Journal of Environmental Radioactivity 175-176 (2017) 70–77

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

Do fungi need to be included within environmental radiation protection assessment models?

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ARTICLE INFO

Article history:
Received 22 February 2017
Received in revised form
20 April 2017
Accepted 20 April 2017
Available online 28 April 2017

Keywords:
Fungi
Dose rate
Mediterranean ecosystem
Naturally occurring radionuclides
ERICA tool

ABSTRACT

Fungi are used as biomonitors of forest ecosystems, having comparatively high uptakes of anthropogenic and naturally occurring radionuclides. However, whilst they are known to accumulate radionuclides they are not typically considered in radiological assessment tools for environmental (non-human biota) assessment. In this paper the total dose rate to fungi is estimated using the ERICA Tool, assuming different fruiting body geometries, a single ellipsoid and more complex geometries considering the different components of the fruit body and their differing radionuclide contents based upon measurement data. Anthropogenic and naturally occurring radionuclide concentrations from the Mediterranean ecosystem (Spain) were used in this assessment. The total estimated weighted dose rate was in the range 0.31–3.4 μGy/h (5^{th}–95^{th} percentile), similar to natural exposure rates reported for other wild groups. The total estimated dose was dominated by internal exposure, especially from ^{226}Ra and ^{210}Po. Differences in dose rate between complex geometries and a simple ellipsoid model were negligible. Therefore, the simple ellipsoid model is recommended to assess dose rates to fungal fruiting bodies. Fungal mycelium was also modelled assuming a long filament. Using these geometries, assessments for fungal fruiting bodies and mycelium under different scenarios (post-accident, planned release and existing exposure) were conducted, each being based on available monitoring data. The estimated total dose rate in each case was below the ERICA screening benchmark dose, except for the example post-accident existing exposure scenario (the Chernobyl Exclusion Zone) for which a dose rate in excess of 35 μGy/h was estimated for the fruiting body. Estimated mycelium dose rate in this post-accident existing exposure scenario was close to the 400 μGy/h benchmark for plants, although fungi are generally considered to be less radiosensitive than plants. Further research on appropriate mycelium geometries and their radionuclide content is required. Based on the assessments presented in this paper, there is no need to recommend that fungi should be added to the existing assessment tools and frameworks; if required some tools allow a geometry representing fungi to be created and used within a dose assessment.

1. Introduction

Many fungi species are known to accumulate high activity concentrations of some radionuclides in their fruiting bodies (Mietelski et al., 1994; Barnett et al., 1999) and they can contribute significantly to human intakes of radioactivity, especially of radiocaesium (Beresford et al., 2001). The effective dose to consumers of fungi varies between different countries due to differences in the radioactive fallout (weapons and accidental) and traditional/culinary practices (Guillén and Baeza, 2014). Whilst a focus has been on the uptake of anthropogenic radionuclides (especially Cs), fungi also uptake naturally occurring radionuclides (Wichterey and Sawallisch, 2002). In addition to radiocaesium, radium, ^{210}Po, and ^{210}Pb have been shown to contribute to the dose received via fungi consumption (Guillén and Baeza, 2014).

However, fungi, a key ecosystem component, have not been selected as an organism considered in the approaches developed in recent years in response to changes in international recommendations (ICRP, 2007; IAEA, 2014) to assess dose rates and risk to wildlife (e.g. ICRP, 2008; Brown et al., 2016; USDoE, 2002).

In this paper we consider how the dose rate to fungi could be

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http://dx.doi.org/10.1016/j.jenvrad.2017.04.014

estimated; some species are included within biodiversity conservation objectives (e.g. BRIG, 2007) and hence may require assessment. We also estimate typical background dose rates (for Mediterranean ecosystems), consider exposure under planned, post-accident and existing scenarios, and finally discuss if there is a need to include fungi in the existing assessment frameworks.

2. Material and methods

2.1. Definition of fungi geometries for exposure modeling

The available approaches to assess the dose rates received by wildlife assume homogenous distribution within the organism, which is typically represented as an ellipsoid (Brown et al., 2008; USDoE, 2002; ICRP, 2008). The radionuclide content of the different parts of the fungal fruiting body (cap, gills, and stem) can differ significantly (Heinrich, 1993; Baeza et al., 2006a). In most fungal species, approximately 90% of radiocaesium has been found to be in the cap and gills, and in the majority of analysed species, the gills had higher activity concentrations than the flesh of the cap. Only rarely has the stalk been found to have more radiocaesium than the cap or gills (Heinrich, 1993). Fungal mycelium in soil can accumulate a significant percentage of the radiocaesium content of soil (Olsen et al., 1990; Vinichuk and Johansson, 2003). Some species of arbuscular mycorrhizal fungi, in symbiosis with a host plant, can reduce the uranium uptake by roots, potentially suggesting a uranium accumulation by mycelium (Dupré de Boulois et al., 2008).

We have defined a geometry for dose assessment which represents the fungal fruiting body as three compartments (i.e. cap, gills, and stem; see Fig. 1), an additional geometry was created to represent the fungal mycelium. These geometries were each entered into Tier 2 of the ERICA Tool (Brown et al., 2008, 2016) to derive dose conversion coefficients (DCC) for internal and external exposure (treating each compartment as a separate 'organism'). The size of most fungal fruiting bodies is within the range where their absolute size will have little impact on the estimated DCC values (Vives i Batlle et al., 2011). Therefore, we have chosen to define geometries representative of *Agaricus bisporus* (the portobello mushroom) and *Macrolepiota procera* (the parasol mushroom) as these have different proportions of gills to cap. Table 1 presents the assumed values of mass and dimensions of each fraction considered for these two species based on measurements of collected fungi; note width and length were assumed to be the same (given as diameter in Table 1). To evaluate the importance of the inhomogeneous radionuclide content within the fungal fruiting body in dose rate assessments, we have also represented the fungal fruiting body as a single homogenous ellipsoid of dimensions based on measurements of complete *A. bisporus* fruiting bodies (Table 1). The data for the fungal mycelium model were collected from mycelium hyphae parameters: diameter (Gooday, 1995), mass and length (Taniwaki et al., 2006). Dry mass was converted to fresh mass assuming a dry/fresh ratio of 0.10 (Guillén and Baeza, 2014). Although the total length of the fungal mycelium can be a number of kilometres (Taniwaki et al., 2006), it was considered to be 100 m in the model because this is the maximal length allowed by ERICA. This model is to be considered as a first approach acknowledging that the actual distribution of fungal mycelium in soil is a variable tri-dimensional geometry of intertwining mass of hyphae with plant roots.

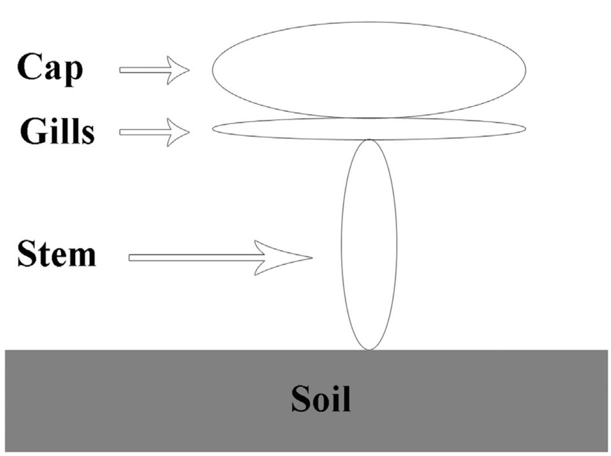

Fig. 1. Conceptual fungi geometry.

2.2. Model input activity concentrations for mediterranean ecosystems

As we are aiming to estimate typical background dose rates and potential dose rates due to anthropogenic sources in the Mediterranean ecosystem, we need to identify suitable data on which to base these calculations. All data used in this task were previously reported for fungi and soil samples collected in Spain (mainly in Cáceres province, Extremadura region) (Baeza et al., 1992, 1993, 2006b).

For natural and anthropogenic (^{137}Cs and ^{90}Sr) radionuclides in soil we have used data from Baeza et al. (1992, 1993) in Cáceres (Spain). The ^{226}Ra content in soil was considered to be in equilibrium with ^{210}Pb and ^{210}Po in soil, as were the activity concentration of ^{232}Th with ^{228}Ra and ^{228}Th, and ^{238}U with ^{234}Th, ^{234}U and ^{230}Th. Additional data for $^{239+240}Pu$ and ^{241}Am from Baeza et al. (2006b) were used. Table 2 lists the mean, standard deviation and range in activity concentrations for the radionuclides considered. In general, the concentration of anthropogenic radionuclides in soil can be considered to be low, because the main source term for most of Spain was global fallout which occurred in 1950–60s.

The radionuclide content of fungi in Mediterranean ecosystems (different locations in Spain and Portugal, but mainly in the Spanish Cáceres province) has been extensively reported in previous papers (Baeza et al., 2004a, 2004b, 2005, 2006b, 2006c; Guillén et al., 2009a, 2009b) (see Table 3). The data were reported as Bq/kg d.m. (dry mass) in the complete fruiting body and have been transformed to Bq/kg f.m. (fresh mass) using the dry/fresh ratio measured for each sample. The reported transfer parameters, defined as the ratio between activity concentration in fruiting body in dry mass and that of surface soil in dry mass, were also converted to fresh mass concentration ratios (CR) using the same dry/fresh ratio for the fungal fruiting bodies. Concentration ratio values for ^{210}Po, ^{7}Be and ^{235}U are not given in Table 3 because their activity concentrations in the corresponding soils were not determined.

Table 4 lists the percentage of the total activity (Bq) assumed to be in the cap, gills and stem. Data for ^{210}Po and ^{210}Pb were only available for stem and a combined "caps and gills" sample (Vaarama et al., 2009). The distribution of these elements between cap and gills was estimated from the mean distribution for uranium, thorium, and plutonium.

For modeling purposes, the activity concentration in each fungi compartment was estimated taking into account the percentages of the total activity reported in each compartment and the percentage of the total mass that each represents (see equation (1)).

Table 1
Mean values of mass and dimensions of different species of fungi, which were used to develop fungi and mycelium geometries in ERICA Tool. Data used for fungi dimensions were based on mushrooms bought at the local market (*A. bisporus*) or field collected (*M. procera*). Masses and dimensions are as entered into the ERICA Tool. *Length in m for mycelium (maximal length allowed in the ERICA Tool).

	Model based on							
	Agaricus bisporus (low gill %)			*Macrolepiota procera* (high gill %)			Single ellipsoid	Mycelium
	Cap	Gills	Stem	Cap	Gills	Stem		
Mass (kg)	0.031	0.003	0.009	0.094	0.039	0.020	0.043	0.00297
% Mass	72	7	22	61	26	13	100	100
Height (m)	0.033	0.002	0.026	0.029	0.011	0.152	0.061	100*
Diameter (m)	0.067	0.067	0.026	0.175	0.175	0.013	0.067	$1.28 \cdot 10^{-5}$
Location	On soil 100%							In soil 100%

Table 2
Mean value, standard deviation (S.D.), and range of anthropogenic and naturally occurring radionuclide activity concentrations in Mediterranean ecosystem soil for in the (Baeza et al., 1992; 1993; 2006a). Radionuclides in brackets are considered to be in secular equilibrium with their parent.

Radionuclide	Mean ± S.D. (Bq/kg d.m.)	Range (Bq/kg d.m.)	Distribution
^{241}Am	0.067 ± 0.009	0.058–0.076	Lognormal
^{137}Cs	21 ± 23	0.6–160	Lognormal
$^{239+240}Pu$	0.39 ± 0.27	0.055–1.04	Lognormal
^{90}Sr	9.2 ± 9.7	0.6–48	Lognormal
^{40}K	650 ± 300	48–1600	Normal
^{226}Ra (^{210}Pb, ^{210}Po)	46 ± 26	13–140	Lognormal
^{232}Th (^{228}Ra, ^{228}Th)	49 ± 33	7–200	Lognormal
^{238}U (^{234}Th, ^{234}U, ^{230}Th)	77 ± 40	16–230	Lognormal
^{235}U	3.5 ± 1.8	0.7–200	Lognormal

Table 3
Mean values, standard deviations, and range of anthropogenic and naturally occurring radionuclide activity concentrations in fungal fruit bodies and CR values reported for Spain. The data from papers reporting data in Bq/kg d.m. (Baeza et al., 2004a, 2004b, 2005, 2006b, 2006c; Guillén et al., 2009a, 2009b) were converted to Bq/kg f.m. using the measured fresh/dry ratio for each sample. The probability distributions used in the ERICA Tool for each radionuclide are also given.

Radionuclide	Activity concentration (Bq/kg f.m.)			CR			Assumed Distribution
	N	Mean ± S.D.	Range	N	Mean ± S.D.	Range	
^{137}Cs	63	4.3 ± 15	0.034–110	24	0.84 ± 2.0	0.0037–9.3	Lognormal
^{90}Sr	16	0.33 ± 0.29	0.005–0.85	11	0.24 ± 0.17	0.059–0.49	Lognormal
$^{239+240}Pu$	17	0.014 ± 0.022	$5.9 \cdot 10^{-5}$ –0.090	6	0.075 ± 0.054	0.020–0.14	Lognormal
^{241}Am	6	0.0059 ± 0.0059	0.0012–0.017	6	0.088 ± 0.088	0.018–0.26	Lognormal
^{40}K	69	150 ± 89	36–580	24	0.14 ± 0.07	0.058–0.29	Normal
^{226}Ra	28	3.4 ± 3.5	0.32–15	12	0.063 ± 0.078	0.0073–0.28	Normal
^{210}Pb	52	5.0 ± 11	0.12–63	10	0.021 ± 0.016	0.0094–0.055	Lognormal
^{210}Po	10	12 ± 21	1.2–70	–	–	–	Lognormal
^{234}U	14	0.33 ± 0.27	0.009–0.85	8	0.039 ± 0.032	0.011–0.093	Lognormal
^{235}U	13	0.014 ± 0.012	$4.3 \cdot 10^{-3}$–0.040	–	–	–	Lognormal
^{238}U	14	0.34 ± 0.28	0.0074–0.93	8	0.037 ± 0.029	0.011–0.085	Lognormal
^{228}Th	14	0.65 ± 0.55	0.0024–1.73	8	0.029 ± 0.023	0.0059–0.064	Lognormal
^{230}Th	14	0.36 ± 0.30	0.0035–0.88	8	0.018 ± 0.012	0.0060–0.038	Lognormal
^{232}Th	14	0.53 ± 0.45	0.0034–1.4	8	0.039 ± 0.037	0.0061–0.10	Lognormal
^{7}Be	13	1.8 ± 4.2	0.15–1-6	–	–	–	Normal

Table 4
Percentage of the total activity in each part of the fungi (cap, gills, and stem) modelled. Data from Baeza et al. (2006a) and Vaarama et al. (2009).

Radionuclide	Percentage of total activity in fungal compartments		
	% Cap	% Gills	% Stem
^{134}Cs	73.5 ± 2.4	22.3 ± 1.0	4.1 ± 0.4
^{85}Sr	26 ± 13	27 ± 14	46 ± 19
^{239}Pu	52 ± 3	22.7 ± 1.6	25.1 ± 1.6
K	62.8 ± 1.5	16.6 ± 0.8	20.6 ± 0.8
Ca	60.1 ± 1.4	4.42 ± 0.24	35.5 ± 1.0
U	57 ± 6	22 ± 3	22 ± 3
Th	64 ± 5	21.2 ± 1.8	15.1 ± 1.4
^{226}Ra	24 ± 6	44 ± 8	32 ± 6
^{210}Pb	38 ± 6	14 ± 3	48 ± 3
^{210}Po	44 ± 6	16 ± 3	40 ± 3

$$A_{C,G,S}(Bq/kg\,f.w) = A_{mushroom}(Bq/kg\,f.w)\frac{\%Total\,Activity\,in\,C,G,S}{\%Total\,Mass\,of\,C,G,S} \quad (1)$$

where $A_{C,G,S}$ is the activity level of the cap, gills or stem.

Two scenarios were considered based on the data of Heinrich (1993) for radiocaesium: (i) gills have a higher total radionuclide activity than the cap (based on data for *A. bisporus*); (ii) gills have a similar total radionuclide activity to the cap (based on data from *M. procera*).

Mycelium has been reported to be able to accumulate a significant percentage of total radiocaesium inventory in soil (range 0.1–50%, mean value 15%) (Vinichuk and Johansson, 2003). The mycelium production in the upper 10 cm of soil in Swedish forests was reported to be about 200 kg dm/(ha˙y) with a range of

20–980 kg dm/(ha·y) (Ekblad et al., 2013). This value was converted into a fresh mass mycelium concentration in soil, assuming 1 year mycellium production, a soil depth of 10 cm, soil density of 1.5 g dm/cm^3, and an assumed dry/fresh ratio for mycelium of 0.10 g dm/g fm. Thus, 200 kg dm/(ha·y) would be equivalent to $1.3 \cdot 10^{-3}$ kg fm mycelium/kg soil, which is within the range of fungal mycelium in soil reported by Vinichuk and Johansson (2003). The radiocaesium mycelium concentration was estimated using equation (2) assuming the mean percentage of soil Cs in mycelium as reported by Vinichuk and Johansson (2003).

$$A(^{137}Cs)_{mycelium}(Bq/kg\,fm) = \frac{0.15 \cdot A(^{137}Cs)_{soil}(Bq/kg\,soil)}{1.3 \cdot 10^{-3}(kg\ fm\ mycelium/kg\,soil)} \tag{2}$$

As no information about the concentration of other radionuclides in the mycelium is available, it was assumed to be the same as in the fruiting body.

2.3. Modeling exposure of fungi using the ERICA tool

The radionuclide background dose rates for the assumed ellipsoid geometry (for fruiting body and mycellium) and the more complex geometries representing *A. bisporus* and *M. procera* fruiting bodies were estimated using the probabilistic functionality of Tier 3 of the ERICA Tool (Brown et al., 2008, 2016) with 10000 simulations. Weighted dose rates were estimated using the default radiation weighting factors from the ERICA Tool of 10 for α, 3 for low energy β and 1 for other β and γ emissions. Table 5 lists the dose conversion coefficients (DCC) for single ellipsoid and mycelium geometries, calculated using the ERICA Tool. For the more complex geometries (Fig. 1) the ERICA Tool was run three times, once for each compartment. A total weighted dose rate for the whole fruiting body was then estimated by using the results for each compartment and weighting these for their contribution to the total mass of the fruiting body. The overall 5th and 95th percentiles were estimated as the weighted sum of the 5th and 95th percentile values respectively for all compartments.

For the purposes of probabilistic modelling, it is necessary to specify an appropriate distribution function for each input parameter. For fungi, radiocaesium has been shown to have a lognormal distribution (Mietelski et al., 1994; Yoshida and Muramatsu, 1994; Baeza et al., 2004a). The distribution patterns for ^{40}K, ^{226}Ra and ^{7}Be have been reported to be normal (Mietelski et al., 1994; Yoshida and Muramatsu, 1994; Baeza et al., 2004a). Where there were no data for defining a distribution, we have assumed a lognormal distribution (Brown et al., 2008; Wood et al., 2013). The assumed activity concentrations of radionuclides in soil were taken from Table 2. The distribution functions for radionuclides in soil were assumed to be lognormal for all radionuclides except ^{40}K, which has previously been observed to have a normal distribution in the region of Spain from which the data originate (Baeza et al., 1992).

3. Results and discussion

Table 6 shows the external, internal, and total weighted (background) dose rate for the different species of fungi modeled. The mean value of the total dose rate for the model based on a single ellipsoid is 1.6 μGy/h, with a predicted range (5th – 95th percentiles) of 0.31–3.4 μGy/h. The use of more complex models based on the heterogeneous distribution within the fungi resulted in a slightly lower dose rate of 1.2 μGy/h for both species modeled with an overall range (5th–95th percentiles) of 0.26–2.9 μGy/h. This implies that the heterogeneous distribution within the different fungi parts is not a key factor when determining dose rate. Therefore, the use of the ellipsoid model is recommended, as it is easier to implement

Table 6
Mean value and range (5th–95th percentile), expressed in μGy/h, of external, internal and total weighted dose rates estimated to the different fungi geometries: *A. bisporus*, in which the radionuclide activity content in gills is usually higher than in cap; *M. procera*, in which the radionuclide activity content in gills and cap is similar; model based on a single ellipsoid; and mycelium.

Exposure	Dose rate (μGy/h)			
	A. bisporus	*M. procera*	Single ellipsoid	Mycelium
External	0.06 (0.020–0.12)	0.06 (0.020–0.12)	0.06 (0.020–0.12)	0.06 (0.020–0.12)
Internal	1.2 (0.21–2.8)	1.2 (0.21–2.8)	1.6 (0.26–3.3)	1.2 (0.20–3.3)
Total	1.2 (0.26–2.9)	1.21 (0.26–2.9)	1.6 (0.31–3.4)	1.3 (0.25–3.3)

Table 5
External and internal Dose Conversion Coefficients (DCC; μGy/h per Bq/kg) calculated using ERICA Tool for the single ellipsoid and mycelium geometries.

Radionuclide	DCC (Single ellipsoid) (μGy/h per Bq/kg)				DCC (Mycellium) (μGy/h per Bq/kg)			
	External exposure	Internal exposure			External exposure	Internal exposure		
		Low β	β/γ	α		Low β	β/γ	α
^{137}Cs	1.13E-04	3.71E-07	1.56E-04	–	1.13E-04	3.62E-07	5.17E-05	–
^{90}Sr	1.25E-10	1.12E-07	5.96E-04	–	1.25E-10	1.08E-07	1.20E-04	–
^{239}Pu	6.04E-08	1.18E-06	3.01E-06	2.97E-03	6.04E-08	1.14E-06	2.48E-06	2.97E-03
^{241}Am	3.29E-06	5.73E-06	2.91E-05	3.16E-03	3.29E-06	5.57E-06	2.18E-05	3.16E-03
^{40}K	2.92E-05	1.28E-07	2.88E-04	–	2.92E-05	1.26E-07	6.06E-05	–
^{226}Ra	3.35E-04	1.63E-06	5.60E-04	1.38E-02	3.35E-04	1.59E-06	1.34E-04	1.38E-02
^{228}Ra	1.88E-04	9.14E-06	2.92E-04	–	1.88E-04	8.89E-06	9.15E-05	–
^{210}Pb	4.01E-07	4.23E-06	2.35E-04	–	4.01E-07	4.10E-06	7.37E-05	–
^{210}Po	1.69E-09	3.66E-13	2.83E-10	3.06E-03	1.69E-09	3.57E-13	1.16E-11	3.06E-03
^{234}U	1.36E-07	8.07E-07	7.49E-06	2.74E-03	1.36E-07	7.87E-07	5.99E-06	2.74E-03
^{235}U	3.07E-05	1.23E-05	1.23E-04	2.54E-03	3.07E-05	1.19E-05	8.68E-05	2.54E-03
^{238}U	1.02E-07	6.68E-07	5.63E-06	2.41E-03	1.02E-07	6.51E-07	4.53E-06	2.41E-03
^{228}Th	2.83E-04	3.73E-06	5.15E-04	1.85E-02	2.83E-04	3.62E-06	1.42E-04	1.85E-02
^{230}Th	1.41E-07	6.49E-07	8.27E-06	2.69E-03	1.41E-07	6.33E-07	6.52E-06	2.69E-03
^{232}Th	1.10E-07	6.44E-07	7.04E-06	2.30E-03	1.10E-07	6.29E-07	5.64E-06	2.30E-03
^{234}Th	4.67E-06	1.59E-06	4.66E-04	–	4.67E-06	1.54E-06	9.92E-05	–
^{7}Be	1.00E-05	–	1.48E-06	–	1.00E-05	–	1.72E-08	–

and in this case, conservative.

The background dose rates determined here for fungi are broadly similar to those estimated by Beresford et al. (2008) for terrestrial Reference Animals and Plants from the ICRP framework (ICRP, 2008). These authors report a range in mean weighted dose rates of *circa* 0.07 μGy/h (Reference Pine tree and Deer) to 0.6 μGy/h (Reference Earthworm) with an overall range in 5th and 95th percentile predictions of 0.04–1.5 μGy/h. For comparison purposes the 5th and 95th percentile dose rates estimate here for fungi were 0.31 and 3.4 respectively.

The majority of the total dose rate is due to internal dose (Table 6). The mean value of the external dose rate was 0.06 μGy/h (0.020–0.12) μGy/h for all models. Naturally occurring radionuclides (^{40}K, ^{228,230,232,234}Th, and ^{226,228}Ra) are the main contributors to the external dose rate for the area of Spain considered here (see Fig. 2a). The principle anthropogenic dose contributor was ^{137}Cs, which contributed about 3.9% ($7.0 \cdot 10^{-3}$ μGy/h) of the total external dose rate.

No difference in the contribution of the various radionuclides assessed to the total internal dose rate was estimated for fungi geometries with different radionuclide distributions between the three modelled compartments. The main contributions to internal dose, for *M. procera* were ^{226,228}Ra and ^{210}Po, which contributed about 87% of the total internal dose rate (Fig. 2b). The contribution of ^{137}Cs was 0.03% ($1.4 \cdot 10^{-3}$ μGy/h) of the total internal dose rate.

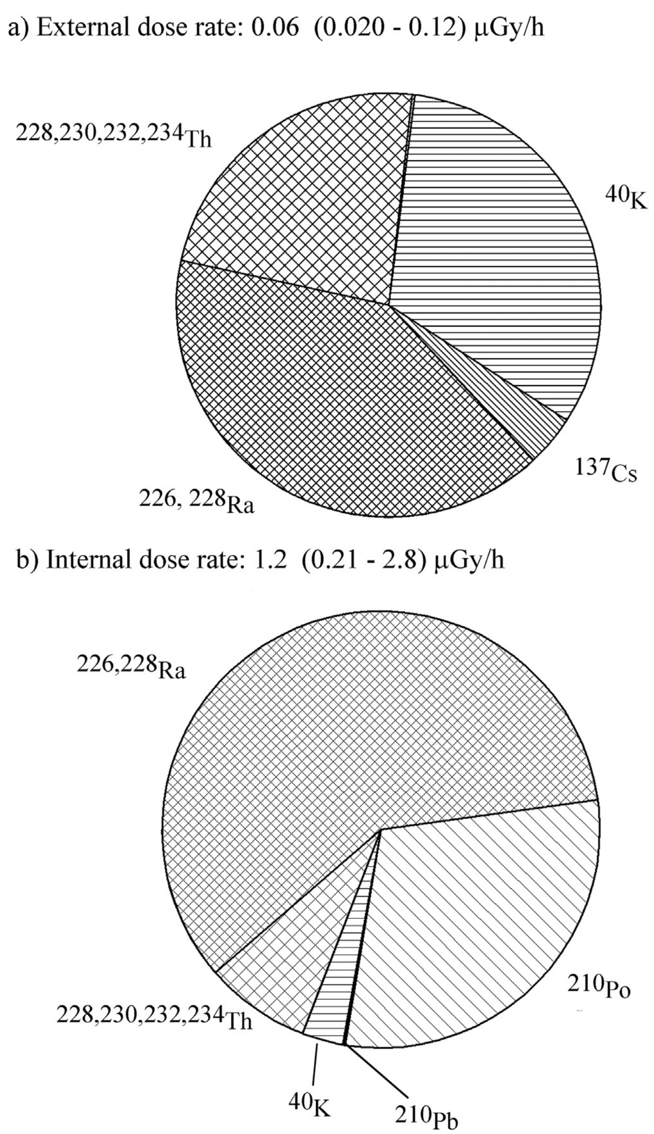

Fig. 2. Contributors of a) external and b) internal dose rate for the model *M. procera*. Minor contributors to dose are not shown.

Estimated mycelium dose rate is shown in Table 6. As the concentration used was the same as for the fruiting body, except for radiocaesium which was estimated using eq. (2), similar dose rates and relationships between internal and external contribution were obtained. These values are to be considered as a first approach, as further research is required related to radionuclide concentration in mycelium and a better geometry for mycelium in soil. Current geometry assumptions and radionuclide activity concentrations may underestimate the dose rate received by mycelium.

3.1. Potential dose rates to fungi under different exposure scenarios

Above we have estimated background exposure rates for fungi (in a Mediterranean ecosystem) and we have demonstrated that the simple ellipsoid geometry is sufficient for assessment purposes. However, it is well known that fungi accumulate high activity concentrations of some anthropogenic radionuclides (Mietelski et al., 1994; Barnett et al., 1999; Guillén and Baeza, 2014) yet, as already noted, fungi are not considered within the existing commonly used environmental assessment frameworks. We have therefore investigated potential dose rates to fungi under different scenarios. This was conducted using Tier 2 of the ERICA Tool (i.e. the analyses were not probabilistic) and assuming the ellipsoid geometry defined above. Where fungi data used in these assessments were reported as Bq/kg d.m. they were converted to Bq/kg f.m. assuming a dry/wet ratio of 0.10. The data sources we have used for these assessments presented activity concentrations in fungi but not always for soil. To determine external dose rates we derived activity concentrations in soil using those in fungi and the CR values in Table 3 where required. For the planned and post-accident existing exposure scenarios, weighted dose rates were only estimated for the anthropogenic radionuclides present at the sites (i.e. there was no consideration of natural background). Radiocaesium activity concentration in the mycelium was estimated from the soil activity concentration as described above for each scenario.

3.1.1. Planned exposure scenario

Data for a range of anthropogenic radionuclides were available for an unspecified fungi species (Fulker et al., 1998) collected close to the Sellafield reprocessing plant (UK) and these data have been used here as an example of a planned exposure situation (Table 7). The total weighted dose rate estimated for the fruit body was about $3.5 \cdot 10^{-3}$ μGy/h predominantly arising from ^{137}Cs (Table 8; Fig. 3). The dose rate estimation for mycelium was about $5.7 \cdot 10^{-2}$ μGy/h, also from ^{137}Cs. This estimated dose rate is below any benchmark values used in assessments and considerably lower than that

Table 7
Activity concentrations in fungi fruit bodies used for dose rate estimations (Bq/kg f.m.) of Post-accident, Planned and Existing exposure scenarios (data from: [a]Lux et al., 1995; [b]Fulker et al., 1998; [c]Wichterey & Sawallisch, 2002).

Post-accident existing exposure scenario[a] (Bq/kg f.m.)		Planned release scenario[b] (Bq/kg f.m.)		Existing exposure scenario[c] (Bq/kg f.m.)	
^{134}Cs	2200	^{241}Am	0.007	^{238}U	25.9
^{137}Cs	45000	^{134}Cs	0.22	^{226}Ra	51.2
^{90}Sr	31	^{137}Cs	9.9	^{210}Pb	28.9
^{238}Pu	4.4	^{239}Pu	0.01	^{210}Po	64
^{239}Pu	8.3				

Table 8
Estimated values of external, internal and total weighted dose rates for fungal fruit bodies and mycelium in the selected scenarios.

Scenario	Dose rate (μGy/h)		
	External (fruit body/mycelium)	Internal (fruit body/mycelium)	Total (fruit body/mycelium)
Post-accident existing exposure	37/97	7.7/330	45/430
Planned exposure	$1.4 \cdot 10^{-3}/3.7 \cdot 10^{-3}$	$2.1 \cdot 10^{-3}/5.4 \cdot 10^{-2}$	$3.5 \cdot 10^{-3}/5.7 \cdot 10^{-2}$
Existing exposure	1.3/1.3	9.7/9.7	11/11

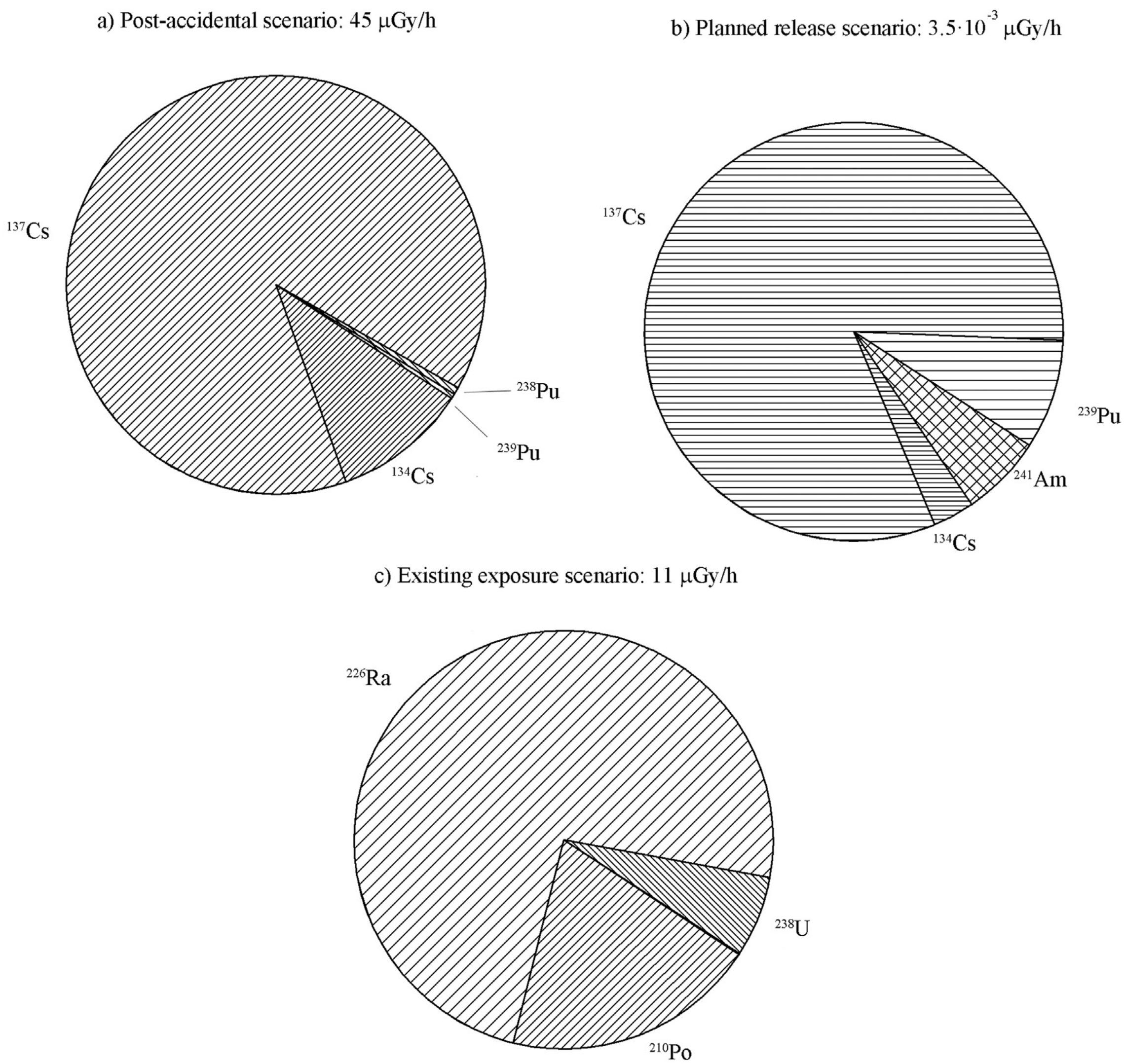

Fig. 3. Contributors to the total dose rate in fungi in a) Post-accident existing exposure, b) Planned release, and c) Existing exposure scenarios.

estimated above for natural background exposure.

3.1.2. Existing exposure scenario

Data were available for fungi collected from a former uranium mining site in Germany (Wichterey and Sawallisch, 2002); for the purposes of this assessment the maximum reported values were used (Table 7). The total weighted dose rate to both the fungal fruit body and mycelium at this site was estimated to be 11 μGy/h with ^{226}Ra and ^{210}Po being the major contributors (Table 8; Fig. 3). Whilst this is equal to the screening dose rate value used in the ERICA Tool (Brown et al., 2008) suggesting further assessment is required. However, the ERICA screening dose rate is for incremental dose and there will be an element of natural background in the dose estimated for this site. Furthermore, fungi are relatively insensitive to ionising radiation, with some species being able to withstand doses in the kGy range (e.g. McNamara et al., 2003). Therefore, a 10 μGy/h screening dose rate is unlikely to applicable to this taxon.

3.1.3. Post-accident existing exposure scenario

We have used data for fungi collected in the Chernobyl Exclusion Zone in 1993 (Lux et al., 1995). Activity concentration data were available for $^{134,137}Cs$, $^{238,239}Pu$ and ^{90}Sr (Table 7). Lux et al. (1995) also presents soil activity concentrations and these have been used in the assessment. The total estimated weighted dose rate was 43 μGy/h predominantly arising from ^{137}Cs due to external exposure (Table 8; Fig. 3). Although above the generic ERICA screening dose rate of 10 μGy/h, this is below other benchmark dose rates proposed for the protection of populations of plant of up to 400 μGy/h (see Howard et al., 2010). The total estimated dose rate for mycelium was about 430 μGy/h, which is slightly above the suggested benchmark for plants. However, again we anticipate that fungi are a relatively radio-insensitive taxon (e.g. McNamara et al., 2003).

4. Conclusions

As discussed above fungi are well known to accumulate high activity concentrations of some radionuclides. However, they have not been included as organisms of assessment for the models developed over the last about 15 years (USDoE, 2002; Brown et al., 2008, 2016; Copplestone et al., 2003). In this paper we have considered how to estimate the exposure of fungal fruiting bodies, the background dose rate of fungi and investigated likely dose rates under different example scenarios. We have show that:

- A fungi geometry representing different components of the fruiting body can be derived and parameterized
- Using a simple ellipsoid geometry estimates similar dose rates to this more detailed compartmentalised geometry leading us to recommend a simple ellipsoid is used for assessment purposes.
- The background dose rates estimated for fungi in Spain were similar to those determined for other (animal and plant) wildlife groups elsewhere in Europe.
- Dose rates estimated for a planned scenario were relatively low suggesting that the omission of fungi from assessment models is not significant.
- For existing and post-accident scenarios dose rates were higher than the screening benchmark dose rate used in the ERICA Tool (which is not directly applicable to the scenarios) but lower than other benchmarks which have been suggested. Furthermore, it is likely that fungi are relatively radioinsensitive.
- The dose rate estimated for mycelium in a post-accident scenario was slightly above the 400 μGy/h benchmark suggested for plants. However, this benchmark may over-estimate the risk to relatively radio-insensitive fungi. Conversely, it is possible that our assumptions used to model exposure of mycelium may underestimate dose.

Based on these findings we feel that there is no need to recommend that fungi should be added to the existing assessment tools and frameworks. However, some tools (e.g. Brown et al., 2016; USDoE, 2002) are flexible enough that if required the user can relatively easily create a geometry representing fungi and conduct a dose assessment.

Acknowledgements

We are grateful to the Autonomous Government of Extremadura (Junta de Extremadura) for the financial support to the LARUEX research group (FQM001), and also to the mobility grant MOV15B006 from Consejería de Educación y Empleo, Junta de Extremadura. The contribution of N.A. Beresford to this paper was facilitated by CEH National Capability funding. The contribution of M.D. Wood was supported by the TREE project (www.ceh.ac.uk/TREE), funded by NERC, the Environment Agency and Radioactive Waste Management Ltd.

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