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REPORT

Radioecological impacts of tin mining

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Abstract The tin mining activities in the suburbs of Jos, Plateau State, Nigeria, have resulted in technical enhancement of the natural background radiation as well as higher activity concentrations of primordial radionuclides in the topsoil of mining sites and their environs. Several studies have considered the radiological human health risks of the mining activity; however, to our knowledge no documented study has investigated the radiological impacts on biota. Hence, an attempt is made to assess potential hazards using published data from the literature and the ERICA Tool. This paper considers the effects of mining and milling on terrestrial organisms like shrubs, large mammals, small burrowing mammals, birds (duck), arthropods (earth worm), grasses, and herbs. The dose rates and risk quotients to these organisms are computed using conservative values for activity concentrations of natural radionuclides reported in Bitsichi and Bukuru mining areas. The results suggest that grasses, herbs, lichens, bryophytes and shrubs receive total dose rates that are of potential concern. The effects of dose rates to specific indicator species of interest are highlighted and discussed. We conclude that further investigation and proper regulations should be set in place in order to reduce the risk posed by the tin mining activity on biota. This paper also presents a brief overview of the impact of mineral mining on biota based on documented literature for other countries.

Keywords Tin mining · Radioecology · Biota · Jos · Dose rate

INTRODUCTION

Naturally occurring radioactive materials (NORM) are found in many mining environments (Bhaumik et al. 2004), and their existence in outcrops enhances the background radiation of the area (Dissanayake and Chandrajith 2009). Mining of minerals involves the removal of large amounts of soil which contain radioactive materials (Ibeanu 2003), and the radioactive materials in the excavated soil may find their way into the food chain and hence to humans. The unceasing release of mining waste (tailings) into the biosphere may result in a build-up of radionuclides in the air, water, and soil, which will impact both human and non-human biota (Ademola 2008).

A regional study of the impacts of mining on the environment was recently conducted by some of the contributing authors (Aliyu et al. 2015b). The study considered the radioecological impacts of zinc, barite, and copper mining in Nasarawa State, Nigeria. Nasarawa and Plateau States share boarders and geological features, and the former is drained by many fast-flowing streams and rivers that take their source from the Jos Plateau. The study suggested that certain terrestrial flora and fauna, which have high radiation susceptibility, are likely to be significantly affected by the solid mineral mining activities.

In a global context, Arogunjo et al. (2009) compared the specific activities of uranium and thorium in soil from the Jos-Plateau tin mines with those for other countries (see Fig. 1). The figure shows that the average specific activities of U and Th in soils of the Jos Plateau tin mines are higher than the averages for the high background natural radiation areas (HBNRAs). Studies of natural population in the HBNRAs (e.g., Forster et al. 2002; Møller and Mousseau 2013; Aliyu and Ramli 2015) have revealed some radiation-induced effects on humans, animals, and plants. Some of the effects recorded in the HBNRAs are changes in physiology, immunology, point mutations and increase in disease frequency.

Efforts have also been made to assess the environmental or radioecological impacts of solid mineral mining globally. For instance, Déjeant et al. (2014) measured the radioactivity levels in Cominak and Somaïr uranium mines in Niger Republic, which shares a border with Nigeria. Other studies that considered the impacts of uranium mining are those conducted by Salbu et al. (2013) in Kazakhstan and Skipperud et al. (2013) in Tadjikistan, and Lind et al. (2013) assessed the environmental impacts of uranium mining in Kadji Sai and Shekaftar regions of Kyrgyzstan. The studies in these uranium mining areas have revealed that ^{226}Ra contributes about 90 % of the dose received by the population in the central Asia countries. In Portugal, studies have been conducted to assess the ecological impacts of mining of radioactive ores in Viseu and Guarda regions by Carvalho et al. (2007). In a later study, Carvalho et al. (2014b) revealed that the use of radioactive water for irrigation from rivers which drain through abandoned and active uranium mines was the major source of radioactive transfer to vegetables grown in some regions of Portugal. Significant levels of leached activities were detected in Iberian rivers (like River Mondego and River Zezere) that had their source from uranium mining and milling region of Portugal (Carvalho et al. 2014a).

Udompornwirat (1993) reviewed the radiological consequence of tin mining on mine workers in SEATRAD member countries (Indonesia, Malaysia, and Thailand). The estimate was made by considering the various pathways of radiological exposure of the workers. The range of annual effective dose due to external radiation exposure among mine workers was estimated at 1–120 mSv. Tin mining and processing in Perak, Malaysia, have also been shown to result in the accumulation of NORM in fish species (Saat et al. 2014). The order of the specific activities of NORM in the fish samples studied by Saat et al. (2014) was ^{228}Ra < ^{226}Ra < ^{40}K. The justification given by the authors for this consistent order of arrangement is that it may be related to the fact that the amount of ^{238}U which is the parent of ^{226}Ra is higher than that of ^{232}Th which is the parent of ^{228}Ra in the fish.

Attempts have been made in the past to assess the human health impacts of tin mining in the Jos Plateau, Nigeria (e.g., Ibeanu 2003; Funtua and Elegba 2005; Ademola and Farai 2006; Jibiri and Agomuo 2007; Jibiri et al. 2007a, b, 2009; Ademola 2008; Ajayi 2008; Arogunjo et al. 2009; Olise et al. 2010, 2014), but few studies have considered non-human biota (but see Møller and Mousseau, 2013). Recently, international standards have also been set to protect non-human biota from the effects of exposure to ionizing radiation (ICRP 2003; UNSCEAR 2008; ICRP 2009; IAEA 2011). Here, we present an initial analysis of the potential hazards of the radioecological impacts of tin mining in Jos, Nigeria. Such a study is both timely and relevant given the growing international interest in the biological impacts of low-dose radiation in the environment.

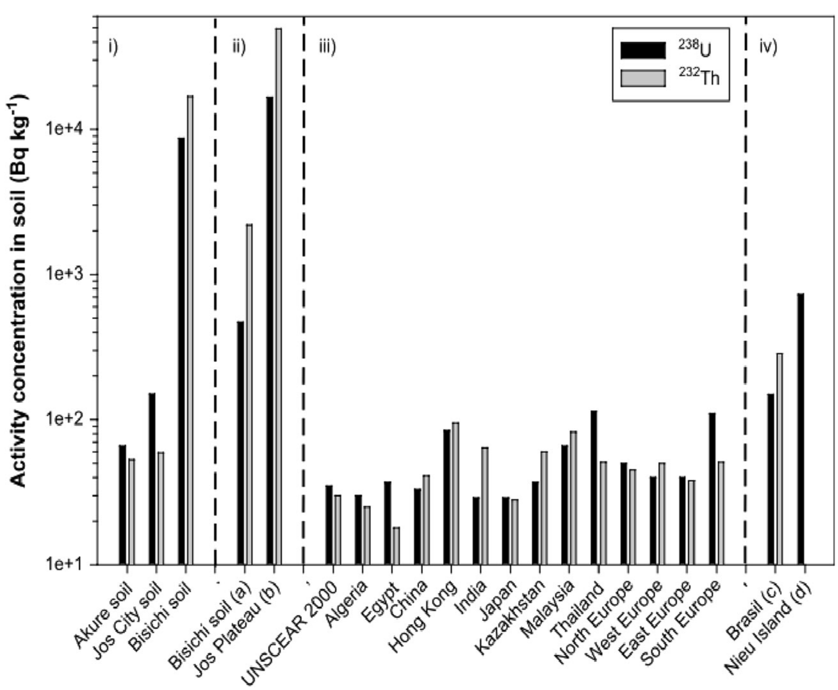

Fig. 1 Activity concentrations of ^{238}U and ^{232}Th in soils. *Panel i* Arogunjo et al. (2009). *Panel ii* other studies conducted in the same area. *Panel iii* UNSCEAR listing of non-contaminated soils (UNSCEAR 2000). *Panel iv* other areas with high natural radioactive background. (a) Jibiri et al. (2007a); (b) Ibeanu (2003); (c) Amaral et al. (1992); (d) Marsden (1960)

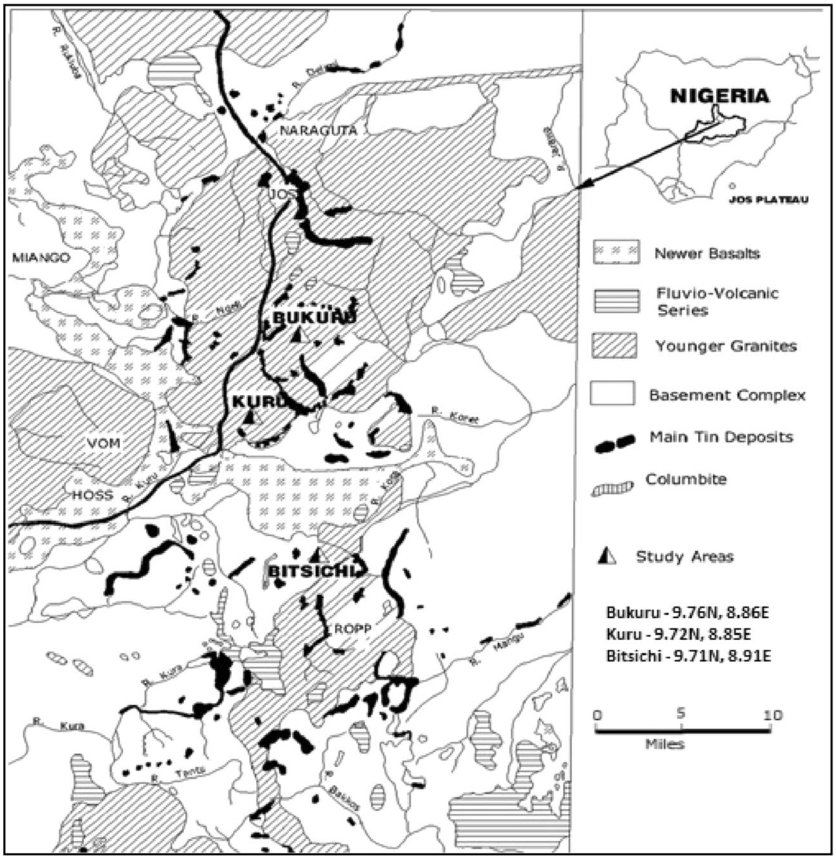

Fig. 2 The Geological Map of the Jos Plateau Study Area (adapted from Olise et al. 2014 with permission from Elsevier)

STUDY AREA

The area of Jos in Nigeria's Plateau State is located on a granitic plateau that is approximately 1100 m above sea level in the North Central part of Nigeria (Olise et al. 2014). The geological formation of the Jos area is a major driver for its selection as a suitable place for tin mining and milling. The lithological formations are younger granite ring complexes and tertiary basaltic volcanic rocks of north central Nigeria (Fig. 2). The hilly rocks are differentiated from the surrounding basement rocks with smoother topography. Weathering activities have greatly impacted the rocks resulting in immense lateralization (Turner 1971; Badejo 1975).

Commercial mining of tin ore has been on-going at the Jos Plateau for over a century. The early history and development of the Jos Plateau is closely associated with the history of tin mining in the area (e.g., Morrison 1977; Freund 1981; Grace 1982). By 1903, the expedition sent by the Royal Niger Company to trace the source of the tin straws of George Nicolas had succeeded in locating the main source of tin ore on the Jos Plateau. An intensive effort was made by colonialists to safeguard the economic interest of British colonial power (Dung-Gwom 2010). The Beron people have been the major labor provider of the Jos plateau tin mines even before the arrival of the British, and at that time tin was purchased with cowries.

During the colonial era, initial tin production in Jos Plateau was about 1.5 metric tons in 1914 and it increased to 17 740 metric tons by 1943. At that time, Nigeria was the sixth leading producer of tin in the world (Onwuka et al. 2013). Tin production in Nigeria rapidly decreased in 1970 due to declining global market demand for tin and the diversion of interests in Nigeria towards oil production and export (Patterson 1986). Despite the formal end of tin mining and production on the Jos Plateau, mining activities have continued at low levels. A recent study by Onwuka et al. (2013) investigated the socio-economic impacts of tin mining in Jos Plateau. They found that tin mining activities in Jos Plateau have contributed both positively and negatively to economic and social aspects of the people in the mining areas. Positive outcomes included job creation, increased income, and the provision and maintenance of social services. Negative impacts included immigration and population growth, land degradation, increased crime rate, loss of heritage and farm lands, health hazards, and economic inflation. Onwuka et al. (2013) noted that the tin mining activities significantly negatively impacted the environment and has generated many social and economic scars on the land as well as on the inhabitants of the mining areas. The authors recommended a full-scale environmental impact assessment (EIA) and new laws to regulate the informal mining activities in these areas.

An analysis of satellite imagery acquired in the years 1975, 1988, and 2005 showed that tin mining activity has caused significant erosion and degradation to the land in Bukuru (Ndace and Danladi 2012) with degraded areas, land losses to development, and tailing ponds increasing by 24.58, 18.51, and 7.57 %, respectively (total land area = 761 km^2), while arable land (farm and grazing land) and forest reserves have decreased by 106.60 km^2 (14.16 %) and 264.89 km^2 (35.18 %), respectively.

MATERIALS AND METHODS

Brief description of ERICA tool

The ERICA integrated approach was developed to aid decision-making related to the environmental effects of ionizing radiation. This approach generally has three components or "Tiers": the assessment of environmental exposure and effects using the ERICA Tool, risk characterization, and management of environmental risks (Beresford et al. 2007; Torudd and Saetre 2013).

Tier 1 is designed to be simple and conservative, requiring a minimum of input data and enabling the user to exit the process and exempt the situation from further evaluation provided that the assessment meets a predefined screening criterion. Here, a predefined screening dose is used to calculate the environmental media concentration limit (EMCL) for all reference organism/radionuclide combinations.

In Tier 1, the risk quotient (RQ) is then obtained by comparing the input media concentrations with the most restrictive EMCL for each radionuclide. These are defined by Eq. (1):

$$RQ_n = \frac{\mathrm{AC}_n}{\mathrm{EMCL}_n}, \quad (1)$$

where AC is the measured activity concentration in the medium for a specific radionuclide n.

If $RQ < 1$, the probability of exceeding the benchmark is acceptably low (<5 %) and this serves as the justification for terminating risk calculations at this stage. In a situation where $RQ > 1$, there is >5 % probability that the benchmark has been exceeded and further assessment is recommended (Tier 2).

The basic equations for Tier 2 assessment are presented in Eqs. (2) and (3).

$$\dot{D}^j_{\mathrm{int}} = \sum_i C^j_i \times \mathrm{DCC}^j_{\mathrm{int},j}, \quad (2)$$

where C^j_i is the average concentration of radionuclide i in the reference organism j (Bq kg^{-1} fresh weight) and DCC^j_i is the radionuclide-specific dose conversion coefficient for internal exposure (μG h^{-1} per Bq kg^{-1} fresh weight).

$$\dot{D}^j_{\mathrm{ext}} = \sum_z v_z \sum_i C^{\mathrm{ref}}_{zi} \times \mathrm{DCC}^j_{\mathrm{ext},zi}, \quad (3)$$

where v is the occupancy factor of the organism j at location z; C^{ref}_{zi} is the average concentration of radionuclide i in the reference media in a given location z, and $\mathrm{DCC}^j_{\mathrm{ext},zi}$ is the dose conversion coefficient for external exposure. The total dose rate $\dot{D}^J_{\mathrm{Tot}}$ is assessed by summing Eqs. (1) and (2). Two RQs [expected (RQ_{exp}) and conservative (RQ_{cons})] are obtained at the end of this assessment.

Tier 2 analysis allows the modeler to be more interactive, to change the default parameters (screening dose rate and radionuclides) and to select specific reference organisms. The evaluation is performed directly against the screening dose rate, with the dose rate and RQs generated for each reference organism selected for assessment. A 'traffic light' system is used to indicate whether the following outcomes can be considered:

(i) Green: of negligible concern (with a high degree of confidence);
(ii) Yellow: of potential concern, where assessment may be needed and/or a refined assessment at *Tier 2* or an in-depth assessment (i.e., Tier 3) is performed; and
(iii) Red: of concern, where the user is recommended to continue the assessment, either at Tier 2 if refined input data can be obtained or at Tier 3.

Decisions to exit an assessment given outcomes (ii) and (iii) should be justified, for example, using information from FREDERICA provided in the ERICA tool as 'look-up effects tables' for different wildlife groups.

In *Tier 2*, the total risk quotient is calculated as

$$\sum RQ = \frac{D_{\mathrm{Tot}}}{D_{\mathrm{lim}}}, \quad (4)$$

where D_{Tot} is the total dose rate and D_{lim} is the screening dose rate.

Tier 3 is a probabilistic risk assessment in which uncertainties within the results may be determined using sensitivity analysis. The assessor can also assess up-to-date scientific literature (which may not be available at Tier 2) on the biological effects of exposure to ionizing radiation in a number of different species.

Table 1 Summary of activity concentrations in soil and dose due to tin mining in Jos, Nigeria

Study	Activity concentrations of radionuclides (Bq kg^{-1})				In situ dose measurements (μSv h^{-1})	Mine location	Type of sample
	^{238}U	^{226}Ra	^{232}Th	^{40}K			
Ibeanu (2003)[a]	3779.1	NA	8175.2	NA	NA	Jos tin Mine	Contaminated soil
Ademola (2008)	722	NA	1680	Not detected	NA	Jos tin Mine	Tin tailing
Ademola and Farai (2006)	NA	66	126	589	NA	Tin mining areas of Bukuru and Bitsichi, Jos	Concrete building blocks
Ajayi (2008)	776.0	NA	2.72	35.4	NA	Soil samples	Tin mine in Bukuru-Jos
Arogunjo et al. (2009)	8.7–51	NA	16.8–98	NA	NA	Tin mining area of Bitsichi, Jos	Soil and mineral sands
Funtua and Elegba (2005)	NA	NA	NA	NA	5–80	Tin mines, Bukuru	NA
Jibiri et al. (2009)	NA	109–163	147–451	466–1062	NA	Bitsichi, Bukuru, and Ropp localities, Jos	Farm soil from the three localities
Jibiri et al. (2007b)	BDL-48	NA	BDL-17	60–494	NA	Old tin mine of Bitsichi	Food items, soil, and local diets
Jibiri and Agomuo (2007)	NA	19–30	27–41	83–129	NA	Old tin mine of Bitsichi	Terrestrial food crops
Jibiri et al. (2007a)	NA	109–470.6	122.7–2189.5	BDL-166.4	NA	Old tin mine of Bitsichi	Soil
Olise et al. (2014)	1.0 ± 40	NA	6.0–170	NA	NA	Bukuru, Bitsichi, and Kuru	Soil and tailing
Olise et al. (2010)	BDL-27420	NA	50–35 800	30–670	NA	Bitsichi, Kuru, and Bukuru	Tailing

NA not available

[a] Data used for ERICA tool

Detailed descriptions of the ERICA tool and the integrated approach for ecological impact assessment have previously been presented in the literature (Beresford et al. 2007; Brown et al. 2008; Larsson 2008; Torudd 2010; Torudd and Saetre 2013; Aliyu et al. 2015c).

Data used in modeling

Published data on the activity concentrations of ^{238}U and ^{232}Th in soil and tailings from Bukuru, Kuru, and Bitsichi were used to conduct a Tier 2 ERICA tool impact assessment to estimate the dose rate and risk quotients for a set of reference organisms. The universal screening dose rate criterion of 10 μGy h^{-1} was used for the assessment procedure. Such a level is often assumed to result in negligible environmental risks (Larsson 2008; Aliyu et al. 2015c). This methodology has proven useful for the assessment of impacts to biota due to exposure to Fukushima-derived radionuclides in marine, freshwater, and terrestrial ecosystems (e.g., Garnier-Laplace et al. 2011; Aliyu et al. 2015c). An earlier study considered the exposure of small mammals at the exclusion zones of Chernobyl nuclear plant based on the data for measured activity concentrations of ^{90}Sr and ^{137}Cs using the ERICA tool (Beresford et al. 2008). This study found good agreement with external dose estimates using thermo-luminescence dosimeter (TLD) results and those predicted using the ERICA tool, providing confidence in the estimates generated by the computer program.

In order to follow regulatory standards, the upper bound of the reported range value for ^{238}U and ^{232}Th that have been reported by Ibeanu (2003) and Olise et al. (2014) was used as these two studies considered all mining areas (see Table 1). Estimates by Ibeanu (2003) were based on gamma spectrometry using an NaI(Tl) detector, while those by Olise et al. (2014) were based on instrumental neutron activation analyses.

RESULTS AND DISCUSSION

A summary of the type of samples and the results of each of these studies is presented in Table 1.

A recent study by Ademola (2014) attempted to measure the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in cattle that were believed to have grazed in the fields around the mining region. The study calculated the effective dose based on the consumption of meat from the cattle in this

Table 2 Risks quotients for reference terrestrial organisms (green—is of negligible concern, yellow—is of potential concern, red—is of significant concern)

Organism	RQ_{exp}	RQ_{Cons}
Amphibian	0.06	0.17
Annelid (Worm)	0.48	1.44
Arthropod - detritivorous	0.20	0.57
Bird	0.02	0.06
Flying insects	0.19	0.57
Grasses & Herbs	4.17	12.51
Lichen & Bryophytes	15.47	40.64
Mammal – large	0.05	0.16
Mammal - small-burrowing	0.05	0.16
Mollusc – gastropod	0.48	1.43
Reptile	0.09	0.26
Shrub	1.70	5.10
Tree	0.08	0.25

region. The study reported high activity concentration of ^{40}K in the studied cattle organs. However, there were limitations of the study design and presentation that raise questions concerning the utility of the findings (Aliyu et al. 2015a). For instance, the very small sample size (only five cows) and limited controls likely biased the results of the study. For example, the lack of sufficient controls made it impossible to determine if the radionuclides detected in cow tissues were the result of mine tailings. In addition and perhaps more to the point, the elevated ^{40}K detected in the tissues was likely the result of the application of inorganic fertilizer, which usually contains the elements nitrogen, phosphorus, and potassium (NPK) and is likely to have influenced the activity concentration of ^{40}K in the cattle feeds and hence their organs. Enhanced radioactivity of NPK fertilizer is well documented in the literature (e.g., Pfister et al. 1976; Fávaro 2005; Boukhenfouf and Boucenna 2011), and this is likely the cause of the reported findings rather than the mine tailings per se.

Tin mining by-products are dumped around mining sites in heaps. These actions may result in biotic radiation exposure via leached activity which may be directly absorbed by flora and fauna through soil or surface water, and this leached activity may lead to radiation contamination of the terrestrial and freshwater ecosystems around the mines. Exposure to NORM in the Jos Plateau exposure may be through (i) leached activity which may be directly ingested by human through drinking water or may indirectly enter the food chain by uptake through vegetation, fish, milk, and meat and (ii) leached activity which may lead to radiation contamination of the terrestrial and freshwater ecosystems around the mines.

Results of the Tier 2 ERICA Tool run based on the data reported by Ibeanu (2003) are presented in Fig. 2 and Table 2. The models show very large variation among different groups in the predicted dose rates. Figure 2 indicates two threshold dose rate levels of interest. The first is the 10 μGy h^{-1} level that is considered of interest by those promoting the ERICA tool (e.g., Beresford et al. 2007). The second is 40 μGy h^{-1} which is often used by governmental and intergovernmental groups as a level of significance for terrestrial animals [IAEA (1992), UNSCEAR (1996), and USDoE (2002)]. However, it is worth noting that recent ecological studies have suggested chronic exposure to radiation levels below 40 μGy h^{-1} often result in measurable population effects, and there is currently much discussion of these levels given controversial studies of organisms living in Chernobyl (e.g., Møller and Mousseau 2011; Garnier-Laplace et al. 2013).

Only three reference groups are predicted to receive doses above 10 μGy h^{-1} (see Fig. 3): grasses and herbs, lichens and bryophytes, and shrubs. Table 2 shows predicted risk quotients and the degree of potential hazards for each group considered in this analysis.

For grasses and herbs, the predicted dose rate is more than 42 μGy h^{-1} and some of the effects observed in this reference organism for a dose rate range of 0–50 μGy h^{-1} are low mass of seed, increased yield, etc. For instance in pea (species name), a dose rate of 42 μGy h^{-1} causes no statistically significant effects on mass of the seeds. However, a dose rate of ~45 μGy h^{-1} to potato has been demonstrated to cause a minor increase (1.3-fold) in the yield of Priekulsky and Lorch cultivars. Other defects in potato are severe changes in leaf color (4.9-fold), moderate increase in % of shorted shoots (*x*2 compared with control), and moderate increase in % death of main top shoot (2 % compared with 0 % in control). This information is available in the effects database of ERICA tool. The interest in pea and potato is due to the fact that these are important food crops in the Plateau State, Nigeria (Ifenkwe and Odurukwe 1990).

The dose rate to lichens and bryophytes is predicted to be ~155 μGy h^{-1}, and this dose rate is more than three times higher than the IAEA recommended value of 40 μGy h^{-1}. This dose rate is of significant concern, and it is likely that there is a need for protective measures for such organisms.

The predicted dose rate for shrubs is ~17 μGy h^{-1}, and based on the ERICA screening limit, this dose rate is of concern (Table 2). A dose rate of 11.2 μGy h^{-1} has been observed to cause major reduction in cumulative stem growth (43 % the control value) in Jack pine (FEDRICA).

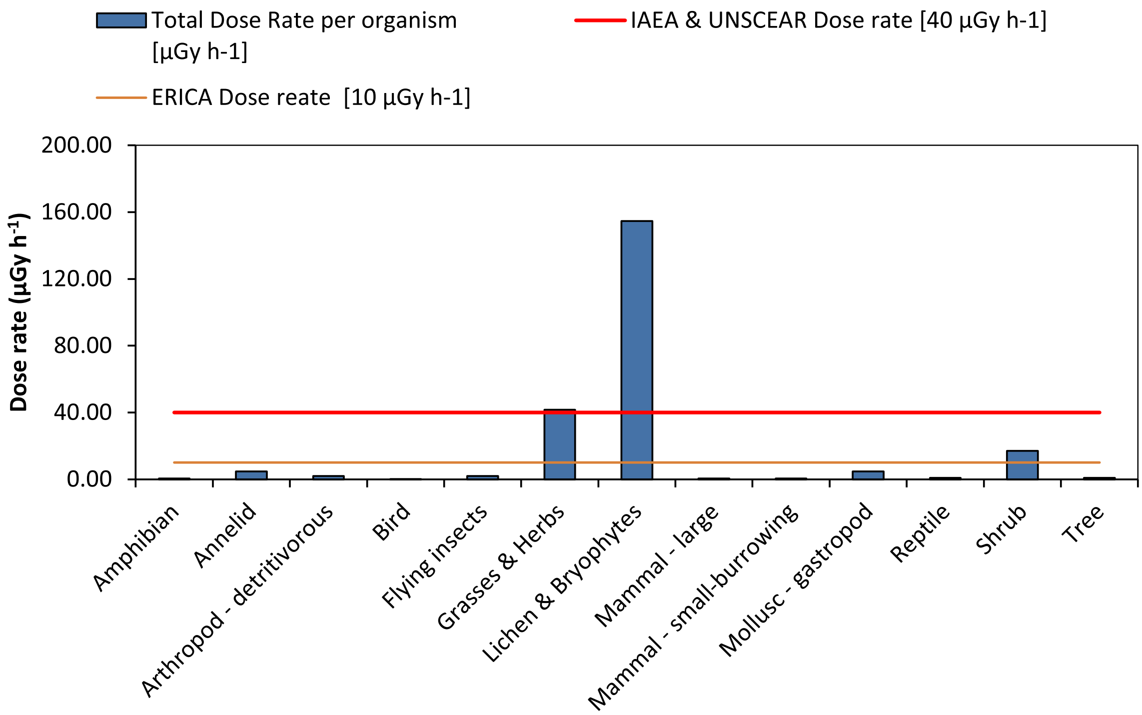

Fig. 3 Total dose rate per organism

Predicted dose rates for other organisms are significantly lower [e.g., annelids (worm) and mollusc—gastropod—receive total dose rates of 4.78 µGy h^{-1} each]. Although the IAEA generally assumes limited impacts to organisms from dose rates ≤50 µGy h^{-1}, there is considerable discussion of these arbitrary thresholds given the lack of sufficient information concerning unknown individual and species variation in sensitivity, the role of multigeneration exposures, and the importance of complex community interactions in determining individual-, population-, and ecosystem-level responses to radiation sources. Recent analyses of organisms inhabiting Chernobyl, Fukushima, and other naturally radioactive regions around the world point to measurable, biologically significant impacts at what are much lower dose rates than those recommended by IAEA (e.g., Møller and Mousseau 2009, 2015; Hiyama et al. 2012, 2013; Yamashiro et al. 2013; Møller et al. 2014). Clearly, further research is needed.

CONCLUSIONS

This paper assessed the potential radioecological impacts of tin mining in Jos, Nigeria, with the aim of investigating if there was a cause for environmental concern. The results of this study have shown that terrestrial organisms like grasses and herbs, lichens and bryophytes, and shrubs likely receive dose rates that are above general accepted regulatory limits and are likely of potential concern. This study has also shown that mining activity may have significant impacts on the production of farm produce (e.g., peas and potatoes). The current analysis does not directly address the potential broader impacts related to the incorporation of radionuclides into the human diet, but our findings clearly point to the need for further investigation of this possible outcome. Although further field studies are needed to directly assess the impacts of mining activity on the environment, our analyses suggest that regulations limiting the dumping of tailings and disposal of process water around the mines and their environs may be prudent and necessary to protect the humans and the broader environment of the region.

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