Journal of Environmental Radioactivity 188 (2018) 108–114

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

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

Assessment of dose rate to terrestrial biota in the area around coal fired power plant applying ERICA tool and RESRAD BIOTA code

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A R T I C L E I N F O

Article history:
Received 4 June 2017
Received in revised form
19 September 2017
Accepted 19 September 2017
Available online 28 September 2017

Keywords:
Dose rate assessment
Biota
ERICA tool
RESRAD BIOTA
Coal fired power plant

A B S T R A C T

This paper presents the environmental radiation risk assessment based on two software program approaches ERICA Tool (version 1.2) and RESRAD BIOTA (version 1.5) to estimate dose rates to terrestrial biota in the area around the largest coal fired power plant in Serbia. For dose rate assessment software's default reference animals and plants and the best estimated values of activity concentrations of ^{238}U, ^{234}U, ^{234}Th, ^{232}Th, ^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{137}Cs in soil were used. Both approaches revealed the highest contribution to the internal dose rate due to ^{226}Ra and ^{210}Po, while ^{137}Cs contributed the most to the external dose rate. In the investigated area total dose rate to biota derived using ERICA Tool ranged from 0.3 to 14.4 μGy h^{-1}. The natural radionuclides exhibited significantly higher contribution to the total dose rate than the artificial one. In the investigated area, only dose rate for lichens and bryophytes exceeded ERICA Tool screening value of total dose rate of 10 μGy h^{-1} suggested as confident that environmental risks are negligible. The assessed total dose rates for reference animals and plants using RESRAD BIOTA were found to be 7 and 3 μGy h^{-1}, respectively. In RESRAD BIOTA - Level 3, 10 species (*Lumbricus terrestris*, *Rana lessonae*, *Sciurus vulgaris*, *Anas platyrhynchos*, *Lepus europaeus*, *Vulpes vulpes*, *Capreolus capreolus*, *Suss crofa*, *Quercu srobur*, *Tilia* spp.) representative for the study area were modeled. Among them the highest total dose rate (4.5 μGy h^{-1}) was obtained for large mammals. Differences in the predicted dose rates to biota using the two software programs are the consequence of the difference in the values of transfer parameters used to calculate activity concentrations in biota. Doses of ionizing radiation estimated in this study will not exhibit deterministic effects at the population level. Thus, the obtained results indicate no significant radiation impact of coal fired power plant operation on terrestrial biota. This paper confirms the use ERICA Tool and RESRAD BIOTA softwares as flexible and effective means of radiation impact assessment.

1. Introduction

Radiation protection and dose rate assessment has historically focused on protection of humans. A decade ago the International Commission for Radiological Protection (ICRP) began to consider environmental radiation protection specifically (ICRP, 2007). As a response to higher demand for environmental radiation protection, much effort has been made in the development of radioecological models, frameworks and approaches. A number of models for assessing the impact of ionizing radiation to the biota were developed in the last decade. Within the projects coordinated by International Atomic Energy Agency (IAEA) (Environmental Modelling for Radiation Safety (EMRAS I (2003–2007), EMRAS II (2009–2011)) and Modelling and Data for Radiological Impact Assessment (MODARIA I (2012–2015))) existing models for radiological impact assessment to biota were tested. For that purpose parameters associated with the transfer of the radionuclide (the whole organism activity concentrations, the concentration ratios) (Beresford et al., 2008a), dose conversion coefficients (Vives i Batlle et al., 2007), as well as the different scenarios for the terrestrial and aquatic ecosystems (Beresford et al., 2008b; Vives i Batlle et al., 2016; Yankovich et al., 2013) have been analyzed.

Models used in radiation protection of biota basically have the same generic structure (Beresford et al., 2008b, 2008c; Vives i Batlle et al., 2007). The radionuclide activity concentrations for a given medium (sediment, soil, water, air) are usually used as an input for the modelling purpose. The most common approach to estimate

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https://doi.org/10.1016/j.jenvrad.2017.09.014
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radionuclide transfer to biota in assessment models uses the radionuclide-specific parameters concentration ratios (CRs), i.e. the ratios of activity concentrations of radionuclides in biota (fresh weight) and those in environmental medium (dry weight) (Howard et al., 2013). The estimation of absorbed dose rate (μGy h^{-1}) to biota is one of the main concepts within the software tools. Dose conversion coefficient (factors) internal (DCC_{int}) and external (DCC_{ext}) are parameters defined as absorbed dose rates (μGy h^{-1}) per unit activity concentration in organism (Bq kg^{-1}fw) or medium (Bq kg^{-1} dw for soil). Detailed explanation and description of the methods used to derive DCCs values could be found in literature (Higley et al., 2003; Pröhl et al., 2003; Ulanovsky et al., 2008). In conjunction with the data for the activity concentrations of the medium the parameters that describe the geometry, occupancy factors, habitat and trophic transfer of the radionuclides to an organism are used to determine the dose rates due to external and internal exposure for biota (Beresford et al., 2008b; Wood et al., 2009). Estimated dose rates are compared with data for radiation effects that are used as guidelines to determine whether the biota is adequately protected and whether certain radiation effects at the population level will be manifested. Copplestone et al. (2008) reported definitions for the umbrella endpoints used to group radiation effects data within the FREDERICA database. Source of uncertainty within the model predictions is associated with the transfer parameters used and assessor decisions regarding transfer can influence the assessment results. There was a high demand for developing more comprehensive transfer databases which will enable model users to further strengthen for 'fitness-for-purpose' and help to reduce the uncertainty in the modelling process (Wood et al., 2009). Detailed information how dose rate parameters are derived, mean transfer parameters values and associated uncertainties are presented in IAEA TRS No 479 (IAEA, 2014).

The coal industry's activities (e.g. coal mining, operation of coal-fired power plants) may potentially lead to increased levels of natural radioactivity in the environment (Charro et al., 2013; Ćujić et al., 2015; Papp et al., 2002). Coals could contain relatively high concentrations of naturally occurring radioactive materials from the uranium and thorium decay series (^{238}U and ^{232}Th). In this study the assessment of the potential impact of ionizing radiation to terrestrial biota in the area surrounding the largest coal fired power plant (CFPP) 'Nikola Tesla' in Serbia was carried out. For the first time in Serbia, the absorbed total dose rates (external and internal) to biota were assessed by applying software program approaches: ERICA Tool, developed under a project funded by European Union (Beresford et al., 2007; Brown et al., 2008) and RESRAD BIOTA code, developed by Argonne National Laboratory in the United States (USDoE, 2004).

2. Materials and methods

2.1. Input data for dose rate assessment

The CFPP complex 'Nikola Tesla' is situated in western Serbia (N 44° 39′, E 20° 11′), on the right bank of the river Sava, 42 km upstream from Belgrade, the Serbian capital city. A total of 95 samples of undisturbed soils were collected from meadows in the study area. The activity concentrations (Bq kg^{-1}) of ^{238}U, ^{226}Ra, ^{232}Th and ^{137}Cs in soil samples were used as input data for dose rate assessment. Although ^{137}Cs is not released from CFPP, it was included in the assessment as one of contributors to the total dose rate. These activity concentrations were determined using an HPGe (ORTEC-AMETEK) with the resolution and relative efficiency of the detector for 1332 keV (^{60}Co) of 1.65 keV and 35%, respectively. In this assessment secular equilibrium for the ^{238}U chain was assumed and it is considered that ^{234}Th, ^{234}U and ^{230}Th are in equilibrium with ^{238}U and that ^{210}Po is in equilibrium with ^{210}Pb and ^{226}Ra. Assuming a representative value of 20% for the loss due to ^{222}Rn emanation from soil (UNSCEAR, 2000), the ^{210}Po and ^{210}Pb concentrations in soil constitute 80% of the concentration of ^{226}Ra. Details on sampling, geological and pedologic settings of the study area and gamma spectrometry analysis can be found in Ćujić et al. (2015).

2.2. Assessment of the dose rate using ERICA tool

The dose rates to terrestrial biota due to analyzed radionuclides were calculated using ERICA Tool (version 1.2) (ERICA, 2007; http://www.erica-tool.com/; Brown et al., 2008, 2016). The assessment was run at Tier 2 for all terrestrial reference organisms (ROs). For the assessment, the soil radionuclide activity concentrations between mean and the highest value were selected as the best estimated one in terrestrial environment surrounding area around the coal fired power plant. The best estimated measured activity concentrations (Bg kg^{-1} dry weight) of radionuclides in soil medium of investigated area (Table 1) were used as the model inputs. In this approach, the measured activity concentrations in soil have been used for the calculation of terrestrial biota activity concentrations, based on the ERICA tool default parameters for Concentration Ratios (CRs) as described by Brown et al. (2008). Detailed explanation on derivation of terrestrial transfer parameters for the ERICA Tool and the default concentration ratios for terrestrial biota could be found in the help manual of the tool and in the literature (Beresford et al., 2008c; Brown et al., 2016; Hosseini et al., 2008). The calculation of the dose rates on the basis of internal, external and total absorbed dose rate (in μGy h^{-1}) is performed applying the method of the Dose Conversion Coefficients (DCC, in μGy h^{-1} per Bq kg^{-1}) (Ulanovsky et al., 2008). For dose conversion, a weighting factor of 10 was used for alpha, 3 for beta and 1 for gamma radiation (Ulanovsky et al., 2008). In ERICA Tool universal screening dose rate criterion for incremental dose rate of 10 μGy h^{-1} is suggested as confident that environmental risks are negligible. In Tier 2 uncertainty factor was set as value 3, thus enabling testing for 5% probability of exceeding the dose screening value.

2.3. Assessment of dose rate using RESRAD biota

The RESRAD-BIOTA code is biota dose assessment computer software that uses bioaccumulation factors (B_{iv}s) and other parameters along with various methods to estimate radionuclide concentrations in animals and plants for dose rate calculation (USDoE, 2004). Level 3 of RESRAD BIOTA code (version 1.5) was applied to assess dose rates to biota (http://www.evs.anl.gov/resrad). At the first step of the assessment reference organisms (animals and plants) which are set as default by the code were used. The best estimated measured activity concentrations (Bg kg^{-1} dry weight) of radionuclides in soil medium of investigated area (Table 3) were used as the model inputs. The transfer parameters are referred to as conventionally termed bioaccumulation factor (parameter equal to CRs in ERICA Tool) in RESRAD BIOTA code (Yu et al., 2013). Numerical multipliers that relate activity concentrations in soil and whole body activity concentrations in biota to external and internal unweighted absorbed dose rates for each radionuclide−geometry combination are defined on the basis of organism geometries (ellipsoids for most organisms). This parameter is referred to as dose conversion factor (DCF) in RESRAD-BIOTA (Higley et al., 2003). At Level 3 of RESRAD BIOTA ten site specific organisms were modeled for dose rate assessment. They corresponded to six organism geometries set as default by the code, with variations in mass, area factor (AF) and geometry factor (GF). Based on the selected geometry the organism DCFs are calculated. During the modelling of the organism the AF representing the time that

Table 1
Activity concentrations of radionuclides (Bq kg^{-1} d.w.) in soil and default reference organisms used in the assessment applying ERICA Tool.

Radionuclid	Soil	Amphibian	Annelid	Detritivorous	Bird	Flying insects	Grasses and herbs	Lichen and bryophytes	Mammals (large)	Mammals (small-burrowing)	Gastropod	Reptile	Shrub	Tree
^{137}Cs	100	45.67	8.10	10.58	56.33	10.58	111.57	378.41	341.49	341.49	4.05	57.40	196.17	13.55
^{210}Pb	48	5.75	23.07	19.17	2.92	19.17	5.76	124.80	1.79	1.79	0.35	1.89	15.36	3.34
^{210}Po	48	4.91	0.48	0.48	0.49	0.48	13.44	124.80	4.26	4.26	0.48	6.14	15.84	3.52
^{226}Ra	60	2.66	2.60	2.60	2.17	2.60	10.80	42.60	2.66	2.66	2.86	2.66	19.80	0.69
^{230}Th	70	0.03	0.64	0.36	0.03	0.36	11.20	26.60	0.01	0.01	0.64	0.15	4.27	0.09
^{232}Th	60	0.02	0.55	0.30	0.02	0.30	9.60	22.80	0.01	0.01	0.55	0.13	3.66	0.08
^{234}Th	70	0.03	0.64	0.36	0.03	0.36	11.20	26.60	0.01	0.01	0.64	0.15	4.27	0.09
^{234}U	70	0.38	2.36	0.73	0.09	0.73	8.95	63.70	0.38	0.38	2.36	0.36	4.27	0.46
^{238}U	70	0.38	2.36	0.73	0.09	0.73	8.95	63.70	0.38	0.38	2.36	0.36	4.27	0.46

organism spends in the medium and GF describes the geometric relationship between the organism and radioactive sources were defined. As terrestrial ecosystems reference organism can be placed in the soil, at the soil and in the air the sum of those three (AF) can not be greater than one. In the case that reference organism spends all of their life cycle in soil GF of 1 was specified to simulate an infinite (4π) source geometry; otherwise GF of 0.5 was specified simulating a semi-infinite (2π) source geometry.

3. Results and discussion

The results of the assessments are presented as figures showing the assessed total dose rates to reference terrestrial organisms using ERICA tool and RESRAD BIOTA, and tables presenting activity concentration of radionuclides for medium and biota, dose rates from the various radionuclides for external, internal and total exposure. Softwares for dose rates assessment to biota are used to assess incremental doses from human activities only. For sites being assessed for Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) contamination, the dose rates estimated include a contribution from background levels of the radionuclides of interest. Vandenhove et al., 2015 pointed out the importance of having information on the background levels of natural radionuclides in TENORM sites, necessary in view of the fact that dose rates should be compared to the background dose rate to determine if the incremental dose is likely to be of concern. Since the background activity concentration in soil of the investigated area in this study were 11 and 14 Bq kg^{-1}, for ^{238}U and ^{232}Th, respectively (Vuković et al., 1996) and much lower than the soil activity concentrations presented in Tables 1 and 3, the background values do not contribute to the dose rates in this assessment. The impact of radon gas on biota is not assessed in this study because it is not possible to conduct this assessment using the applied softwares. Radon gas measurements in surface air were not done in the study area. Vives i Batlle et al. (2011b, 2012) used alternative methods to assess radon contribution to dose rates to biota, signaling the direction of future investigations.

3.1. Dose rates assessed by ERICA tool

Radionuclide activity concentrations (Bq kg^{-1} fresh weight) of terrestrial reference organisms calculated using activity concentrations of the medium and default CRs of the Tool are presented in Table 1. External, internal and total absorbed dose rates assessed from ^{137}Cs, ^{210}Po, ^{210}Pb, ^{226}Ra, ^{230}Th, ^{234}Th, ^{232}Th, ^{234}U and ^{238}U for reference organisms are presented in Table 2. Among analyzed radionuclides the highest external dose rate for reference organisms was that arising from ^{137}Cs, in the range 9.00×10^{-3} – 3.10×10^{-2} μGy h^{-1}, and that of ^{226}Ra, in the range 1.08×10^{-2} – 5.46×10^{-2} μGy h^{-1}. The highest internal dose rate (μGy h^{-1}) due to ^{226}Ra was assessed for the following organisms: annelid, detritivorous and flying insects (3.54×10^{-1}); bird (3.11×10^{-1}); grasses and herbs (1.47); amphibian (3.90×10^{-1}) and shrub (2.70). In mammals (large and small-burrowing) the highest internal dose rate was found to arise from ^{210}Po (1.32×10^{-1}μGy h^{-1}) and ^{226}Ra (3.70×10^{-1} and 3.59×10^{-1}μGy h^{-1}). In lichen and bryophytes the highest internal dose rates were due to ^{210}Po (3.81 μGy h^{-1}), ^{226}Ra (5.90 μGy h^{-1}), ^{234}U (1.75 μGy h^{-1}) and ^{238}U (1.54 μGy h^{-1}). For tree the highest internal dose rate arised from ^{210}Po (1.09×10^{-1}μGy h^{-1}). Among analyzed reference organisms the highest internal dose rates were found for lichens and bryophytes which are attributed to the species CR value and the higher contribution of ^{226}Ra. Although the only method of quantifying transfer in ERICA Tool the CR concept is not really applicable for lichens and bryophytes, because of their mode of nutrition (they uptake the most of nutritients from the atmosphere) and lack of well-developed root system (Dragovic et al., 2010; Dowdall et al., 2005). Total adsorbed dose rates for terrestrial referent organisms due to exposure of radionuclides in soil are presented in Fig. 1.

In investigated study area only total dose rate for lichen and bryophytes exceeded the ERICA Tool universal screening dose rate criterion for incremental dose rate of 10 μGy h^{-1}. However, these dose rates are 10 times lower than those obtained for lichens and bryophytes in an area of phosphate-fertiliser production in Belgium assessed by the same software using radionuclide activity concentrations in soil (Vandenhove et al., 2015). It was reported that morbidity for lichen and bryophytes appears after chronic exposure to high dose rate of 20.5×10^{3} μGy h^{-1}(Woodwell and Gannutza, 1967). There are no reported effects for lichens and bryophyte in the FREDERICA database for the lower dose rates (Copplestone et al., 2008). In the area around former uranium mine Žirovski vrh in Slovenia, the calculated dose rate arising from ^{238}U, ^{226}Ra and ^{232}Th for reference animals and plants were found to be 4.85×10^{-1} and 3.3×10^{1} μGy h^{-1}, respectively, with the highest one for lichens and bryophytes, which is in accordance with the results of this study (Černe et al., 2012). At Kadji Sai site in Kyrgyzstan, included an uranium mine, a coal-fired thermal power plant and a processing plant for the extraction of uranium from the ash produced in that area, total dose rate for lichens and bryophytes was assessed to be 1.64×10^{2} μGy h^{-1} and mostly arised from ^{226}Ra (Oughton et al., 2013). The total dose rate for annelids assessed in this study was found to be 0.6 μGy h^{-1}, which is in the range (0.05–2.6 μGy h^{-1}) of doses calculated by the same approach for annelids from an area in Norway with naturally enriched ^{232}Th (Mrdakovic Popic et al., 2012). In the findings this study are in accordance with those obtained for terrestrial biota from five randomly chosen areas in Greece, which also indicated soil ^{226}Ra as the main contributor to internal dose rate (Satiropoulou et al. 2016). The results obtained in this study indicated the artificial radionuclide ^{137}Cs (in Serbia mainly originated from the Chernobyl accident; Petrović et al., 2013) contributes mostly to the external dose rate.

Table 2
Assessed external (D_{ext}), internal (D_{int}) and total (D_{tot}) dose rates (μGy h^{-1}) for reference organisms applying ERICA Tool.

Nuclide	Amphibian	Annelid	Detritivorous	Bird	Flying insects	Grasses and herbs	Lichen and bryophytes	Mammals (large)	Mammals (small-burrowing)	Gastropod	Reptile	Shrub	Tree
	D_{ext}												
^{137}Cs	3.00×10^{-2}	3.00×10^{-2}	3.10×10^{-2}	1.10×10^{-2}	1.20×10^{-2}	1.10×10^{-2}	1.16×10^{-2}	5.60×10^{-3}	2.80×10^{-2}	1.20×10^{-2}	2.70×10^{-2}	1.10×10^{-2}	9.00×10^{-3}
^{210}Pb	2.78×10^{-5}	2.88×10^{-5}	2.93×10^{-5}	1.34×10^{-5}	1.39×10^{-5}	1.92×10^{-5}	1.40×10^{-5}	3.70×10^{-6}	2.50×10^{-5}	1.39×10^{-5}	2.26×10^{-5}	9.60×10^{-6}	6.24×10^{-6}
^{210}Po	2.16×10^{-7}	2.16×10^{-7}	2.21×10^{-7}	8.16×10^{-8}	8.16×10^{-8}	8.16×10^{-8}	8.35×10^{-8}	4.13×10^{-8}	2.06×10^{-7}	8.16×10^{-8}	1.97×10^{-7}	7.68×10^{-8}	6.72×10^{-8}
^{226}Ra	5.34×10^{-2}	5.40×10^{-2}	5.46×10^{-2}	2.04×10^{-2}	2.10×10^{-2}	1.98×10^{-2}	2.07×10^{-2}	1.08×10^{-2}	5.10×10^{-2}	2.10×10^{-2}	4.92×10^{-2}	1.92×10^{-2}	1.62×10^{-2}
^{230}Th	1.40×10^{-5}	1.47×10^{-5}	1.47×10^{-5}	4.90×10^{-6}	5.04×10^{-6}	9.80×10^{-6}	5.04×10^{-6}	1.75×10^{-6}	1.26×10^{-5}	5.04×10^{-6}	1.19×10^{-5}	5.46×10^{-6}	3.08×10^{-6}
^{232}Th	8.40×10^{-6}	8.40×10^{-6}	9.00×10^{-6}	2.58×10^{-6}	2.64×10^{-6}	6.60×10^{-6}	2.63×10^{-6}	7.80×10^{-7}	7.20×10^{-6}	2.58×10^{-6}	6.60×10^{-6}	3.00×10^{-6}	1.26×10^{-6}
^{234}Th	7.70×10^{-4}	7.70×10^{-4}	7.70×10^{-4}	3.22×10^{-4}	3.22×10^{-4}	3.29×10^{-4}	3.25×10^{-4}	1.54×10^{-4}	7.70×10^{-4}	3.22×10^{-4}	7.00×10^{-4}	3.01×10^{-4}	2.59×10^{-4}
^{234}U	1.19×10^{-5}	1.19×10^{-5}	1.26×10^{-5}	4.83×10^{-6}	4.97×10^{-6}	9.80×10^{-6}	5.02×10^{-6}	1.19×10^{-6}	1.05×10^{-5}	4.97×10^{-6}	9.10×10^{-6}	4.13×10^{-6}	1.26×10^{-6}
^{238}U	8.40×10^{-6}	8.40×10^{-6}	9.10×10^{-6}	3.36×10^{-6}	3.50×10^{-6}	7.00×10^{-6}	3.50×10^{-6}	7.00×10^{-7}	7.00×10^{-6}	3.43×10^{-6}	6.09×10^{-6}	2.80×10^{-6}	4.83E-07
	D_{int}												
^{137}Cs	6.85×10^{-3}	1.13×10^{-3}	1.27×10^{-3}	1.07×10^{-2}	1.48×10^{-3}	1.56×10^{-2}	4.47×10^{-2}	1.16×10^{-1}	5.81×10^{-2}	5.67×10^{-4}	9.76×10^{-3}	2.75×10^{-2}	4.34×10^{-3}
^{210}Pb	1.43×10^{-3}	5.52×10^{-3}	3.79×10^{-3}	7.59×10^{-4}	4.19×10^{-3}	1.32×10^{-3}	2.37×10^{-2}	4.66×10^{-4}	4.48×10^{-4}	7.99×10^{-5}	4.71×10^{-4}	3.51×10^{-3}	8.69×10^{-4}
^{210}Po	1.52×10^{-1}	1.48×10^{-2}	1.48×10^{-2}	1.52×10^{-2}	1.48×10^{-2}	4.17×10^{-1}	3.81×10^{0}	1.32×10^{-1}	1.32×10^{-1}	1.48×10^{-2}	1.90×10^{-1}	4.91×10^{-1}	1.09×10^{-1}
^{226}Ra	3.59×10^{-1}	3.54×10^{-1}	3.54×10^{-1}	3.11×10^{-1}	3.54×10^{-1}	1.47×10^{0}	5.90×10^{0}	3.70×10^{-1}	3.59×10^{-1}	3.90×10^{-1}	3.59×10^{-1}	2.70×10^{0}	9.76×10^{-2}
^{230}Th	7.35×10^{-4}	1.73×10^{-2}	9.59×10^{-3}	7.35×10^{-4}	9.59×10^{-3}	3.02×10^{-1}	7.17×10^{-1}	2.56×10^{-4}	2.56×10^{-4}	1.73×10^{-2}	4.10×10^{-3}	1.15×10^{-1}	2.39×10^{-3}
^{232}Th	5.37×10^{-4}	1.27×10^{-2}	7.00×10^{-3}	5.37×10^{-4}	7.00×10^{-3}	2.21×10^{-1}	5.26×10^{-1}	1.87×10^{-4}	1.87×10^{-4}	1.27×10^{-2}	3.00×10^{-3}	8.42×10^{-2}	1.74×10^{-3}
^{234}Th	1.25×10^{-5}	2.63×10^{-4}	9.78×10^{-5}	1.36×10^{-5}	1.17×10^{-4}	4.48×10^{-3}	6.72×10^{-3}	4.93×10^{-6}	4.65×10^{-6}	2.44×10^{-4}	7.15×10^{-5}	1.71×10^{-3}	4.60×10^{-5}
^{234}U	1.07×10^{-2}	6.61×10^{-2}	2.03×10^{-2}	2.46×10^{-3}	2.03×10^{-2}	2.51×10^{-1}	1.75×10^{0}	1.07×10^{-2}	1.07×10^{-2}	6.61×10^{-2}	1.02×10^{-2}	1.20×10^{-1}	1.29×10^{-2}
^{238}U	9.19×10^{-3}	5.66×10^{-2}	1.74×10^{-2}	2.11×10^{-3}	1.74×10^{-2}	2.15×10^{-1}	1.54×10^{0}	9.19×10^{-3}	9.19×10^{-3}	5.66×10^{-2}	8.71×10^{-3}	1.02×10^{-1}	1.11×10^{-2}
	D_{tot}												
^{137}Cs	3.69×10^{-2}	3.11×10^{-2}	3.23×10^{-2}	2.17×10^{-2}	1.35×10^{-2}	2.66×10^{-2}	5.62×10^{-2}	1.22×10^{-1}	8.61×10^{-2}	1.26×10^{-2}	3.68×10^{-2}	3.85×10^{-2}	1.33×10^{-2}
^{210}Pb	1.46×10^{-3}	5.55×10^{-3}	3.82×10^{-3}	7.73×10^{-4}	4.20×10^{-3}	1.34×10^{-3}	2.37×10^{-2}	4.70×10^{-4}	4.73×10^{-4}	9.38×10^{-5}	4.94×10^{-4}	3.52×10^{-3}	8.76×10^{-4}
^{210}Po	1.52×10^{-1}	1.48×10^{-2}	1.48×10^{-2}	1.52×10^{-2}	1.48×10^{-2}	4.17×10^{-1}	3.81×10^{0}	1.32×10^{-1}	1.32×10^{-1}	1.48×10^{-2}	1.90×10^{-1}	4.91×10^{-1}	1.09×10^{-1}
^{226}Ra	4.12×10^{-1}	4.08×10^{-1}	4.08×10^{-1}	3.31×10^{-1}	3.75×10^{-1}	1.49×10^{0}	5.92×10^{0}	3.81×10^{-1}	4.10×10^{-1}	4.11×10^{-1}	4.08×10^{-1}	2.72×10^{0}	1.14×10^{-1}
^{230}Th	7.49×10^{-4}	1.74×10^{-2}	9.60×10^{-3}	7.40×10^{-4}	9.59×10^{-3}	3.02×10^{-1}	7.17×10^{-1}	2.58×10^{-4}	2.69×10^{-4}	1.73×10^{-2}	4.12×10^{-3}	1.15×10^{-1}	2.39×10^{-3}
^{232}Th	5.45×10^{-4}	1.27×10^{-2}	7.01×10^{-3}	5.39×10^{-4}	7.00×10^{-3}	2.21×10^{-1}	5.26×10^{-1}	1.88×10^{-4}	1.94×10^{-4}	1.27×10^{-2}	3.00×10^{-3}	8.42×10^{-2}	1.75×10^{-3}
^{234}Th	7.83×10^{-4}	1.03×10^{-3}	8.68×10^{-4}	3.36×10^{-4}	4.39×10^{-4}	4.81×10^{-3}	7.04×10^{-3}	1.59×10^{-4}	7.75×10^{-4}	5.66×10^{-4}	7.71×10^{-4}	2.01×10^{-3}	3.05×10^{-4}
^{234}U	1.07×10^{-2}	6.61×10^{-2}	2.04×10^{-2}	2.47×10^{-3}	2.04×10^{-2}	2.51×10^{-1}	1.75×10^{0}	1.07×10^{-2}	1.07×10^{-2}	6.61×10^{-2}	1.02×10^{-2}	1.20×10^{-1}	1.29×10^{-2}
^{238}U	9.20×10^{-3}	5.66×10^{-2}	1.74×10^{-2}	2.12×10^{-3}	1.74×10^{-2}	2.15×10^{-1}	1.54×10^{-0}	9.19×10^{-3}	9.20×10^{-3}	5.66×10^{-2}	8.72×10^{-3}	1.02×10^{-1}	1.11×10^{-2}

Table 3
Activity concentrations of radionuclides (Bq kg^{-1} d.w.) in soil, reference animals and plants and assessed external (D_{ext}), internal (D_{int}) and total (D_{tot}) dose rates (μGy h^{-1}) applying RESRAD BIOTA code.

Nuclide	Activity concentrations			D_{ext}		D_{int}		D_{tot}	
	Soil	Animal	Plant	Animal	Plant	Animal	Plant	Animal	Plant
^{137}Cs	100	1.10 × 10+4	9.50 × 10+2	4.58×10^{-02}	4.58×10^{-02}	$5.38 \times 10^{+00}$	4.63×10^{-01}	$5.42 \times 10^{+00}$	5.08×10^{-01}
^{210}Pb	48	4.33 × 10-1	4.80 × 10-1	1.18×10^{-02}	1.18×10^{-02}	2.71×10^{-02}	3.00×10^{-02}	3.89×10^{-02}	4.17×10^{-02}
^{210}Po	48	2.03 × 10-1	4.80 × 10-2	2.35×10^{-07}	2.35×10^{-07}	1.25×10^{-02}	2.96×10^{-03}	1.25×10^{-02}	2.96×10^{-03}
^{226}Ra	60	3.60 × 100	6.54 × 100	9.58×10^{-02}	9.58×10^{-02}	$1.24 \times 10^{+00}$	$2.25 \times 10^{+00}$	$1.33 \times 10^{+00}$	$2.35 \times 10^{+00}$
^{230}Th	70	1.15 × 10-1	6.12 × 10-2	5.75×10^{-04}	5.75×10^{-04}	7.33×10^{-03}	3.92×10^{-03}	7.92×10^{-03}	4.50×10^{-03}
^{232}Th	60	1.15 × 10-1	6.12 × 10-2	4.17×10^{-04}	4.17×10^{-04}	4.42×10^{-02}	2.81×10^{-02}	4.46×10^{-02}	2.85×10^{-02}
^{234}Th	70	1.15 × 10-1	6.12 × 10-2	3.65×10^{-02}	3.65×10^{-02}	$0.00 \times 10^{+00}$	$0.00 \times 10^{+00}$	3.65×10^{-02}	3.65×10^{-02}
^{234}U	70	2.87 × 10-1	2.65 × 10-1	5.21×10^{-04}	5.21×10^{-04}	1.48×10^{-02}	1.48×10^{-02}	1.53×10^{-02}	1.53×10^{-02}
^{238}U	70	2.87 × 10-1	2.65 × 10-1	3.68×10^{-02}	3.68×10^{-02}	1.32×10^{-02}	1.33×10^{-02}	5.00×10^{-02}	5.00×10^{-02}

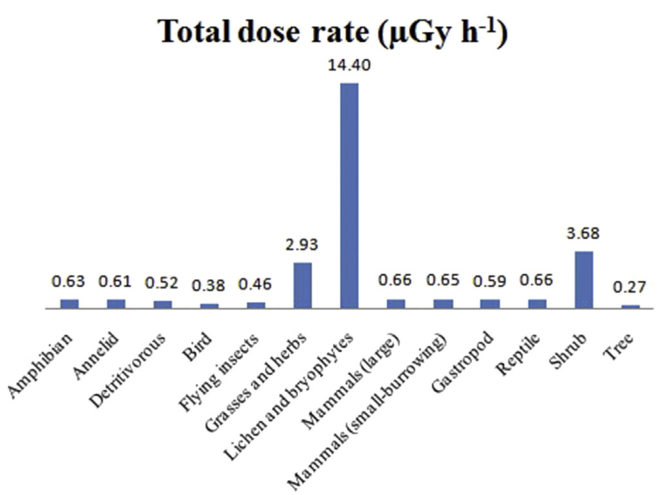

Fig. 1. Total dose rates for terrestrial reference organisms obtained by ERICA Tool.

Table 4
Organisms and parameters (dimension, mass, area factor, geometry factor) used for dose rate assessment by RESRAD BIOTA.

Organism	Geometry					*AF*	*GF* (*soil*)
	N	Dimension (cm)			Mass (kg)		
		x	*y*	*z*			
Lumbricus terrestris	2	2.5	1.2	0.62	0.003	1	1
Rana lessonae	3	10	2	2	0.01	0.5	0.5
Sciurus vulgaris	4	45	8.7	4.9	0.3	1	0.5
Anas platyrhynchos					2.5	0.55	0.5
Lepus europaeus	5	50	26	13	7	1	0.5
Vulpes vulpes							
Capreolus capreolus	6	100	42	33	20	1	0.5
Sus scrofa					100		0.75
Quercus robur	7	270	66	48	500	1	0.5
Tilia spp.							

3.2. Dose rate assessed by RESRAD BIOTA code

Radionuclide activity concentrations (Bq kg^{-1} fresh weight) in terrestrial reference organisms (animals and plants) calculated using activity concentrations of the medium and default B_{iv}s of the code are presented in Table 3. External, internal and total absorbed dose rates assessed from ^{137}Cs, ^{210}Po, ^{210}Pb, ^{226}Ra, ^{230}Th, ^{234}Th, ^{232}Th, ^{234}U and ^{238}U for reference animals and plants are presented in Table 3. The greatest contribution to the total dose rate was due to ^{137}Cs and ^{226}Ra. The total dose rates of radiation exposure due to terrestrial radionuclides were found to be 6.96 μGy h^{-1} for reference animals and 3.06 μGy h^{-1} for reference plants.

In Table 4. Latin names, masses (kg), geometries (x-length, y-height, z-width), geometry factors (GF) and area factors (AF) for ten selected species representative for the study area are presented.

Assessed external, internal and total absorbed dose rates arising from ^{137}Cs, ^{210}Po, ^{210}Pb, ^{226}Ra, ^{230}Th, ^{234}Th, ^{232}Th, ^{234}U and ^{238}U for modeled organisms are presented in Table 5. The greatest contribution to the total dose rate was from ^{137}Cs and ^{210}Po. The total dose of radiation exposure due to terrestrial radionuclides (Fig. 2) for modeled animals was the highest (4.5 μGy h^{-1}) for mammals (*Capreolus capreolus*, *Sus scrofa*) and the lowest (3.06 μGy h^{-1}) for amphibian (*Rana lessonae*). The assessed dose rates were less than benchmarks values for terrestrial animals (40 μGy h^{-1}) and plants (400 μGy h^{-1}) which are used in RESRAD BIOTA code as safe ones.

In available literature there is a lack of data for biota dose rates assessed by RESRAD BIOTA code. The majority of data derived using this code arise from intercomparisons of different approaches in the frame of EMRAS and MODARIA projects (Vives i Batlle et al., 2007; 2011a; Johansen et al., 2012).

3.3. Differences in estimated dose rates using two software programs

The results obtained in this study showed that the highest contribution to the total dose rate assessed by both applied models arises from ^{137}Cs, ^{226}Ra and ^{210}Po. Assessed total dose rate (14.35 μGy h^{-1} for lichens and bryophytes) for reference plant by ERICA Tool was several times higher compared to total dose rate (3.04 μGy h^{-1}) for reference plant assessed by RESRAD BIOTA code in the investigated area. On the other side, assessed total dose rates were less than 1 μGy h^{-1} for terrestrial reference animals by ERICA Tool, while in RESRAD BIOTA total dose rate was 6.5 μGy h^{-1} for reference animals and for modeled organisms varied from 1.5 to 4.5 μGy h^{-1}. The differences in the assessed dose rates obtained by two approaches are due to the differences in the values of the transfer parameters used for calculation of the biota activity concentrations used in the applied models (Howard et al., 2013; Yu et al., 2013). In addition, calculation processes of the DCCs and DCFs are different in the models used. The Monte Carlo technique was used in ERICA Tool to simulate radiation transfer to biota in the observed medium (Vives i Batlle et al., 2004; Taranenko et al., 2004). The dosimetric models have been developed for a wide range of water and terrestrial organisms, and for different habitats (Vives i Batlle et al., 2004; Taranenko et al., 2004), this approach is summarized and implemented within ERICA Tool-a (Brown et al., 2008). ERICA Tool dosimetry module was written in FORTRAN which is connected with electronic database which obtained almost all radionuclides (838) and their decay properties (ICRP, 1983; Eckerman et al., 1994). In RESRAD BIOTA internal and

Table 5
External (D_{ext}) internal (D_{int}) and total (D_{tot}) (μGy h^{-1}) dose rates assessed for modeled organisms applying RESRAD BIOTA.

Nuclid	*Lumbricus terrestris*	*Rana lessonae*	*Sciurus vulgaris*	*Anas platyrhynchos*	*Lepus europaeusc Vulpes vulpes*	*Capreolus capreolus*	*Sus scrofa*	*Quercu srobur Tilia* spp.
D_{ext}								
^{137}Cs	3.32×10^{-02}	1.60×10^{-02}	1.46×10^{-02}	8.04 × 10-03	1.22 × 10-02	8.96×10^{-03}	1.34 × 10-02	6.71×10^{-03}
^{210}Pb	6.54×10^{-02}	3.02×10^{-02}	2.74×10^{-02}	1.50 × 10-02	2.32 × 10-02	1.75×10^{-02}	2.63 × 10-02	1.35×10^{-02}
^{210}Po	2.43×10^{-05}	7.67×10^{-06}	4.46×10^{-06}	2.45 × 10-06	2.78 × 10-06	1.64×10^{-06}	2.45 × 10-06	1.11×10^{-06}
^{226}Ra	3.55×10^{-05}	1.04×10^{-05}	4.79×10^{-06}	2.63 × 10-06	2.49 × 10-06	1.37×10^{-06}	2.06 × 10-06	9.21×10^{-07}
^{230}Th	9.75×10^{-03}	2.26×10^{-03}	1.03×10^{-03}	5.67 × 10-04	5.96 × 10-04	3.76×10^{-04}	5.63 × 10-04	2.71×10^{-04}
^{232}Th	1.17×10^{-03}	2.41×10^{-04}	9.38×10^{-05}	5.17 × 10-05	4.01 × 10-05	2.01×10^{-05}	3.01 × 10-05	1.37×10^{-05}
^{234}Th	2.32×10^{-07}	1.13×10^{-07}	1.05×10^{-07}	5.79 × 10-08	8.88 × 10-08	6.58×10^{-08}	9.92 × 10-08	5.00×10^{-08}
^{234}U	3.69×10^{-05}	1.26×10^{-05}	8.17×10^{-06}	4.50 × 10-06	5.54 × 10-06	3.39×10^{-06}	5.08 × 10-06	2.33×10^{-06}
^{238}U	9.75×10^{-03}	2.26×10^{-03}	1.03×10^{-03}	5.67 × 10-04	5.96 × 10-04	3.75×10^{-04}	5.63 × 10-04	2.70×10^{-04}
D_{int}								
^{137}Cs	$1.48 \times 10^{+00}$	8.17×10^{-01}	$1.93 \times 10^{+00}$	1.06 × 10+00	$2.45 \times 10^{+00}$	$3.17 \times 10^{+00}$	3.17 × 10+00	3.16 × 10-01
^{210}Pb	$1.24 \times 10^{+00}$	6.17×10^{-01}	$1.24 \times 10^{+00}$	6.79 × 10-01	$1.24 \times 10^{+00}$	$1.24 \times 10^{+00}$	1.24 × 10+00	2.25 × 10+00
^{210}Po	4.05×10^{-02}	2.03×10^{-02}	4.05×10^{-02}	2.23 × 10-02	4.05×10^{-02}	4.05×10^{-02}	4.05 × 10-02	2.59 × 10-02
^{226}Ra	1.48×10^{-02}	7.42×10^{-03}	1.48×10^{-02}	8.17 × 10-03	1.48×10^{-02}	1.48×10^{-02}	1.48 × 10-02	1.48 × 10-02
^{230}Th	1.29×10^{-02}	6.46×10^{-03}	1.29×10^{-02}	7.13 × 10-03	1.29×10^{-02}	1.30×10^{-02}	1.30 × 10-02	1.31 × 10-02
^{232}Th	2.70×10^{-02}	1.35×10^{-02}	2.70×10^{-02}	1.49 × 10-02	2.70×10^{-02}	2.70×10^{-02}	2.70 × 10-02	3.00 × 10-02
^{234}Th	1.26×10^{-02}	6.29×10^{-03}	1.26×10^{-02}	6.92 × 10-03	1.26×10^{-02}	1.26×10^{-02}	1.26 × 10-02	2.99 × 10-03
^{234}U	7.29×10^{-03}	3.65×10^{-03}	7.29×10^{-03}	4.01 × 10-03	7.29×10^{-03}	7.29×10^{-03}	7.29 × 10-03	3.91 × 10-03
^{238}U	3.00×10^{-06}	1.79×10^{-06}	3.86×10^{-06}	2.13 × 10-06	3.96×10^{-06}	4.01×10^{-06}	4.01 × 10-06	3.67 × 10-05
D_{tot}								
^{137}Cs	$1.52 \times 10^{+00}$	8.29×10^{-01}	$1.94 \times 10^{+00}$	1.07 × 10+00	$2.48 \times 10^{+00}$	$3.18 \times 10^{+00}$	$3.18 \times 10^{+00}$	3.23 × 10-01
^{210}Pb	$1.30 \times 10^{+00}$	6.50×10^{-01}	$1.27 \times 10^{+00}$	6.96 × 10-01	$1.26 \times 10^{+00}$	$1.25 \times 10^{+00}$	$1.27 \times 10^{+00}$	2.26 × 10+00
^{210}Po	4.05×10^{-02}	2.03×10^{-02}	4.05×10^{-02}	2.23 × 10-02	4.05×10^{-02}	4.05×10^{-02}	4.05×10^{-02}	2.59 × 10-02
^{226}Ra	1.49×10^{-02}	7.42×10^{-03}	1.48×10^{-02}	8.17 × 10-03	1.48×10^{-02}	1.48×10^{-02}	1.48×10^{-02}	1.48 × 10-02
^{230}Th	2.27×10^{-02}	8.71×10^{-03}	1.40×10^{-02}	7.67 × 10-03	1.35×10^{-02}	1.33×10^{-02}	1.35×10^{-02}	1.34 × 10-02
^{232}Th	2.82×10^{-02}	1.38×10^{-02}	2.71×10^{-02}	1.49 × 10-02	2.71×10^{-02}	2.70×10^{-02}	2.71×10^{-02}	3.00 × 10-02
^{234}Th	1.26×10^{-02}	6.29×10^{-03}	1.26×10^{-02}	6.92 × 10-03	1.26×10^{-02}	1.26×10^{-02}	1.26×10^{-02}	2.99 × 10-03
^{234}U	7.33×10^{-03}	3.66×10^{-03}	7.29×10^{-03}	4.02 × 10-03	7.29×10^{-03}	7.29×10^{-03}	7.29×10^{-03}	3.91 × 10-03
^{238}U	9.75×10^{-03}	2.26×10^{-03}	1.03×10^{-03}	5.67 × 10-04	6.00×10^{-04}	3.79×10^{-04}	5.67×10^{-04}	3.07 × 10-04

external exposure DCFs are estimated using the Monte-Carlo n-particle transport code (MCNP). Linear interpolation between these energies is used to calculate the absorbed fraction for a required energy, which than used to calculate the internal and external exposure DCFs for a given radionuclide (Kamboj et al., 2002). Based on results of the case study around Sellafield nuclear power plant, Wood et al. (2009) concluded that differences in assessed dose rates for mammals comes from differences in used DCCs vs. DCFs, while differences in dose rates for plants can be explained by the difference in the transfer and habitat parameters used within the two models. In addition to the above parameters, variability occurred as a consequence of different numbers of decays or daughter products being included within the estimation of dose rate (Vives i Batlle et al., 2011a; Johansen et al., 2012).

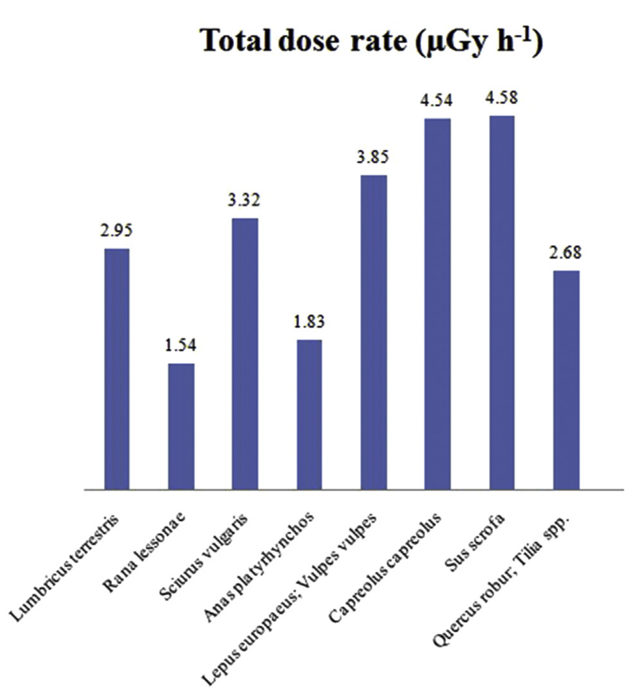

Fig. 2. Total dose rates for organisms modeled by RESRAD BIOTA code.

4. Conclusions

The ERICA Tool and RESRAD BIOTA based assessment indicated no risk for terrestrial biota arising from ionizing radiation in the area surrounding the largest Serbian CFPP. The highest total dose rates were assessed to be 14.4 μGy h^{-1} for lichen and bryophytes using ERICA Tool and 4.5 μGy h^{-1} for mammals (*Capreolus capreolus*, *Sus scrofa*) using RESRAD BIOTA. The calculated dose rates indicated that natural radionuclides exhibited higher contribution to the total dose rate than the artificial one. Internal dose rate, which was significantly higher than external, is mainly attributed to ^{226}Ra and ^{210}Po. According to assessed dose rates no deterministic effects to biota populations as a consequence of radiation exposure will be manifested in the investigated area. The results obtained here can be used as a valuable database for future estimations of the environmental impact of ionizing radiation in order to draw more reliable findings about the radiological exposure to terrestrial biota.

Acknowledgements

This research work was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Project No. III43009). M. Ćujić also gratefully acknowledges the support of the International Atomic Energy Agency and all collaborators in the activities C6/SRB/11005 and K4-TM-48957.

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