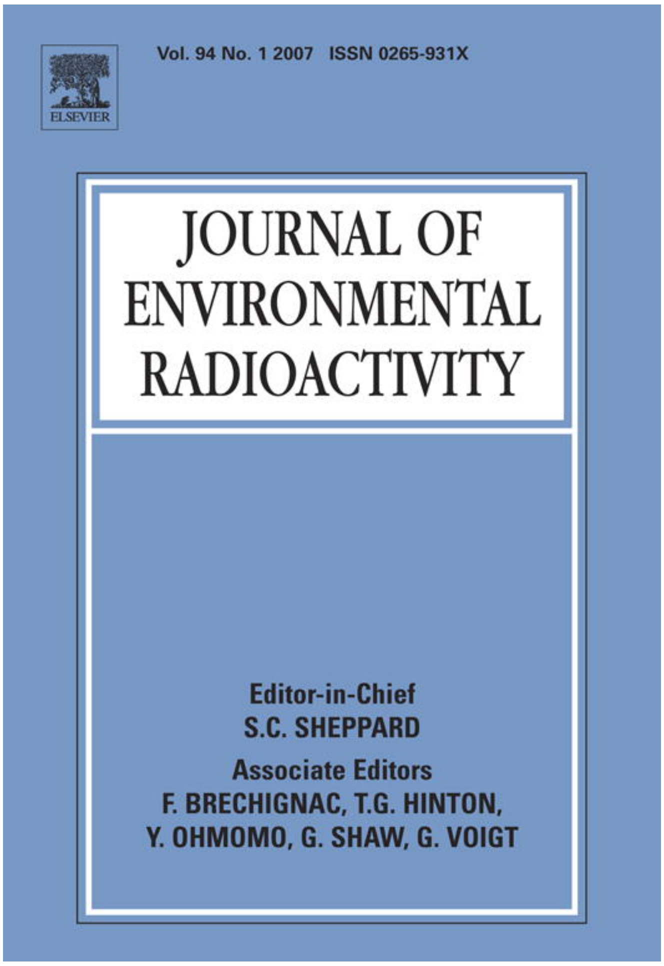
Vol. 94 No. 1 2007 ISSN 0265-931X
ELSEVIER
JOURNAL OF ENVIRONMENTAL RADIOACTIVITY
Editor-in-Chief
S.C. SHEPPARD
Associate Editors
F. BRECHIGNAC, T.G. HINTON,
Y. OHMOMO, G. SHAW, G. VOIGT

Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Journal of Environmental Radioactivity 94 (2007) 31–40
JOURNAL OF ENVIRONMENTAL RADIOACTIVITY
www.elsevier.com/locate/jenvrad

Estimation of annual effective dose due to natural radioactive elements in ingestion of foodstuffs in tin mining area of Jos-Plateau, Nigeria

N.N. Jibiri [a,*], I.P. Farai [a], S.K. Alausa [b]

[a] *Radiation and Health Physics Research Laboratory, Department of Physics, University of Ibadan, Oyo State, Nigeria*
[b] *Department of Physics, Olabisi Onabanjo University Ago-Iwoye, Nigeria*

Received 8 June 2006; received in revised form 1 September 2006; accepted 13 December 2006
Available online 6 March 2007

Abstract

Soils and food crops from a former tin mining location in a high background radiation area on the Jos-Plateau, Nigeria were collected and analyzed by gamma spectrometry to measure their contents of ^{40}K, ^{238}U and ^{232}Th. As well as collecting samples, in situ dose rates on farms were measured using a precalibrated survey meter. Activity concentrations determined in food crops were compared with the local food derivatives or diets to investigate the possible removal or addition of radionuclides during food preparation by cooking or other means. Potassium-40 was found to contribute the highest activity in all the food products. The activity concentration of ^{40}K, ^{238}U and ^{232}Th in local prepared diets ranged between 60 and 494 Bq kg^{-1}, between BDL and 48 Bq kg^{-1} and between BDL and 17 Bq kg^{-1}, respectively. The internal effective dose to individuals from the consumption of the food types was estimated on the basis of the measured radionuclide contents in the food crops. It ranged between 0.2 μSv y^{-1} (beans) and 2164 μSv y^{-1} (yam) while the annual external gamma effective dose in the farms due to soil radioactivity ranged between 228 μSv and 4065 μSv.

Keywords: Radioactivity; Radionuclide; Food crops; Diet; Effective ingestion dose; Mining; Nigeria

* Corresponding author.
E-mail addresses: jibirinn@yahoo.com, nnamdi.jibiri@mail.ui.edu.ng (N.N. Jibiri).

0265-931X/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvrad.2006.12.011

1. Introduction

Ingestion of radionuclides through food intake accounts for a substantial part of average radiation doses to various organs of the body and also represents one of the important pathways for long term health considerations (McDonald et al., 1999; Fernandez et al., 2004; Hernandez et al., 2004). The status of the soil on which food crops are grown will determine, to a significant extent, the quality of foodstuffs produced. An essential feature of soil is its ability to accumulate and retain over long periods radioactive isotopes introduced into the environment from external sources. Human dietary composition varies from place to place and from one individual to another. Natural radionuclides entering the food chain are mostly derived from the soil and, as a result, variation in soil radionuclide content is a prime source of geographic variability. Plant uptake also varies from species to species; hence the intake of different food products forms a secondary source of variability.

In Nigeria, the most important food basket of the country consists of grains and tubers (roots). These crops constitute a large percentage of the total diet for both low and medium income consumers in Nigeria. The major staples are yam, cassava, sorghum, maize, millet and rice. For instance, the consumption of rice represents about 9% of total calorie intake. Per capita consumption per annum of rice is about 24.8 kg (Olayemi, 1998; see also Table 5). While root crops are important foods in Nigeria, cereals account for one-half of calories consumed. Since food consumption is generally related to specific geographical locations as well as cultural, economic, social and even political conditions, food consumption and energy intake in the northern part of the country, where the present study is located, revolve largely around one food group: cereals. It has been found that cereals account for over 64% of the average daily energy intake and an average consumer has a daily intake of about 2393 kcal (Omosaiye, 2001; Maziya-Dixon et al., 2004).

In some parts of the world, population growth and movement, industrial development and food security have resulted in pressure to use agricultural lands containing relatively high levels of radioactivity, for instance in the monazite areas of India and Brazil, and in parts of Iran with ^{226}Ra anomalies where exposures up to tens of mSv, and in extreme cases 100 mSv, occur annually (UNSCEAR, 2000; Banzi et al., 2000). The area studied in the present investigation (Bitsichi) is a former tin mining location with relatively high background radiation (Babalola, 1984; Sanni et al., 1985; Oresegun and Babalola, 1990, 1993; Farai and Jibiri, 2000; Farai and Ademola, 2001; Jibiri, 2001), although no data presently exist on the radionuclide contents of food crops in this area. Soils in the area are rich in natural radionuclides and it is possible that they may accumulate in food crops above desirable levels. The aim of the present study is, therefore, to determine the activity concentrations of ^{40}K, ^{238}U and ^{232}Th in different agricultural crops grown in the area and to estimate the effective ingestion dose to individuals consuming locally produced food in the area.

2. Materials and methods

2.1. Sampling

A map of Jos-Plateau showing the location of the sampling site at Bitsichi is shown in Fig. 1. The local food crops grown in the area were identified and, to ensure good coverage, the entire area was divided into six sub-areas of about 3 km^2. The full range of food items identified could not be collected at each sampling site since no single sub-area contained all the food types grown in the area as a whole. However, an effort was made to ensure adequate collection of representative samples of the food crops identified in the

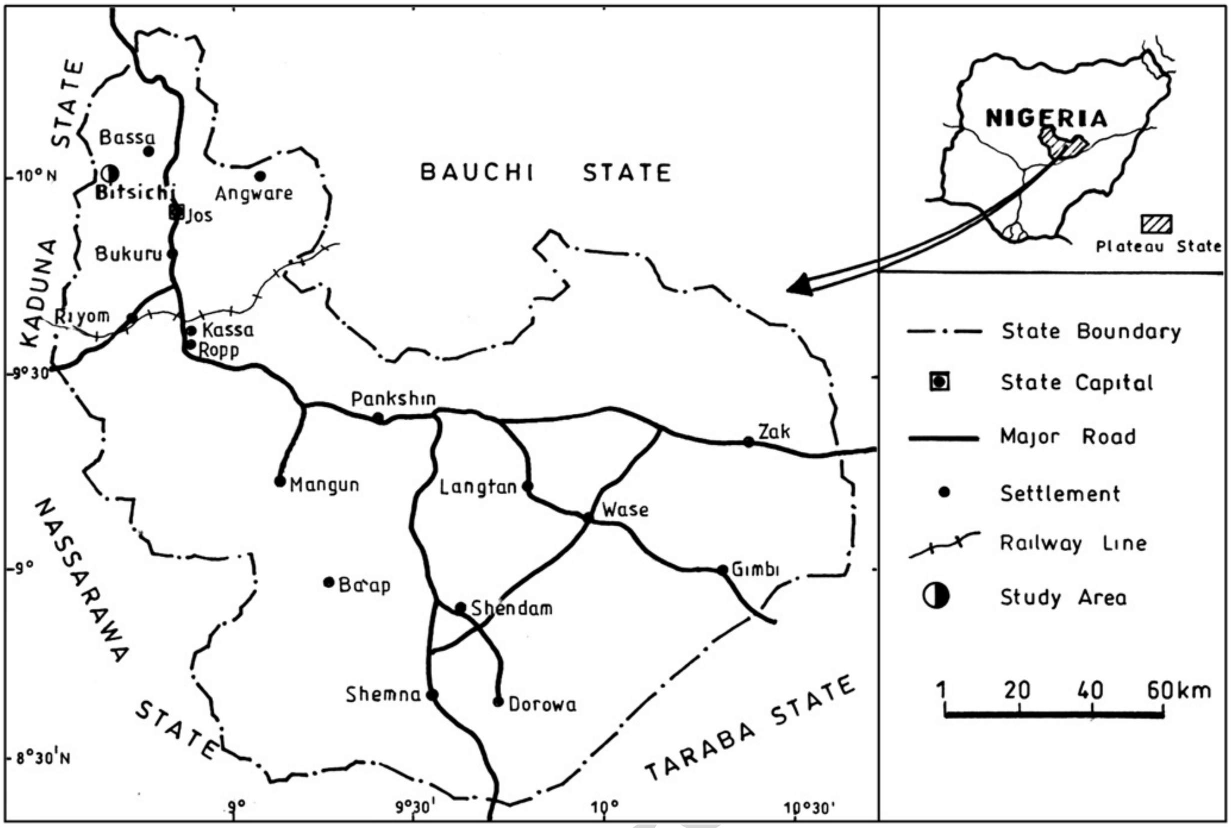

Fig. 1. Map of Jos-Plateau, Nigeria showing the study location (Bitsichi).

study area. The different food items collected and the number of each sample is presented in Table 1. Soil samples were collected to a depth of 150 mm from four different points in the farms where food samples were collected and, thereafter, thoroughly mixed together to provide a representative sample for that site. Aerial dose rate measurements were also performed in the farms using a precalibrated survey meter (Morgan Series 1000 – mini rad meter by Mini Instruments Ltd., England).

The soil samples, after drying for several days at room temperature until a constant weight was reached, were crushed to pass through a 2 mm mesh sieve. The sieved samples were transferred into uncontaminated empty cylindrical plastic containers of uniform size (60 mm height by 65 mm diameter) and sealed for a period of about 4 weeks. This was done to allow ^{222}Ra and its short-lived daughters to reach secular equilibrium prior to gamma spectroscopy. Since the study focused on human ingestion of foods grown and consumed by the population in the study area, only the edible parts of the food crops were prepared for analysis. For instance, the peel of cassava tuber, yam tuber and cocoyam were all discarded. The items were thereafter air dried to a constant weight, then homogenized and transferred into calibrated geometry sample containers and sealed in the same way as the soil samples.

The food samples, after preparation, represent the raw foodstuffs which are sold in local markets to consumers. Consumption of these foods without any further preparation would deliver the maximum ingestion dose to consumers. However, to investigate any possible removal of radionuclides during cooking, parts of the food items were prepared using typical local practices. For instance, cassava is made into fufu, yam into dafefen-doya (boiled yam), maize into soyeyen-masara (fried) or dafefen-masara (boiled) and groundnut into kulikuli (nut ball). After preparing samples in these ways they were analyzed for their radionuclide contents.

2.2. Radioactivity determination

The samples (food items, soil and local diets) were counted for 36,000 s (10 h) using a low-level gamma spectrometry system consisting of a 76 mm × 76 mm NaI (Tl) detector (Model No. 802-series,

Table 1
The different samples of food items collected and their food group

Food group	Sub-food type: group/food	Scientific names	Number of samples
Grains/cereals	Dyare		2
	Millet	*Pennisetum glaucum*	3
	Maize	*Zea mays*	4
	Guinea corn	*Sorghum bicolor* L.	2
	Acha	*Digitaria exilis stapf*	4
Vegetables	Tuberous		
	Sweet potato	*Ipomoea batatas*	3
	Irish potato	*Solanum tuberosum*	4
	General		
	Okra	*Abelmoschus esculentus*	3
	Tomato	*Lycopersicon esculentum*	3
	Pepper	*Capsicum annum*	3
	Garden egg	*Solanum gilo*	2
	Leafy		
	Kuca		3
Tubers	Yam	*Dioscorea* sp.	4
	Cassava	*Manihot esculenta*	4
	Cocoyam	*Colocasia esculenta*	3
Legumes	Groundnut	*Arachis hypogaea* Linn.	3
	Local bean (Sword beans)	*Canavalia ensiformis*	2
	Soya beans	*Glycine max* Merr.	3

Kuca and Dyare are local vegetable and cereal crops, respectively.

Canberra Inc.) coupled to a Canberra Series 10 plus Multichannel Analyzer (MCA) (Model No. 1104) through a preamplifier base. The detector has a resolution of about 8% at 0.662 MeV, which is capable of distinguishing the gamma ray energies of the radionuclides of interest in this study. The photopeak at 1.46 MeV was used for the measurement of ^{40}K while those at 1.76 MeV peak from ^{214}Bi and 2.614 MeV from ^{208}Tl were used for the measurement of ^{238}U and ^{232}Th, respectively. The net area under each photopeak, after background corrections, was used to calculate the activity concentration of each radionuclide in the food and soil samples. The activity concentration in the samples was obtained using the following expression (Olomo et al., 1994; Akinloye and Olomo, 2000):

$$C\,(\mathrm{Bq\ kg^{-1}}) = \frac{C_n}{\varepsilon P_\gamma M_s} \quad (1)$$

where C is the activity concentration of the radionuclide in the sample, C_n is the count rate under each photopeak due to each radionuclide, ε is the detector efficiency for the specific γ-ray, P_γ is the absolute transition probability of the specific γ-ray and M_s is the mass of the sample (kg). The mass of samples analyzed ranged between 80 g and 200 g for the food samples while a uniform mass of 200 g was used for the soil samples.

3. Results and discussion

3.1. Radioactivities and external dose rates

The activity concentrations of the radionuclides in the soil samples are shown in Table 2 while those in the food items and the diets are presented in Tables 3 and 4, respectively. The

Table 2
Activity concentrations (Bq kg^{-1}, dry weight) of ^{40}K, ^{238}U and ^{232}Th and total effective dose rates in the farm soil

Locations	^{40}K	^{238}U	^{232}Th	Effective dose rate (μSv h^{-1})
Farm 1	93.0 ± 9.6	145.2 ± 16.3	373.5 ± 8.9	0.2
Farm 2	135.7 ± 7.1	175.1 ± 19.6	515.2 ± 10.1	0.3
Farm 3	166.4 ± 12.4	10.9 ± 15.2	122.7 ± 11.2	0.07
Farm 4	128.8 ± 17.2	72.5 ± 13.8	168.4 ± 7.8	0.1
Farm 5	BDL	427.1 ± 12.4	1036.5 ± 8.8	0.6
Farm 6	55.1 ± 11.5	470.6 ± 10.9	2189.5 ± 9.2	1.2

BDL, below detection limit.

errors in Tables 2 and 3 are combined uncertainties in the counting measurements. As shown in Table 2, ^{232}Th exhibited the highest activity concentrations in soils at virtually all the sampling sites. This contrasts with previous studies in which ^{40}K contents have usually been found to be higher in areas with lower background radioactivities (Olomo et al., 1994; Jibiri and Bankole, 2006). Table 3 shows that ^{40}K was highest in all the food samples despite having the lowest activity concentrations in soil samples. This may be attributed, in part, to the heavy use of NPK fertilizers by farmers to improve crop yield following impoverishment of the soil by decades of mining operations in the area (Pasquini and Alexander, 2005; Yusuf et al., 2004). The activity concentrations of ^{40}K, ^{238}U and ^{232}Th in the food crops from this area were about 10× higher than those obtained in other parts of the country. For instance, in tuber products the radionuclide levels varied from 10.6 Bq kg^{-1} to 46.4 Bq kg^{-1} for ^{40}K, 0.5 Bq kg^{-1} to 2.7 Bq kg^{-1} for ^{238}U and from BDL to 1.4 Bq kg^{-1} for ^{232}Th (Akinloye and Olomo, 2000) while in cereal

Table 3
Activity concentrations of radionuclides in crops (Bq kg^{-1}, dry weight) and the estimated total effective dose from ingestion of the food items

Food items	^{40}K	^{238}U	^{232}Th	Effective dose (μSv y^{-1})
Maize	243.2 ± 21.2	34.1 ± 14.2	BDL	63.5
Millet	144.4 ± 12.8	4.6 ± 3.4	BDL	39.4
Acha (Hungry rice)	BDL	BDL	BDL	–
Dyare	179.4 ± 25.3	4.7 ± 1.1	8.1 ± 3.2	1.9
Guinea corn	85.9 ± 25.6	5.2 ± 1.3	7.6 ± 1.6	111.9
Yam	684.5 ± 40.6	85.5 ± 10.2	89.8 ± 6.2	2164.1
Cocoyam	537.1 ± 18.1	34.0 ± 15.1	33.3 ± 7.2	81.0
Cassava	539.6 ± 21.2	27.4 ± 9.4	22.2 ± 5.2	519.4
Sweet potato	423.7 ± 30.8	23.6 ± 11.1	35.6 ± 12.3	169.6
Irish potato	494.4 ± 22.1	10.7 ± 3.6	17.1 ± 9.8	22.2
Okra	213.0 ± 19.4	BDL	BDL	–
Tomato	158.9 ± 28.9	13.9 ± 6.4	9.6 ± 4.1	27.4
Pepper	132.4 ± 19.2	4.5 ± 3.8	BDL	9.4
Garden egg	122.3 ± 22.2	32.1 ± 19.2	BDL	–
Kuca	80.6 ± 17.2	10.4 ± 7.1	BDL	–
Soya beans	546.8 ± 28.6	8.3 ± 4.2	BDL	9.4
Groundnut	398.6 ± 12.9	7.4 ± 3.2	9.8 ± 3.4	12.8
Local beans	453.6 ± 15.8	9.4 ± 2.4	18.9 ± 6.4	0.2

–, MAC for the food items is not available; BDL, below detection limit.

Table 4
Activity concentrations of radionuclides (Bq kg^{-1}, dry weight) in prepared foods and percent reduction in radionuclide activity concentrations due to cooking

Food diets	^{40}K	^{238}U	^{232}Th
Alibor	169.9 (68.5)	24.7 (9.9)	5.1 (77.0)
Fufu	275.5 (48.9)	47.6 (−73.8)	17.2 (22.6)
Fried maize	60.3 (75.0)	12.7 (62.6)	BDL
Cooked maize	98.6 (59.5)	18.1 (47.1)	BDL
Boiled cocoyam	403.8 (24.8)	BDL	BDL
Boiled Irish potato	493.6 (0.002)	21.1 (−97.2)	6.5 (62.2)
Boiled sweet potato	244.2 (42.4)	BDL	6.5 (81.8)
Fried groundnut	488.5 (22.6)	34.2 (−362.2)	BDL
Kulikuli	207.5 (48.0)	BDL	BDL
Boiled groundnut	268.5 (32.6)	19.1 (−158.2)	BDL
Boiled yam	468.1 (31.6)	21.3 (75.1)	BDL

BDL, below detection limit.

crops the values of the radionuclides varied from 36.4 Bq kg^{-1} to 186.9 Bq kg^{-1} for ^{40}K, 0.2 Bq kg^{-1} to 1.4 Bq kg^{-1} for ^{238}U and from 0.3 Bq kg^{-1} to 1.8 Bq kg^{-1} for ^{232}Th (Arogunjo, 2003). In cooked foods, the activity concentrations of ^{40}K, ^{238}U and ^{232}Th ranged between 60.32 Bq kg^{-1} and 493.63 Bq kg^{-1}, between BDL and 47.6 Bq kg^{-1} and between BDL and 17.2 Bq kg^{-1}, respectively. As shown in Table 4, there appears to be removal of radionuclides from foodstuffs during cooking when compared with the values in Table 3. The percent reductions ranged between 0.002 and 75% for ^{40}K, 9 and 75% for ^{238}U and 22 and 82% for ^{232}Th. However, there were also apparent increases in ^{238}U activities in some foodstuffs, indicated by negative 'percentage reduction' values. This may be due to the presence of ^{238}U in water used for cooking although this was not investigated as part of the present study but may be examined in future work. The overall conclusion from this part of the study is that cooking can have a major influence on the radionuclide composition of foodstuffs.

The activity concentrations of ^{40}K, ^{238}U and ^{232}Th measured in each of the soil samples from the farms indicate the quantity of radioactivity present but do not provide a measure of radiation risk in the form of an absorbed dose rate. The absorbed dose rate, D (nGy h^{-1}) in air at 1 m above ground level due to the presence of ^{238}U, ^{232}Th and ^{40}K in the soil samples at each site was calculated using the following equation (UNSCEAR, 2000):

$$D = aC_{\mathrm{U}} + bC_{\mathrm{Th}} + cC_{\mathrm{K}} + dC_{\mathrm{Cs}} \tag{2}$$

where a is the dose rate per unit ^{238}U activity concentration (4.27×10^{-10} Gy h^{-1}/Bq kg^{-1}), C_{U} is the concentration of ^{232}U in the sample (Bq kg^{-1}), b is the dose rate per unit ^{238}Th activity concentration (6.62×10^{-10} Gy h^{-1}/Bq kg^{-1}), C_{Th} is the concentration of ^{232}Th in the sample (Bq kg^{-1}), c is the dose rate per unit ^{40}K activity concentration (0.43×10^{-10} Gy h^{-1}/Bq kg^{-1}), C_{K} is the concentration of ^{40}K in the sample (Bq kg^{-1}), d is the dose rate per unit ^{137}Cs activity concentration (0.30×10^{-10} Gy h^{-1}/Bq kg^{-1}) and C_{Cs} is the concentration of ^{137}Cs in the sample (Bq kg^{-1}). Since ^{137}Cs was not detected in any of the samples the last term in Eq. (2) was assumed to be zero. The absorbed dose rate (nGy h^{-1}) in air at 1 m above the ground determined at each farm does not directly give the radiological hazard to which an individual is exposed. There are two additional factors that must be considered. The first is a factor which converts Gy to Sv that accounts for the biological effectiveness of the dose in causing damage in human tissue. The second is the occupancy factor that specifies the proportion of the total time spent outdoors. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recommended 0.7 Sv Gy^{-1} as the first factor and 0.2 as the second factor. According to Adejuwon (2002), an average of 10 h per day is spent by farmers from this area and generally for peasant farmers in the country. As such an outdoor occupancy factor of 0.4 ($\approx$10 h per day) has been assumed in this study. Using these assumptions, the total effective gamma dose due to radionuclides in the soil at the different farms investigated ranged between 0.07 μSv h^{-1} and 1.16 μSv h^{-1}, giving an annual external dose of 228 μSv and 4065 μSv, respectively. The aerial dose rates obtained using a survey meter were found to vary between 0.50 μSv h^{-1} and 1.47 μSv h^{-1}. The dose rate estimates from both in situ and soil measurements are in reasonable agreement and indicate dose rates 20× higher than the world average terrestrial value of 0.055 μSv h^{-1} (UNSCEAR, 2000). The major contributor to gamma radiation exposure in the area is ^{232}Th.

3.2. Effective dose due to ingestion

Effective dose is a useful concept that enables the radiation doses from different radionuclides and from different types and sources of radioactivity to be added. It is based on the risks of radiation induced health effects and the use of the International Commission on Radiological Protection (ICRP) metabolic model that provides relevant conversion factors to calculate effective doses from the total activity concentrations of radionuclides measured in foods (ICRP, 1994, 1996). Estimates of the radiation induced health effects associated with intake of radionuclides in the body are proportional to the total dose delivered by the radionuclides while resident in the various organs. Radiation doses ingested are obtained by measuring radionuclide activities in foodstuffs (Bq kg^{-1}) and multiplying these by the masses of food consumed over a period of time (kg d^{-1} or kg y^{-1}). A dose conversion factor (Sv Bq^{-1}) can then be applied to give an estimate of ingestion dose. Thus, according to Till and Moore (1988), the ingested dose is given by:

$$H_{\mathrm{T,r}} = \left(U^{\mathrm{Bl}}C_{\mathrm{r}}^{\mathrm{Bl}} + U^{\mathrm{Pf}}C_{\mathrm{r}}^{\mathrm{Pf}} + U^{\mathrm{Mi}}C_{\mathrm{r}}^{\mathrm{Mi}} + \cdots\right)g_{\mathrm{T,r}} \tag{3}$$

Eq. (3) can rewritten as:

$$H_{\mathrm{T,r}} = \sum\left(U^{i}C_{\mathrm{r}}^{i}\right)g_{\mathrm{T,r}} \tag{4}$$

where i denotes a food group, the coefficients U^i and C_{r}^i denote the consumption rate per year (kg) and activity concentration of the radionuclide (Bq), respectively, and $g_{\mathrm{T,r}}$ is the dose coefficient for intake by ingestion of radionuclide r (Sv Bq^{-1}). The values of g for ^{40}K, ^{238}U, ^{232}Th and ^{137}Cs are 5.9×10^{-9} Sv Bq^{-1}, 4.8×10^{-8} Sv Bq^{-1}, 2.3×10^{-7} Sv Bq^{-1} and 1.3×10^{-8} Sv Bq^{-1}, respectively, for adult members of the public (ICRP, 1994, 1996; RIFE, 2005). Using these conversion factors, the effective doses due to ingestion were estimated and these values are presented in Table 3. The food consumption statistics used for the different food crops in Nigeria, based on Federal Office of Statistics (FOS) and Food and Agriculture Organization (FAO) data, are presented in Table 5. In this study, the calculation of individual doses and risks from ingestion pathways carried out were based on the assumption that all food is consumed at the point of production and that the required amount of food is produced in the given location. In essence, foodstuffs are obtained wholly from local sources.

Table 5
The mean annual consumption (MAC) values per kg per person

Food type	MAC[a]
Maize	20.67
Millet	36.24
Rice	26.35
Guinea corn	44.70
Other cereals	0.60
Cassava	115.46
Irish potatoes	3.24
Sweet potatoes	14.35
Yam	75.15
Other roots	6.50
Wheat	18.55
Beans	0.02
Soya beans	2.58
Groundnut	2.76
Tomatoes	7.19
Pepper	8.06

[a] Data were collected from the Federal Office of Statistics Nigeria (2006).

Furthermore, in estimating doses to individuals from agricultural food products, it is usually important to consider the peculiarity of the food availability to such an individual and the nature of the environment from which he/she derives his/her food products. The three types of individual usually considered are:

(i) Control individuals whose diet consists of food grown on undisturbed soil.
(ii) Local individuals who obtain 10% of their food from a disturbed soil.
(iii) Theoretical 'maximally exposed' individuals whose diet is obtained solely from food grown on disturbed soil.

This study focuses on a mining area with disturbed soils and the assessment of dose is based on assumptions (ii) and (iii). From a radiation protection perspective, a conservative estimate of dose (assumption (iii)) is important in developing a Protective Action Guide (PAG) and in planning and legislation of food policy and administration (Fernandez et al., 2004). A PAG is defined as an action or measure taken to avoid exposure to radiation that would occur from future ingestion of foods contaminated with radioactive materials due to local or international releases.

The estimated total effective dose due to the intake of radionuclides varied from 0.2 $\mu Sv\ y^{-1}$ in local beans to 2164.1 $\mu Sv\ y^{-1}$ in yam. The tuber crops were found to deliver a higher ingestion dose than the other crop types. It is, however, expected that lower doses will be delivered after cooking and preparation of foodstuffs, as evident from the percent reductions in radionuclide activity concentrations shown in Table 4. Generally, the dose from ingestion of radionuclides can be considered to be low when compared with natural external exposures of about 2000 $\mu Sv\ y^{-1}$.

4. Conclusion

The effective dose due to ingestion of crops grown in an area of high background radiation (Bitsichi town, an old tin mining area on the Jos-Plateau, Nigeria) has been estimated based on measured activity concentrations of ^{40}K, ^{238}U and ^{232}Th in different food crops. The activity concentration of ^{40}K was highest in all the food crops and this could be due in part to the use of fertilizer by farmers to improve crop yields on the farms in the area. Tuber crops were found to deliver a higher ingestion dose than cereal crops which constitute the major food type of nutritional importance in the area under study. The external dose on the farms due to soil radioactivity and estimated ingestion dose related to local food products were relatively high when compared to studies in other parts of the country. However, they are considered to be sufficiently low to result in negligible harmful effects when dietary habits, food choices and occupancy times on local farms are taken into account.

Acknowledgement

The authors are grateful to the International Foundation for Science (IFS), Sweden, for providing the research grant used in carrying out this study under its food science programme. We are also grateful to the Department of Physics, University of Ibadan, Nigeria, for granting access to the gamma spectrometry system used in this study.

References

Adejuwon, C.O., 2002. Introduction to Crop Taxonomy, Anatomy and Physiology, first ed. Ibadan University Press, Nigeria.

Akinloye, M.K., Olomo, J.B., 2000. The measurement of the natural radioactivity in some tubers cultivated in farmlands within the Obafemi Awolowo University Ile-Ife, Nigeria. Nigerian Journal of Physics 12, 60–63.

Arogunjo, A.M., 2003. Natural radionuclides content of some local cereals in Akure, Southwestern Nigeria. Nigeria Journal of Pure and Applied Physics 2, 34–35.

Babalola, I.A., 1984. Radiation measurement and assay of tailing from high natural radioactivity in Plateau State. Nigerian Journal of Science 18, 98–101.

Banzi, F.P., Kifanga, L.D., Bundala, F.M., 2000. Natural radioactivity and radiation exposure at Minjingu phosphate mine in Tanzania. Journal of Radiological Protection 20, 41–51.

Farai, I.P., Ademola, J.A., 2001. Population dose due to building materials in Ibadan, Nigeria. Radiation Protection Dosimetry 95, 69–73.

Farai, I.P., Jibiri, N.N., 2000. Baseline studies of terrestrial outdoor gamma dose rate level in Nigeria. Radiation Protection Dosimetry 88, 247–250.

Fernandez, G., Rodriquez, I.M., Castro, G.V., Carrazana, G., Martizez, R.N., 2004. Radiological surveillance of foods and drinking water in the Cuban Republic. Proceedings of the 11th Conference of the International Radiation Protection Association (IRPA), Madrid, Spain, May 23–28.

Federal Office of Statistics Nigeria (FOS), 2006. Compilation of FOS/FAO annual consumption data/food balance sheet of Nigeria. A publication of Federal Office of Statistics (FOS), Nigeria.

Hernandez, F., Hernandez-Armas, J., Catalan, A., Fernandez-Aldecoa, J.C., Landeras, M.I., 2004. Activity concentrations and mean effective dose of foodstuffs on the Island of Tenerife, Spain. Radiation Protection Dosimetry 111, 205–210.

International Commission on Radiological Protection (ICRP), 1994. Dose Co-efficient for the Intakes of Radionuclides by Workers (ICRP Pub. No. 68). Pergamon Press, Oxford.

International Commission of Radiological Protection (ICRP), 1996. Age-Dependent Doses to Members of the Public from Intake of Radionuclides: Part 5. Compilation of Ingestion and Inhalation Dose Co-efficient (ICRP Pub. No. 72). Pergamon Press, Oxford.

Jibiri, N.N., 2001. Assessment of health risk associated with terrestrial gamma radiation dose rate levels in Nigeria. Environment International 27, 21–26.

Jibiri, N.N., Bankole, O.S., 2006. Soil radioactivity and radiation absorbed dose rates at roadsides in high-traffic density area in Ibadan Metropolis, southwestern, Nigeria. Radiation Protection Dosimetry 118, 453–458.

Maziya-Dixon, B., Akinyele, I.O., Oguntona, E.B., Sanusi, R.A., Harris, E., 2004. Nigeria Food Consumption and Nutrition Survey 2001—2003 (Summary). The International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria (Nigeria Food Survey 1, 1—75).

McDonald, P., Jackson, D., Leonard, D.R.P., McKay, K., 1999. An assessment of ^{210}Pb and ^{210}Po terrestrial foodstuffs from regions of potential technological enhancement in England and Wales. Journal of Environmental Radioactivity 43, 15—29.

Olayemi, J.K., 1998. Food Security in Nigeria. Research Report No. 2 — Series of Development Policy Center, Agodi, Ibadan, Nigeria.

Olomo, J.B., Akinloye, M.K., Balogun, F.A., 1994. Distribution of gamma emitting-natural radionuclides in soils and water around nuclear research establishments, Ile-Ife, Nigeria. Nuclear Instruments and Methods in Physics Research Section A 353, 553—557.

Omosaiye, O., 2001. A Report on Rural Private Sector Agro-industrial Development in Plateau State: Integrated Programme 4. United Nations Industrial Development Organizations: Institutional Strengthening for Economic Development (private sector support programme).

Oresegun, M.O., Babalola, I.A., 1990. Occupational radiation exposure associated with milling of Th—U rich Sn in Nigeria. Health Physics 58, 213—215.

Oresegun, M.O., Babalola, I.A., 1993. The environmental gamma radiation level of Jos, Nigeria. Nigerian Journal of Science 27, 263—268.

Pasquini, M.W., Alexander, M.J., 2005. Soil fertility strategies on the Jos Plateau: the need for integrating empirical and scientific knowledge in agricultural development. The Geographical Journal 171, 112—124.

Radioactivity in Food and the Environment (RIFE), 2005. The Centre for Environment, Fisheries and Aquaculture Science (CEFAS). Radioactivity in Food and the Environment, 2004 Report, RIFE-10.

Sanni, A.O., James, D., Schweikert, E.A., 1985. Radioactivity of the by-products of tin mining in Nigeria. Nigerian Journal of Science 20, 115—120.

Till, J.E., Moore, R.E., 1988. A pathway analysis approach for determining acceptable levels of contamination of radionuclide in soil. Health Physics 55, 541—548.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000. UNSCEAR 2000 Report to the General Assembly. United Nations, New York.

Yusuf, A.A., Amapu, I.Y., Eben-Johnson, A.F., Chude, V.O., 2004. The characteristics and fertility of tin mine spoils of the Jos Plateau, Nigeria. Nigerian Journal of Soil Research 5, 44—52.