorded for locations in the Ukraine, Sweden, Norway and Germany in Europe and Japan in Eastern Asia. The locations and the year of observation associated with these records, correlates to the accidental releases and dispersion patterns of the Chernobyl and Fukushima accidents (Steinhauser et al., 2014). For European locations in particular, areas from which sampled mushrooms showed high ^{137}Cs activity are consistent with the projected areas of highest fallout (Fig. 1).

Table 2 shows ^{137}Cs activity data for a large number of *Tricholoma* species, and there are likely to be differences in contaminant uptake between these, making the observation of any temporal trend difficult. The number of individual observations within a particular species and the earlier mentioned lack of homogeneity of fallout/deposition are also factors that make it difficult to decipher any trend in the concentrations. However, there were relatively more reported observations (34) for *T. equestre*, both for the samples from this study (14) as well as for the literature observations (20). Of the latter, a sub-set of thirteen samples were from European locations. A temporal plot of these ^{137}Cs activity concentrations (13 each from this study and from the literature) is shown in Fig. 3B, and the plot of samples from this study are shown in Fig. 3A.

There is no discernable pattern or trend for the observations from this study, most likely due to the variability associated with the small number of observations (many from areas that were not considered as highly impacted), the natural inhomogeneity in spatial deposition and also the shorter observation interval (1998 - 2007). Some indication may be inferred from two separate observations made at the same location, the Augustów Primeval Forest, in 1999 and in 2006. Weather conditions, soil type, dominant tree type (e.g. Scot pine in evergreen needle-type forests), geochemical composition and assumed deposition of radiocaesium were the same for this area (Figs. 1 and 2), where multiple specimens of *T. equestre* were collected at different points from the sampling location and pooled to form composite samples. These show a reduction of about 25% in ^{137}Cs activity (even when measurement uncertainty is taken into account) over the period from 1999 to 2006 as seen in Fig. 4A. The combined set of observations for *T. equestre* samples from the current study and other European locations (Fig. 4B) gives a larger data set over a longer interval (1987 - 2008). This set of samples includes data for the Ukraine which was heavily impacted by the Chernobyl accident. A similar variability is seen in this graph, which is strongly influenced by the very high activity levels reported for locations in Sweden and the Ukraine (Ukrainian locations indicated on the graph). The regression for this set of data is not significant ($r = 0.46$), but relatively lower activities are seen in the more recent Ukrainian samples. The observation may be compared to the trend observed for ^{137}Cs in *B. edulis* samples from Poland, measured at different locations (Bem et al., 1990; Grabowski et al., 1994; Korky and Kowalski, 1989; Mietelski et al., 1994; Calmet et al., 1998, Falandysz et al., 2021c), that showed a gradual decline (statistically significant, $r = 0.98$) in activity over almost a quarter of a century since the Chernobyl accident.

7. Conclusion

In a manner similar to other wild, forest and woodland growing fungi, the fruiting bodies of *Tricholoma* spp. provide an evidence of radioactive ^{137}Cs contamination, reflecting historical releases from weapons testing and from serious accidental discharges such as Chernobyl. The ectomycorrhizal nature of the species results in a delayed manifestation of this contamination, because of the time taken for the deposited radioactivity to permeate to the appropriate soil horizon layers which host the mycelial networks of this species. The results of this investigation may also suggest species selective differences in bioconcentration potential, with samples of some species e.g. *T. portentosum*, showing lower levels of activity over similar time periods. The proximity of the Polish sampling sites combined with the prevailing weather conditions in the aftermath of the Chernobyl accident, led to uneven patterns of fallout over much of Poland, but with more severe impacts in north-eastern regions. The resulting inhomogeneity in ^{137}Cs contamination over other regions (and the limited number of observations) make it difficult to decipher any temporal contamination pattern for the observations on *Tricholoma* mushrooms in Polish regions. The higher number of observations over a longer interval, collectively including other European sites, show a similar variability of ^{137}Cs activity in *T. equestre*, but after approximately two decades following the Chernobyl accident, relatively lower activities were reported in the more recent Ukrainian samples. Further monitoring of ^{137}Cs activity in wild mushrooms would help to consolidate this observation and also provide a good indication of the environmental activity levels.

CRediT authorship contribution statement

JF: Conceptualization, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Writing - original draft, review & editing. **MS**; Resources, Methodology, Figure, Formal analysis, Data curation. **ARF**: Data curation and analysis, Investigation, Writing – review & editing. **DM**: Formal analysis, Data curation, Review & editing. **LC**: Methodology, Formal analysis, Data curation. **DS-P**, Formal analysis, Data curation. **TZ**, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no competing interests.

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