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Natural radionuclides distribution, depth profiles of caesium-137 and risk assessment for soil samples in west regions of China

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Abstract
An analysis of natural radioactivity in soils collected around Chinese Nuclear Test site is presented. The radioactivities of ^{238}U, ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were determined by HPGe gamma-ray spectrometry, and potential radiological hazards were evaluated. The depth profiles of radionuclides in three selected areas of Gansu were analyzed, and a new method for detection of ^{137}Cs specific activities were measured using ultra-low background gamma spectrometer named GeTHU-II developed by Tsinghua University at China Jinping Underground Laboratory. The radioactivity concentrations of ^{137}Cs were significantly different in these three areas and gradually decreased from surface to underground 15 cm.

Keywords Natural radioactivity · Depth profiles · Soil · ^{137}Cs · Gamma spectrometry

Introduction

The harm of radionuclides in soil should not be ignored. Natural radioactivity in the environment is the main source of radiation exposure in the human body. In general areas, 67.7% of environmental radiation is related to soil. Radionuclides can enter the biological chain through the soil–plant system and eventually enter the human body to form a cumulative dose, which adversely affects the health of humans and animals, and affects the quality of water and air through the ecological cycle. According to UNSCEAR [1], natural radiation is the largest contributor to the external dose of the world population. The contributions of natural radionuclides ^{232}Th, ^{226}Ra, and ^{40}K to the level of background radiation are approximately 14%, 55.8% and 13.8%, respectively [2, 3]. Many surveys have been carried out regarding to the natural radioactivity level in soil [4–6]. The soil samples were collected from plateau tourism hotspots [7], tea garden [8], two sides of river, along the beach, two shipyards [9], area near a refinery area in Ras Tanura and around nuclear power plants [10, 11]. In addition to natural radionuclides, measurements of man-made radionuclides radioactivity in soil, especially ^{137}Cs, and assessment of the radiation doses are of great interest to the researchers. It is well known that the sources of soil nuclear pollution are nuclear tests, nuclear energy production, coal combustion and coal-fired power plants. From 1945 to 1980, a total of 543 atmospheric nuclear tests were carried out worldwide. And in China, 26 nuclear tests were conducted at Chinese Nuclear Test (CNT) site, 22 of which were atmospheric tests [12, 13]. ^{137}Cs is regarded as the most important constituent of global radioactive fallout, and its application in soil erosion measurement can rapidly yield detailed information on soil erosion, deposition, and spatial redistribution [14, 15]. Thus, the investigation about the distribution of natural radionuclides and ^{137}Cs in soil, especially around the nuclear test sites, is of great importance.

International investigations have been ongoing to estimate the distribution of long-lived radionuclides in the environment and radiation doses for people living in the vicinity of the nuclear test sites [16]. Four hundred mathematical models have been developed to predict parameters of soil–plant-animals transfer of ^{137}Cs and ^{90}Sr in agroecosystems as well as current doses of humans living in nearby settlements [17]. Although literature on regional radiation measurement in China is abundant [18, 19], there are very few specific studies related to natural

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and man-made radionuclides assessment from large scale surrounding area in recent years, especially around nuclear weapons test sites. Soil monitoring around nuclear test sites is, therefore, extremely useful for emergency preparedness as well as for environmental protection and human health. This study was done to determine the natural radioactivity concentrations in soil around Chinese Nuclear Test (CNT) site from Xinjiang, Tibet and Gansu province. In addition, the absorbed dose (D) in air, the radium equivalent (Ra_{eq}), the external hazard index (H_{ex}) and the internal hazard index (H_{in}), the annual effective dose equivalent (AED), the life time cancer risk (LTCR), and the depth profiles of radionuclides were obtained. The obtained results were compared with national and international mean values. The study will help establish the natural radiation background levels in the research region, keep abreast of the latest changes in radiation levels around nuclear weapon testing sites, assess the radiation risk for residents, and provide a scientific basis for international comparisons.

Experimental

Samples

The surface soil samples were collected from 15 sampling locations in 6 areas of Xinjiang, Tibet and Gansu province. Sampling was carried out in relatively open uncultivated areas, and topsoil with a vertical depth of 10 cm were adopted, generally within a range of 10 m × 10 m, using plum shaped distribution points or serpentine distribution points (no less than 5 sampling points) according to the terrain. Remove rocks, grass roots and other sundries from the soil collected at multiple points. After on-site mixing, take 2–3 kg of samples, seal them in a double-layer plastic bag, and then store them in a cloth bag of the same size. In addition, soils with depths of 0-5 cm, 5-10 cm, and 10-15 cm were collected in parts of Gansu Province using the similar method to that of surface soil collection. The ambient gamma dose rate in situ were measured during sampling at a height of 1 m above ground level by a 3″ × 3″ NaI(Tl) scintillation spectrometer (FH40G + FHZ672E−10, Thermo FISHER, USA), ranged from 45 to 126 nGy h^{-1}. In the laboratory, soil samples were dried in a drying oven at 105 °C for 24 h after removing stones and grass. The dried samples were then ground into fine powder and sieved with a 2 mm mesh screen. The sieved samples were sealed in a 300 mL cylindrical plastic container (75 mm diameter by 70 mm height) at least four weeks before analysis so as to attain a long-term radioactive equilibrium between ^{226}Ra and ^{232}Th with their daughters.

Radioactivity analysis

When these soil samples were analyzed, ^{226}Ra activity of the samples was determined by its daughters (^{214}Pb and ^{214}Bi) through the intensity of the 351.9 keV and 609.3 keV gamma lines. ^{232}Th activity was obtained through the ^{208}Tl and ^{228}Ac emissions at 583.1 keV and 911.1 keV, respectively. ^{40}K and the artificial radionuclide ^{137}Cs were measured directly using its 1460 keV and 661 keV gamma ray line, respectively. Samples were measured by HPGe detector and a multichannel analyzer with 8192 channels.

^{137}Cs specific activities in part depth profiles samples were measured using an ultra-low background gamma spectrometer, named GeTHU-II. The spectrometer was equipped with a Broad Energy Germanium Detector (BEGe, Canberra) detector (91.10 mm, h31.60 mm) reaching minimum detectable activities (MDA) as low as 1.0 mBq kg^{-1}. The GeTHU-II spectrometer was developed by Tsinghua University in the China Jinping Underground Laboratory (CJPL). CJPL is located in the middle of the 17.5 km Jinping tunnel, it is an underground research facility in Sichuan province with the deepest rock overburden in the world, covering about 2400 meters of rock. A shield containing 20 cm thick lead bricks, 20 cm thick plastic plates, and 5 cm thick copper plates was used to reduce background radiation. In the CJPL laboratory the muon flux is $(2.0 \pm 0.4) \times 10^{-10}$ cm^{-2} s^{-1} measured at the depth of 6720 m.w.e (water equivalent meter) [20]. The integral background count rates (40-2700 keV) varied from 3.76 to 74.1 cps, and the average count rate measured within the CJPL is 73.4 cps [21]. The detector has a relative efficiency of 67% (relative to a 3″ × 3″ NaI(Tl) crystal), has a resolution of 1.67 keV for 1332.5 keV gamma-ray transition of ^{60}Co, with a peak to Compton ratio of 74.2 (30-2700 keV) and background continuum rate of 0.2 cpm.

Gamma spectrometry analytical techniques were used to determine the natural and artificial radionuclides ^{238}U, ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs. The spectrometer used for the soil analyses from Tibet was a GEM50195 type (ORTEC®), with an efficiency of 51% and resolution of 1.9 keV. The software GammaVision® was used to spectral analysis.

Geometric efficiency for soil matrices in the cylindrical plastic container was determined by a reference soil material (National Institute of Metrology, Beijing, China), spiked with a series of radionuclides (^{241}Am, ^{109}Cd, ^{57}Co, ^{139}Ce, ^{131}I, ^{133}Ba, ^{51}Cr, ^{134}Cs, ^{137}Cs, ^{54}Mn, ^{88}Y, ^{65}Zn, ^{60}Co, ^{22}Na, ^{40}K), its product code is 14NTR/70-080503. A broad-energy type High Purity Germanium (HPGe) gamma spectrometry consisting of detector named BE5030 were also used to analysis soil samples, with the relative efficiency of 50.5%, and a resolution of 1.88 keV for the 1332 keV ^{60}Co peak. The program GENIE 2000 was used to analyze the spectra.

Table 1 The sample information and radioactivity concentration of the soil samples from Gansu, Xinjiang and Tibet [26–30]

Site no.	Activity concentration (Bq kg^{-1})				
	^{238}U	^{226}Ra	^{232}Th	^{137}Cs	^{40}K
Jiuquan, Guazhou					
1	18.2 ± 1.3	17.0 ± 1.4	22.0 ± 1.6	1.3 ± 0.1	339 ± 25
2	18.7 ± 1.4	18.3 ± 1.4	24.4 ± 1.8	3.2 ± 0.2	384 ± 28
3	61 ± 5	24.8 ± 1.9	25.5 ± 1.9	ND(0.34)	409 ± 30
4	37.0 ± 2.7	40.7 ± 3.2	67 ± 5	27 ± 2.0	645 ± 47
Jiuquan, Dunhuang					
5	12.1 ± 0.9	10.7 ± 0.8	22.7 ± 1.7	ND(0.38)	403 ± 29
6	21.1 ± 1.5	13.2 ± 1.0	25.3 ± 1.8	ND(0.41)	513 ± 37
7	16.8 ± 1.2	20.7 ± 1.6	26.6 ± 1.9	4.4 ± 0.3	453 ± 33
8	19.2 ± 1.4	18.6 ± 1.4	24.4 ± 1.8	6.3 ± 0.5	602 ± 44
9	17.7 ± 1.3	17.9 ± 1.4	25.3 ± 1.8	3.1 ± 0.2	547 ± 40
10	23.3 ± 1.7	17.7 ± 1.4	36.9 ± 2.7	2.7 ± 0.2	644 ± 47
11	21.9 ± 1.6	25.0 ± 1.9	32.5 ± 2.4	10.7 ± 0.8	473 ± 35
12	19.4 ± 1.4	18.0 ± 1.4	23.8 ± 1.7	ND(0.32)	441 ± 32
13	25.0 ± 1.8	16.5 ± 1.2	30.9 ± 2.2	1.0 ± 0.1	439 ± 32
14	ND(16.45)	13.7 ± 1.1	31.2 ± 2.3	3.1 ± 0.2	523 ± 38
Bayingguole, Heshuo					
15	ND(30.2)	22.9 ± 1.7	30.8 ± 2.4	0.7 ± 0.1	564 ± 41
16	ND(28.6)	16.4 ± 1.2	29.1 ± 2.2	2.3 ± 0.2	703 ± 51
17	41.7 ± 3	35.3 ± 2.7	81 ± 6	18.9 ± 1.4	705 ± 51
18	50 ± 4	38.5 ± 2.7	88 ± 7	13.9 ± 1	683 ± 50
Bayingguole, Yuli					
19	ND(30.1)	15.6 ± 1.1	28.1 ± 2.2	16.9 ± 1.2	560 ± 41
Bayingguole, Bohu					
20	ND(21.8)	4.76 ± 0.3	13.6 ± 1.1	0.8 ± 0.1	483 ± 35
Tibet, Lhasa					
21	47.0 ± 11.7	40.6 ± 2.8	73 ± 6	2.0 ± 0.4	685 ± 44
22	57.8 ± 13.6	36.6 ± 2.4	72 ± 6	4.2 ± 0.6	685 ± 44
23	41.6 ± 11.4	41.5 ± 2.8	80 ± 6	ND(0.52)	688 ± 43
24	59.0 ± 11.3	41.5 ± 2.8	77 ± 6	5.4 ± 0.6	692 ± 45
25	10.4 ± 10.5	35.1 ± 2.4	74 ± 6	0.2 ± 0.1	700 ± 46
Tibet, Linzhi					
26	46.7 ± 12.4	30.9 ± 2.0	83 ± 6	3.8 ± 0.4	528 ± 34
27	54.7 ± 13.6	39.2 ± 2.6	75 ± 5	4.1 ± 0.6	537 ± 36
28	52.6 ± 11.9	28.1 ± 1.8	71 ± 6	2.6 ± 0.4	650 ± 42
29	49.7 ± 11.8	52.4 ± 3.4	82 ± 6	2.4 ± 0.4	625 ± 40
30	40.0 ± 12.2	53.2 ± 3.6	82 ± 6	3.1 ± 0.4	666 ± 44
31	43.0 ± 9.7	22.9 ± 1.6	58 ± 4	2.1 ± 0.4	531 ± 34
32	53.3 ± 12.2	46.7 ± 3.0	77 ± 5	1.1 ± 0.4	727 ± 48
33	41.3 ± 11.3	40.7 ± 2.8	70 ± 4	0.7 ± 0.2	680 ± 44
34	37.7 ± 10.2	31.7 ± 2.2	57 ± 4	0.02 ± 0.1	544 ± 36
35	40.2 ± 12.3	35.2 ± 2.4	70 ± 5	12.7 ± 1.0	651 ± 42
Range	ND-61.0	4.8–53.2	13.6–88	ND-27.0	339–727
Median	37.0	25.0	57.0	2.6	564
Average	32.6	28.1	51.2	4.6	574
China	33	32	41	–	440
Iran	–	24.3	25.8	–	457.7
Lima	–	25.8	40.3	1.5	632
Karbala	–	33.35	38.28	5.52	430.27
Molise	31	–	41	–	468
Worldwide	37	34	33	–	419

ND not detected, numbers inside parenthesis indicate the detection limit

The activity concentration in Bq kg^{-1} in the topsoil samples was calculated according to the following equation.

$$A = \frac{(n_s/T_s - n_b/T_b)}{\varepsilon \times \eta \times m} \quad (1)$$

where A is the activity concentration in Bq kg^{-1} in a sample; n_s and n_b are the net count under the selected photopeaks of the sample and background, respectively; T_s and T_b are the spectrum live time of the sample and background, respectively; ε is the absolute transition probability for the gamma line in the radionuclide; η is the detection efficiency for the selected gamma line for the sample or for the calibration source and m is the dry mass of the sample (in kilogrammes).

In order to determine the background distribution of the environment around the detector, a blank sample was counted in the same way and the geometry of the background spectra was used to correct the net peak areas of the gamma-rays of the isotopes. A counting time of 86,400 s was set for activity and background.

The Minimum Detectable Concentration (MDC) is the minimum detectable activity concentration of low-background high-purity germanium gamma spectroscopy. The MDC was calculated according to Eq. (2).

$$\mathrm{MDC} = \frac{4.66}{\varepsilon \times \eta \times m}\sqrt{n_b/T_b} \quad (2)$$

where MDC is minimum detectable activity concentration in Bq kg^{-1} in a sample, providing a level of confidence of approximately 95%; n_b is the net count under the selected photopeaks of the background; T_b is the spectrum live time of the background. ε is the absolute transition probability for the gamma line in the radionuclide; η is the detection efficiency for the selected gamma line for the sample or for the calibration source and m is the dry mass of the sample (in kg).

Potential radiological hazards

Potential radiological hazards were assessed by calculating the absorbed dose rate (D) [22], the annual effective dose equivalent (AED) [22], the radium equivalent activity (Ra_{eq}) [23], the external hazard index (H_{ex}) and the internal hazard index (H_{in}) [23], and the life time cancer risk (LTCR) [24].

Table 2 Potential radiological hazards estimated by measuring the soil samples from Gansu, Xinjiang, Tibet

Location	Code	*D* (nGy/h)	AED(μSv/y)	Ra_{eq}	H_{ex}	H_{in}	LTCR
Jiuquan, Guazhou	1	35.3	43.2	75	0.20	0.25	1.66E−04
	2	39.2	48.1	83	0.22	0.27	1.85E−04
	3	43.9	54	93	0.25	0.32	2.07E−04
	4	86	106	186	0.50	0.61	4.07E−04
Jiuquan, Dunhuang	5	35.5	43.5	74	0.20	0.23	1.67E−04
	6	42.8	52	89	0.24	0.28	2.02E−04
	7	44.5	55	94	0.25	0.31	2.10E−04
	8	48.4	59	100	0.27	0.32	2.29E−04
	9	46.3	57	96	0.26	0.31	2.19E−04
	10	57	70	120	0.32	0.37	2.71E−04
	11	51	62	108	0.29	0.36	2.40E−04
	12	41.1	50	86	0.23	0.28	1.94E−04
	13	44.6	55	95	0.26	0.30	2.11E−04
	14	47.0	58	99	0.27	0.30	2.22E−04
Mean ± SD		47.4 ± 12.1	58 ± 15	100 ± 27	0.27 ± 0.07	0.32 ± 0.09	2.24E−04 ± 5.74E−05
Median		44.6	55	94	0.26	0.31	2.11E−04
Range		35.3–86	43.2–106	74–186	0.20–0.50	0.23–0.61	1.66E−04–4.07E−04
Bayingguole, Heshuo	15	53	65	110	0.30	0.36	2.49E−04
	16	47.5	58	99	0.27	0.31	2.24E−04
	17	30.6	37.5	61	0.17	0.18	1.44E−04
	18	54	67	112	0.30	0.35	2.57E−04
Bayingguole, Yuli	19	94	116	205	0.55	0.65	4.46E−04
Bayingguole, Bohu	20	100	122	218	0.59	0.69	4.71E−04
Mean ± SD		63 ± 25	78 ± 31	134 ± 57	0.36 ± 0.15	0.42 ± 0.18	2.99E−04 ± 1.19E−04
Median		54	66	111	0.30	0.36	2.53E−04
Range		30.6–100	37.5–122	61–218	0.17–0.59	0.18–0.69	1.44E−04 - 4.71E−04
Tibet, Lhasa	21	91	112	198	0.53	0.64	4.32E−04
	22	89	109	192	0.52	0.62	4.20E−04
	23	96	118	209	0.56	0.68	4.54E−04
	24	94	116	204	0.55	0.66	4.45E−04
	25	90	110	194	0.53	0.62	4.25E−04
Tibet, Linzhi	26	86	106	190	0.51	0.60	4.07E−04
	27	86	106	188	0.51	0.61	4.06E−04
	28	83	101	179	0.48	0.56	3.91E−04
	29	100	122	217	0.59	0.73	4.70E−04
	30	102	125	222	0.60	0.74	4.82E−04
	31	68	83	146	0.40	0.46	3.19E−04
	32	98	121	213	0.57	0.70	4.65E−04
	33	89	110	193	0.52	0.63	4.22E−04
	34	72	88	155	0.42	0.50	3.39E−04
	35	85	105	185	0.50	0.59	4.03E−04
Mean ± SD		89 ± 9	109 ± 11	192 ± 20	0.52 ± 0.05	0.62 ± 0.07	4.19E−04 ± 4.36E−05
Median		89	110	193	0.52	0.62	4.22E−04
Range		68–102	83–125	146–222	0.40–0.60	0.46–0.74	3.19E−04–4.82E−04
Mean ± SD		67.77 ± 23.69	83.12 ± 29.05	145.34 ± 53.11	0.39 ± 0.14	0.47 ± 0.17	3.20E−04 ± 1.12E−04
Median		67.60	82.90	146.36	0.40	0.46	3.19E−04
Range		30.55–101.99	37.47–125.08	61.40–221.99	0.17–0.60	0.18–0.74	1.44E−04–4.82E−04

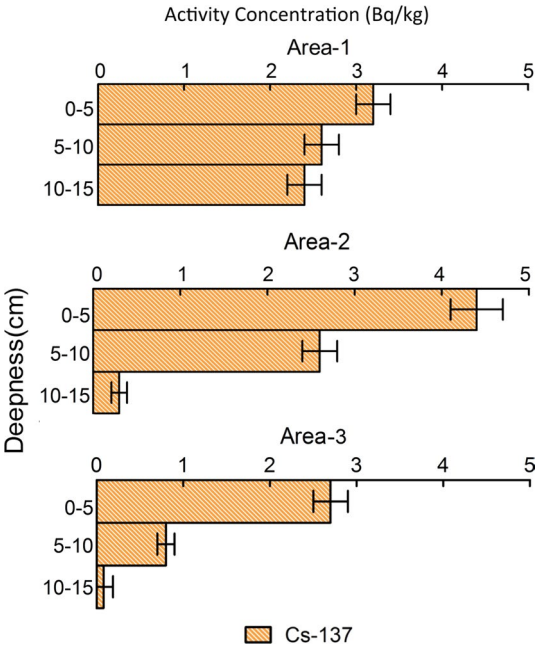

Fig. 1 Depth profiles of radionuclides ^{137}Cs in soil at selected area of Gansu

The external dose rates due to radionuclides in soil were calculated from the measured activities of ^{226}Ra, ^{232}Th and ^{40}K in soil. Absorbed gamma dose rate in the air at 1 m above the ground level were calculated by Eq. (3) [22].

$$D = 0.0417C_K + 0.462C_{Ra} + 0.604C_{Th} \quad (3)$$

where D is the absorbed dose rate in air (nGy h^{-1}); the coefficients 0.0417, 0.462 and 0.604 are the dose conversion factors (nGy h^{-1} per Bq kg^{-1}) for the ^{40}K, ^{238}U and ^{232}Th series, respectively, and C_K, C_{Ra} and C_{Th} are obtained the activity concentrations of the mentioned isotopes in soil (Bq kg^{-1}) for ^{40}K, ^{238}U and ^{232}Th, respectively. It is assumed that all the decay products of ^{226}Ra and ^{232}Th are in radioactive equilibrium with their precursors, as well as a negligible contribution of the artificial radionuclide ^{137}Cs and other isotopes (members of ^{235}U chain, ^{87}Rb, etc.) to the human exposure, and these were not included in the calculation.

The annual effective dose was calculated by the following Eq. (4).

$$\mathrm{AED} = D \times T \times f \times C_C \times 10^{-3} \quad (4)$$

where AED is annual effective dose (μSv/y); D is the absorbed γ dose rate (nGy/h); T means the term of 1 year expressed in hours, 8760 h/year is equal to 365 days × 24 h per year; f is the fraction of time spent outdoors by inhabitants of the considered area corresponds to 0.2; C_c is for the conversion coefficient from absorbed dose in air to effective dose received by adults, amount to 0.7 Sv/Gy.

Owing to exploitation of the natural resources (soil, sand, etc.), it is important to assess radiological hazard connected with the use of studied samples as a source of building materials. Radium equivalent activity was calculated by Eq. (5). The Ra_{eq} should not exceed 370 Bq kg^{-1} and the H_{ex} should be less than unity [23].

$$\mathrm{Ra_{eq}} = C_{Ra} + 1.43 \times C_{Th} + 0.077 \times C_K \quad (5)$$

The hazard risk due to external (H_{ex}) from gamma rays was expressed by the following index of Eq. (6), internal hazard index (H_{in}) is introduced to describe the hazard of radon and its short-lived products in building material, given by the Eq. (7) and recommended to be less than unity [23].

$$H_{ex} = C_{Ra}/370 + C_{Th}/259 + C_K/4810 \quad (6)$$

$$H_{in} = C_{Ra}/185 + C_{Th}/259 + C_K/4810 \quad (7)$$

The life time cancer risk (LTCR) was obtained by Eq. (8) [24]:

$$\mathrm{LTCR} = \mathrm{AED} \times \mathrm{DL} \times \mathrm{RFSE} \quad (8)$$

where DL is the duration of life time, 70 years; and RFSE is the risk factor for stochastic effects of the common population, 0.055/Sv [25].

Results and discussion

Activity concentrations

Results of gamma spectrometry measurements for ^{238}U, ^{226}Ra, ^{232}Th, ^{137}Cs and ^{40}K are presented in Table 1. The activity concentrations of above-mentioned radionuclides in soil samples range from ND (Not Detected) to 61.0 Bq kg^{-1}, 4.8 to 53.2 Bq kg^{-1}, 13.6 to 88 Bq kg^{-1}, ND to 27.0 Bq kg^{-1} and 339 to 727 Bq kg^{-1}, respectively, with average values of 32.6, 28.1, 51.2, 4.6 and 574 Bq kg^{-1}, respectively. The obtained results were also compared with data from Iran [26], Lima [27], Karbala [28], Molise [29], and UNSCEAR [30].

Exposure from radionuclides

The absorbed γ dose rate in air, annual effective dose, hazard indices and life time cancer risk calculated from radionuclides in soil samples are shown in Table 2. The calculated mean outdoor γ dose rates is 67.77 nGy·h^{-1}, which is lower

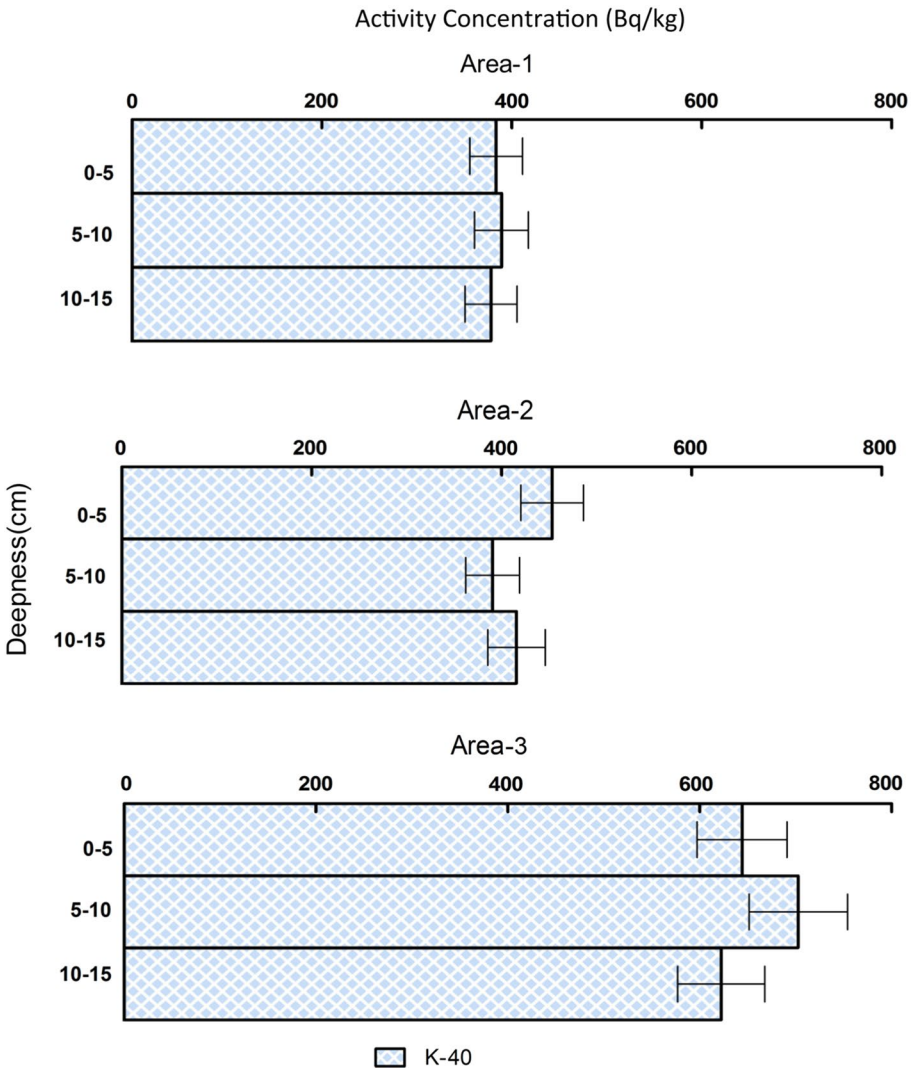

Fig. 2 Depth profiles of radionuclides ^{40}K in soil at selected area of Gansu

than Chinese average of 81.5 nGy/h, but higher than the worldwide mean value of 58 nGy/h [30]. The mean value of radium equivalent activity is 145.34 Bq kg^{-1}, lower than the reference 370 Bq kg^{-1}. The external and internal hazard indices doesn't exceed unity, which indicates that the γ radiation of soil is at a safe level. The life time cancer risk is 3.20 E−04/Sv, which is also at a very low level.

Depth profiles of radionuclides

Depth profiles of radionuclides in selected area of Gansu are illustrated in Figs. 1, 2 and 3 for ^{137}Cs, ^{40}K and ^{238}U, ^{226}Ra, ^{232}Th. There is a significant difference about ^{137}Cs activity concentration among these three areas ($\chi^2 = 6.5$, $P = 0.039$), and the ^{137}Cs activity concentration decreases with the increase of soil depth from surface to underground 15 cm. However, there is no correlation between the activity concentrations of other radionuclides and the depth of soil. The change rules in activity concentration of ^{40}K, ^{238}U, ^{226}Ra and ^{232}Th has not been observed.

Conclusions

For the purpose of this study, the surface soil samples were collected from 15 sampling locations in 6 areas of Xinjiang, Tibet and Gansu province. The gamma activity of natural radionuclides ^{238}U, ^{226}Ra, ^{232}Th, ^{137}Cs and ^{40}K was estimated using gamma spectrometry system with NaI (Tl) detector. The results indicated that the range of natural radioactivity concentrations of ^{238}U and ^{226}Ra were consistent with data from other countries or regions. The ^{232}Th and ^{40}K activity concentrations were higher than the worldwide and Chinese activity concentrations reported by UNSCEAR (2008), and the average of the ^{226}Ra activity concentrations was relatively lower than the corresponding

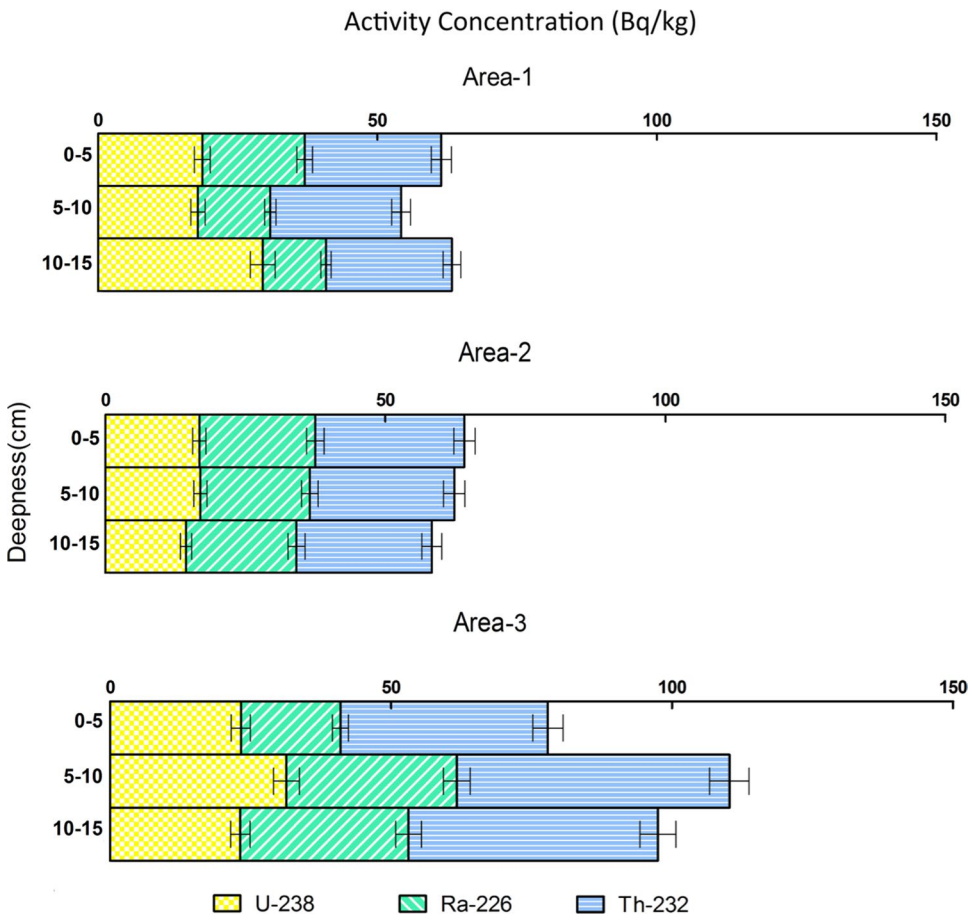

Fig. 3 Depth profiles of radionuclides ^{238}U, ^{226}Ra and ^{232}Th in soil at selected area of Gansu

Chinese and world activity values. Except for ^{137}Cs activity concentration, there are significant differences among Gansu, Xinjiang and Tibet region about ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K activity concentrations. The active concentrations of ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K in Tibet soil are higher than those in Gansu and Xinjiang. The similarity of ^{137}Cs activity values in Gansu, Xinjiang and Tibet suggests that the source of ^{137}Cs in soil is due to the nuclear tests conducted in the northern hemisphere.

Potential radiological hazards data indicate that the potential radioactive risks caused by radioactivity are within acceptable limits in the survey area, which could alleviate public concerns about the effects of soil radioactivity.

Through the analysis of the depth profile of radionuclides in selected areas of Gansu, it was found that the vertical distribution of ^{137}Cs in the topsoil is as follow: from the surface to the ground 15 cm, as the soil depth increases, the radioactive concentration gradually decreases. Thorring et al. [31] found that the depth distribution of fallout ^{137}Cs was not significantly affected by the chemical composition of precipitation, which also indicates that the source of ^{137}Cs in the soil around the nuclear test region is only due to the nuclear tests performed in the northern hemisphere and not to any local nuclear source. Due to the depth of the soil sampling is not deep enough, the variation of radioactivity concentrations of ^{40}K, ^{238}U, ^{226}Ra and ^{232}Th cannot be found.

The results can be used as reference data for radiation assessment in western China and provide baseline data for studies of natural radionuclides and artificial radionuclides in the region.

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Compliance with ethical standards

Conflict of interest No conflicts of interest were reported.

References

1. UNSCEAR (2000b) Report to the general assembly, with scientific annexes, vol 1: Sources. UNSCEAR: New York
2. Bavarnegin E, Fathabadi N, Moghaddam MV, Farahani MV, Moradi M, Babakhni A (2013) Radon exhalation rate and natural radionuclide content in building materials of high background areas of Ramsar, Iran. Environ Radioact 117:36–40

3. Bozkurt A, Yorulmaz N, Kam E, Karahan G, Osmanlioglu AE (2007) Assessment of environmental radioactivity for Sanliurfa region of southeastern Turkey. Radiat Meas 42(8):1387–1391
4. Kilicaslan S, Oner F, Yigitoglu I, Yamcicier S, Akkurt I, Eser E, Gursoy G, Koc H, Cetin B (2018) Determination of natural radioactivity levels in soil and travertine of the region of Tokat and Sivas, Turkey. Arab J Geosci 11(128):1–7
5. Lotfalinez P, Kashian S, Kotahi MS, Fathivand A (2017) Estimation of natural radioactivity and radiation exposure in environmental soil samples of Golestan, Iran. Iran J Med Phys 14:98–103
6. Rajesh S, Kerur BR (2019) Assessment of natural radioactivity levels due to 238U, 232Th, and 40 K in the soil samples of Raichur district, Karnataka, India. Radiat Prot Environ 41(1):51–54
7. Bakar ASA, Zaini H, Ahmad S (2017) Measurements of natural radioactivity in soil of Fraser's hill, Pahang, Malaysia. AIP Conf Proc 1799(030009):1–10
8. Miah A, Miah MMH, Kamal M, Chowdhury MI, Rahmatullah M (2012) Natural radioactivity and associated dose rates in soil samples of Malnichera tea garden in Sylhet district of Bangladesh. J Phys G Nucl Partic 2(6):147–152
9. Uddin S, Barua BS, Shariff A, Hasan M, Rashid A, Kamal M (2014) Investigation of elemental and radiological contamination of soils in two shipyards in Chittagong, Bangladesh. Radiochim Acta 102(8):741–749
10. Alashahri F, Taher AE (2019) Investigation of natural radioactivity levels and evaluation of radiation hazards in residential-area soil near a ras Tanura refinery, Saudi Arbia. Pol J Environ 28(1):25–34
11. Luan YX, Ma ZH, Pan LG (2012) Establishion of radioactive contamination monitoring network and bioremediation of the soil around the nuclear facilities in China. Trans Tech Publ 347–353:512–521
12. Ren T, Zhang S, Li Y, Zhong ZQ, Su XuC, Tang X (1998) Methodology of retrospective investigation on external dose of the downwind area in JiuQuan region, China. Radiat Prot Dosim 77(1/2):25–28
13. Bu W, Ni Y, Guo Q, Zheng J, Uchida S (2015) Pu isotopes in soils collected downwind from Lop Nor: regional fallout vs. global fallout. Sci Rep UK 5:12262
14. Liu C, Li S, Wang Z, Guo Z, Zhao Y, Li Z, Jiang L (1997) Migration of radionuclides ^{85}Sr, $^{134/137}$Cs and ^{60}Co in unsaturated Chinese loess. Radiochim Acta 76:91–95
15. Hosseinali M, Ahmadi H, Feiznia S, Rivaz F, Naseri S (2017) Multivariate geostatistical analysis of fallout radionuclides activity measured by in situ gamma-ray spectrometry case study: loessial paired sub-catchments in northeast Iran. Quatern Int 429:108–118
16. Evseeva T, Belykh E, Geraskin S, Majstrenko T (2012) Estimation of radioactive contamination of soils from the "Balapan" and the "Experimental field" technical areas of the Semipalatinsk nuclear test site. J Environ Radioact 109:52–59
17. Baranov SA, Mukusheva MK, Spiridonov SI (2009) Application of GIS technologies for analysis of radioecological condition at the STS. In: Book of reports of the joint ISTC-IAEA workshop, Vienna, 15–18 June, pp 23–26
18. Liu XM, Lin WH (2018) Natural radioactivity in the beach sand and soil along the coastline of Guangxi Province, China. Mar Pollut Bull 135:446–450
19. Shao Y, Yang GS, Xu DD, Yamada M, Tazoe H, Luo M, Cheng HX, Yang K, Ma LL (2019) First report on global fallout ^{236}U and uranium atom ratios in soils from Hunan province, China. J Environ Radioact 197:1–8
20. Wu YC, Hao XQ, Yue Q, Li YJ, Cheng JP, Kang KJ, Chen YH, Li J, Li JM, Li YL, Liu SK, Ma H, Ren JB, Shen MB, Wang JM, Wu SY, Xue T, Yi N, Zeng XH, Zeng Z, Zhu ZH (2013) Measurement of Cosmic Ray Flux in China JinPing underground Laboratory. Chin Phys C 37(8):45–49
21. Zeng Z, Su J, Ma H, Yi HG, Cheng JG, Yue Q, Li JL, Zhang H (2014) Environmental gamma background measurements in China Jinping Underground Laboratory. J Radioanal Nucl Chem 301(2):443–450
22. UNSCEAR (2000) Sources and effects of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, Report to the General Assembly. UNSCEAR: New York
23. Korkulu Z, Özkan N (2013) Determination of natural radioactivity levels of beach sand samples in the black sea coast of Kocaeli (Turkey). Radiat Phys Chem 88:27–31
24. Sergio LG, Angelica PT, Carmelo PA, Jorge CF, Maria MC, Marusia RV (2015) Lifetime effective dose assessment based on background outdoor gamma exposure in Chihuahua city, Mexico. Int J Environ Res 12:12324–12339
25. ICRP (2007) The 2007 Recommendations of the International Commission on Radiological Protection Publication 103. Elsevier, Amsterdam
26. Kardan MR, Fathabdi N, Attarilar A, Esmaeili-Gheshlaghi MT, Karimi M, Najafi A, Hosseinib SS (2017) A national survey of natural radionuclides in soils and terrestrial radiation exposure in Iran. J Environ Radioact 178–179:168–176
27. Luciana-Mo M, Mercader RC, Taylor MA (2016) Activities of ^{232}Th, ^{226}Ra, ^{40}K and ^{137}Cs in surface soil and external dose assessment at two zones of Buenos Aires Province, Argentina. Environ Earth Sci 75:320
28. Pourimani R, Mortazavi-Shahroodi MM (2018) Radiological assessment of the artificial and natural radionuclide concentrations of wheat and bareley samples in Karbala, Iraq. Iran J Med Phys 15:126–131
29. Matthias L, Wolfango P, Pavel P, Valeria F, Piergiorgio A, Marco B, Francesco B, Angela C, Massimiliano DD, Benedetto G, Luca I, Stefano N, Diego A, Christian DP, Giuseppe G (2013) Radionuclide mapping of the Molise region (Central Italy) via gamma-ray spectrometry of soil samples: relationship with geological and pedological paraments. J Radioanal Nucl Chem 298:317–323
30. UNSCEAR (2008) Sources and effects of ionizing radiation, Report of General Assembly with Scientific Annexes. UNSCEAR, New York
31. Thorring H, Skuterud L, Steinnes E (2014) Influence of chemical composition of precipitation on migration of radioactive caesium in natural soils. J Environ Radioact 134:114–119