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ORIGINAL ARTICLE

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

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Abstract In the frame of establishing the radiological baseline of the Buenos Aires Province, Argentina, this work assesses the total outdoor external dose and the activity values of ^{40}K, ^{226}Ra, ^{232}Th and ^{137}Cs in superficial soils of La Plata and Lima cities. In the latter, the most important nuclear emplacement of the country is located. At La Plata, 49 sites were analyzed, which correspond to the green public spaces of the city while at Lima 6 sites around the nuclear power plants were studied. For La Plata, the external dose contribution and activity distribution maps of ^{40}K, ^{226}Ra, ^{232}Th and ^{137}Cs were obtained using the Kriging geo-statistical method. Activity values of ^{226}Ra and ^{232}Th resulted lower than their worldwide average ones, while the ^{40}K levels were higher than the corresponding one. The activity dataset was analyzed together with the activity values determined previously in unperturbed soils of the region. The Pearson correlation coefficient was re-calculated, obtaining correlations more significant when all activity data were considered. No correlation between activity superficial distributions and the height above sea level or the geomorphological units was found. The activity values obtained in Lima soils lie in the range of the values determined for La Plata soils. Like in La Plata, ^{137}Cs activity around the nuclear facility could be associated only with the nuclear power tests. The average total external annual dose for La Plata inhabitants are in the range of 0.19 to 0.25 mSv/year, similar to those determined for Lima residents. The present work complements previous reports contributing to the establishment of the radiological baseline for soils of Buenos Aires Province, Argentina, the province with the most important nuclear activities of the country.

Keywords Soil radioactivity · Total outdoor external dose · Surface distribution · Radiological baseline · Argentina

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Introduction

Nuclear power plants and other nuclear facilities release radionuclides into the environment, which may be a health hazard (Cho et al. 2014). To sort out the emitted man-made ionizing radiations from natural ones it is essential to build regional radiological maps and determine the radiological baseline around nuclear facilities before their operation. It is also important to assess the natural exposition dose of the inhabitants as a reference to compare with radiological levels during normal operation or after a possible accident.

Although Argentina has set in motion its nuclear plan (ARN 2014), the environmental radiological studies in the country are scarce. In the case of Buenos Aires Province, where several nuclear facilities are located, only four works are found in literature. These are: the ^{137}Cs activity studies at San Pedro soils published by Bujan et al. (2003), activity levels of ^{40}K, ^{232}Th, ^{226}Ra and ^{137}Cs reported for unperturbed soils at La Plata and Ezeiza (Montes et al. 2012, 2013) and, close to the nuclear power plants and nuclear facilities at Lima, only ^{137}Cs soils activities (ARN 2011).

The start-up of a new nuclear power plant at Lima and the plans to build another one at the same place (Nucleoeléctrica Argentina 2014) make relevant the analysis of soil samples at Lima before the expansion of the nuclear facilities.

This work reports the ^{40}K, ^{232}Th, ^{226}Ra and ^{137}Cs activities of the top 10 cm of La Plata and Lima urban soils. The total external doses measured in situ with a Geiger-Müller detector and the calculated outdoors annual committed effective dose (ACED), obtained from the radionuclide activities are also reported. The start-up of a new nuclear power plant at Lima and the plans to build another one at the same place (Nucleoeléctrica Argentina 2014) make relevant the analysis of soil samples at Lima before the expansion of the nuclear facilities. In addition, this work contributes to complete the monitoring of surface soils at La Plata and at the surroundings of nuclear facilities in the Buenos Aires Province by comparing the current results with previous studies (Montes et al. 2012, 2013) and determining new correlation coefficients.

Materials and methods

Studied regions

Figure 1a shows the studied region in Buenos Aires Province, Argentina. The nuclear facilities next to Lima (approximately 10,000 inhabitants; INDEC 2010) are located at $\approx$100 km to the northwest of Buenos Aires, Argentine capital, beside the Parana River (Fig. 1b). La Plata is the capital city of the Province and it is at 56 km to the southeast of Buenos Aires city. La Plata has a territorial surface of 942 km^2 and an estimated population of 740,000 (INDEC 2010). The city has quite a few green parks, a beltway recreation area and many squares; each square is separated by six blocks to the next one (Municipalidad de La Plata 2014). In the urban area, the altitude varies from 5 to 25 m above sea level and several geomorphological units are identified: convex ridgeline (CR), old inner estuary (OIE), sloping area (SA) and floodplain (F) (Hurtado et al. 2006). Figure 1c displays the geomorphological units for each sampling point at La Plata.

Soil sampling and experimental techniques

Superficial soil samples were extracted from public spaces at Lima (Fig. 1b) and La Plata (Fig. 1c). In total, 55 soil samples were obtained, 6 around Lima and 49 at La Plata. At Lima, sampling sites correspond to accessible places with free top soil around the Atucha nuclear power plants, including the central square of the city, whereas at La Plata the sampling points correspond to parks, beltway and squares inside the city. The sampling was carried out using a metal corer of 30 mm diameter and 10 cm length. Three surface soil sub-samples were collected at each location and then mixed into one unique sample to reduce microvariability.

Soil samples were dried at 363 K, ground and sieved through a 2 mm mesh. Subsequently, they were put into a 2 L Marinelli-type container, sealed and kept for 3 weeks to attain the secular equilibrium of the radioactive chains. A GMX10 gamma EG&G Ortec detector with relative efficiency of 40 % and a resolution of 1.97 keV at 1332 keV was used to take the spectra. The detector was coupled to a standard electronics chain, with a multichannel analyzer of 8192 channels. The detector was kept inside an EG&G Ortec low-background chamber. The energy calibration curve was obtained using specific radioactive sources (^{137}Cs, ^{60}Co, ^{133}Ba and ^{152}Eu). The efficiency calibration was performed using an admixture of known amounts of ^{176}Lu (3.7 g of Lu_2O_3, corresponding to an activity of 2.5 Bq) and ^{138}La (0.20 g of La_2O_3, equivalent to 8.3 Bq of activity) dispersed in soil substrate (Perillo Isaac et al. 1997). The laboratory background was determined and used to correct the peak areas. The spectra were recorded for 4 days and analyzed with commercial software. Soil ^{226}Ra activity was determined using the ^{214}Pb and ^{214}Bi activity values while the ^{232}Th chain activity was determined from the activity of ^{208}Tl, ^{212}Bi, ^{212}Pb and ^{228}Ac radionuclides. Activities for ^{40}K and ^{137}Cs in soils were determined using the well-known photo-peaks 1460.75 and 661.62 keV, respectively. Errors in the activity values were obtained by error propagation considering the mass of soil sample, the number of counts in the photo-peaks and the detector efficiency. A total correlation between activity values of individual photo-peaks was taken into account in the case of the radionuclide chains activities.

At each location, the external dose at 1 m above soil surface was measured using a Geiger Müller portable detector Radiation Alert™, with effective diameter of 45 mm and a mica window. At each public space, 100 individual data were collected (33, 33 and 34 at each sub-sampling point) and the mean dose was determined by arithmetic averaging. The associated error was assumed as its standard deviation.

Results and discussion

Activity in surface soils at La Plata

Table 1 shows the activities of ^{232}Th, ^{226}Ra, ^{40}K and ^{137}Cs determined for La Plata soils and Table 2 displays the statistical information regarding the radioactivity distributions in the studied area. The resulting activity ranges for

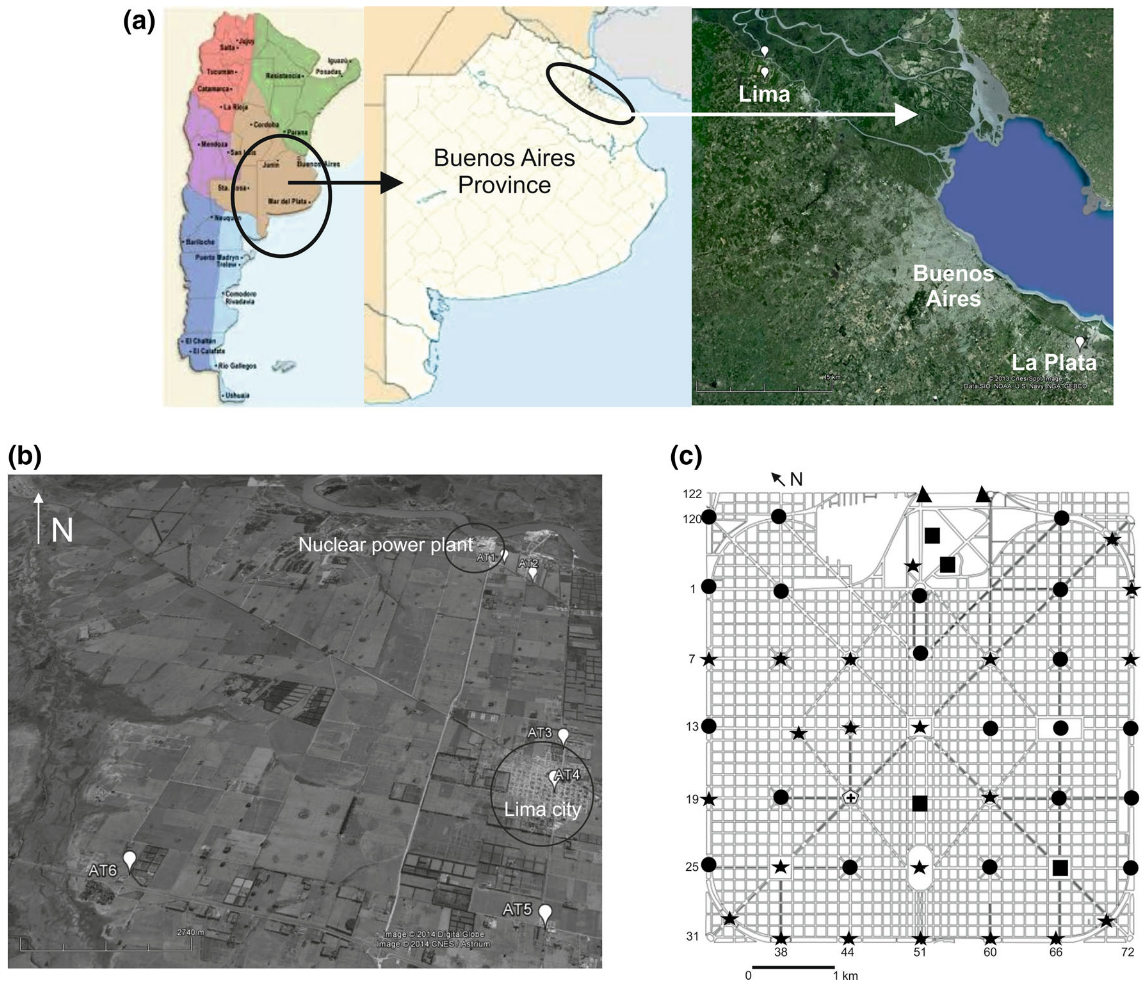

Fig. 1 **a** Location of La Plata and Lima in Buenos Aires Province, Argentina. **b** Soil sampling points at Lima. **c** Soil sampling locations at La Plata. The *different symbols* denote the geomorphological unit that they belong to; *triangles*, *circles*, *stars* and *squares* stand for old inner estuary (OIE), convex ridgeline (CR), sloping area (SA) and floodplain (F), respectively

natural radionuclides are 24–45 Bq/kg for ^{232}Th, 16–27 Bq/kg for ^{226}Ra and 449–690 Bq/kg for ^{40}K. Figure 2a shows the box plot of activity values for each radionuclide. For comparison, the figure also displays the worldwide average activities for ^{232}Th, ^{226}Ra and ^{40}K given by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2008) and the interval of activity values observed in unperturbed soils around La Plata (considering the mean activity value of the top 10 cm of soil) (Montes et al. 2012, 2013).

Mainly, the ^{232}Th activity values are lower than the corresponding worldwide average reported by UNSCEAR (2008) but lie within the activity intervals determined for unperturbed soils of the region (gray band in Fig. 2a).

^{40}K activities in the urban soils are higher than 412 Bq/kg, the worldwide average value reported by UNSCEAR (2008), but the values are similar to those determined for unperturbed soils of the region (gray band in Fig. 2a).

It is worth noting that the ^{226}Ra activities in urban soils are lower than the worldwide average value (UNSCEAR 2008) also lower than the values reported for the unperturbed soils of the region.

New Pearson correlation coefficients have been calculated taking into account the activities of unperturbed soils already published (Montes et al. 2012) and the results reported here (see Fig. 2b). These coefficients allow establishing, as before, a positive correlation among all radionuclides, but the values found in this study are higher than the previously reported, thus rendering correlations that are more reliable.

Only ^{137}Cs was detected as an anthropogenic gamma-ray emitter. The activity values for this radionuclide lie between the detection limit (0.02 Bq/kg) and a maximal value of 3.5 Bq/kg (see Table 1; Fig. 2a). Comparing these activities with those determined for unperturbed soils at La Plata (Montes et al. 2013) and taking into

Table 1 ^{232}Th, ^{226}Ra, ^{40}K and ^{137}Cs activity values, in Bq/kg, of La Plata soils

Streets		32 St	38 St	44 St	53 St	60 St	66 St	72 St	Park zone	
122 St	^{232}Th	NS	NS	NS	24 ± 3	25 ± 3	NS	NS	40 ± 5	B1
	^{226}Ra				16 ± 2	16 ± 2			26 ± 3	
	^{40}K				449 ± 47	526 ± 54			630 ± 65	
	^{137}Cs				1.2 ± 0.2	0.9 ± 0.2			1.7 ± 0.3	
120 St	^{232}Th	39 ± 5	41 ± 4	NS	NS	NS	39 ± 4	34 ± 4	39 ± 5	B2
	^{226}Ra	23 ± 3	25 ± 3				20 ± 2	16 ± 2	27 ± 3	
	^{40}K	642 ± 66	530 ± 57				654 ± 67	600 ± 62	585 ± 60	
	^{137}Cs	1.0 ± 0.2	0.8 ± 0.2				0.4 ± 0.2	0.4 ± 0.2	2.3 ± 0.3	
1 St	^{232}Th	41 ± 5	31 ± 4	NS	32 ± 4	NS	35 ± 4	35 ± 4	41 ± 5	B3
	^{226}Ra	27 ± 3	19 ± 3		20 ± 3		25 ± 5	21 ± 3	26 ± 3	
	^{40}K	571 ± 59	526 ± 55		541 ± 56		549 ± 57	573 ± 59	648 ± 67	
	^{137}Cs	0.8 ± 0.2	0.6 ± 0.2		1.0 ± 0.2		1.7 ± 0.3	0.6 ± 0.2	0.5 ± 0.2	
7 St	^{232}Th	39 ± 5	34 ± 4	37 ± 5	38 ± 5	45 ± 5	36 ± 4	36 ± 5		
	^{226}Ra	23 ± 3	25 ± 3	22 ± 3	23 ± 3	27 ± 3	22 ± 3	21 ± 3		
	^{40}K	629 ± 65	607 ± 63	607 ± 62	563 ± 68	645 ± 67	560 ± 58	598 ± 62		
	^{137}Cs	2.1 ± 0.2	2.0 ± 0.3	2.8 ± 0.3	2.4 ± 0.2	$<L_D$	3.5 ± 0.3	0.5 ± 0.2		
13 St	^{232}Th	36 ± 5	33 ± 5	32 ± 4	39 ± 4	36 ± 4	42 ± 5	36 ± 4		
	^{226}Ra	24 ± 3	19 ± 3	18 ± 3	26 ± 2	22 ± 3	25 ± 3	23 ± 3		
	^{40}K	631 ± 65	578 ± 60	532 ± 55	595 ± 61	583 ± 60	690 ± 71	596 ± 62		
	^{137}Cs	0.9 ± 0.2	0.7 ± 0.2	1.9 ± 0.3	2.4 ± 0.2	2.4 ± 0.3	0.7 ± 0.2	0.4 ± 0.2		
19 St	^{232}Th	37 ± 5	34 ± 4	41 ± 5	39 ± 5	39 ± 5	40 ± 5	38 ± 5		
	^{226}Ra	22 ± 3	19 ± 3	21 ± 3	26 ± 3	21 ± 3	22 ± 3	24 ± 3		
	^{40}K	634 ± 65	590 ± 60	621 ± 63	637 ± 65	614 ± 64	660 ± 68	610 ± 63		
	^{137}Cs	0.7 ± 0.2	0.3 ± 0.1	0.4 ± 0.2	0.5 ± 0.2	0.4 ± 0.2	1.9 ± 0.2	0.9 ± 0.2		
25 St	^{232}Th	35 ± 5	30 ± 4	37 ± 5	39 ± 5	34 ± 4	39 ± 5	35 ± 4		
	^{226}Ra	22 ± 3	17 ± 3	22 ± 3	23 ± 3	18 ± 3	21 ± 3	19 ± 3		
	^{40}K	617 ± 64	575 ± 60	643 ± 66	618 ± 64	575 ± 59	659 ± 67	600 ± 62		
	^{137}Cs	0.6 ± 0.2	0.6 ± 0.2	2.7 ± 0.3	3.2 ± 0.2	1.3 ± 0.2	$<L_D$	0.7 ± 0.2		
31 St	^{232}Th	36 ± 4	39 ± 5	39 ± 5	32 ± 5	42 ± 5	32 ± 4	37 ± 4		
	^{226}Ra	21 ± 3	21 ± 3	21 ± 3	19 ± 3	21 ± 3	20 ± 3	24 ± 3		
	^{40}K	658 ± 68	626 ± 64	609 ± 63	588 ± 61	626 ± 64	554 ± 57	518 ± 64		
	^{137}Cs	1.1 ± 0.3	$<L_D$	$<L_D$	0.4 ± 0.2	1.2 ± 0.3	0.8 ± 0.2	0.5 ± 0.2		

The crossings of the right column and the upper row give the soil codes. NS means that no soil is available for sampling

Table 2 Statistics information of activity data, percentile value (pv), standard deviation (SD) and variation coefficient (VC)

Radionuclide	Interval	Mean	90th pv	SD	VC (%)
^{232}Th	24–45	37	41	4	11.2
^{226}Ra	16–27	22	26	3	13.6
^{40}K	449–690	597	654	46	7.7
^{137}Cs	<0.2–3.5	1.1	2.4	0.9	76.6

All values are expressed in Bq/kg

account that, on average, 82 % of the stratospheric material is deposited in the hemisphere by injection (Valkovic 2000), almost all the ^{137}Cs findings reported here should arise from atmospheric nuclear tests carried out only in the southern hemisphere. Indeed, more than 60 atmospheric nuclear explosions were performed in the southern hemisphere at the Malden, Christmas and Marshal Islands, the Mururoa, Fangataufa and Bikini atolls and Emu and Maralinga in Australia.

Being the nuclear weaponry the solely source of ^{137}Cs around La Plata region, this radionuclide can be used as a tracer element to study erosion and/or other soil disturbances, if the reference profiles have been determined. The current ^{137}Cs activities (Table 1; Fig. 2a) are mostly lower than the average values reported for unperturbed soils (Montes et al. 2013). Therefore, it must be

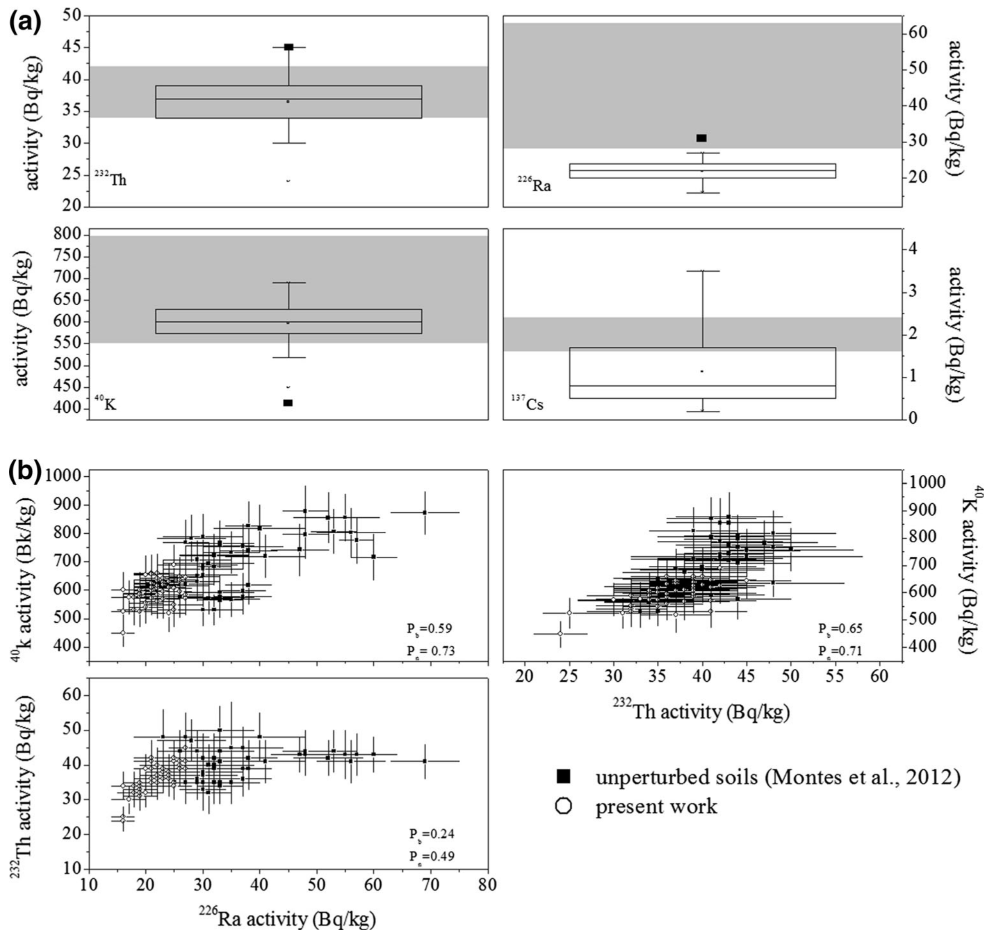

Fig. 2 **a** *Box plot* of ^{232}Th, ^{226}Ra, ^{40}K and ^{137}Cs activity values. *Black squares* denote the average activity values worldwide reported by UNSCEAR (2008) and the *gray* bands represent the activity interval determined for unperturbed soils of the region taking into account only the *top* 10 cm of soil (Montes et al. 2012, 2013); **b** correlation between activity values of ^{226}Ra, ^{232}Th and ^{40}K. P_b is the Pearson coefficient determined only with activity values of unperturbed soils, P_n is the Pearson coefficient determined considering all dataset of La Plata region

concluded that most of the studied soils have been disturbed, probably by mixing with deeper soil layers with lower activity of ^{137}Cs (e.g., by construction and maintenance works).

Variations on the surface activity levels for the radionuclides where evaluated through the ANOVA test considering the height above sea level and the geomorphological units of the region (Fig. 1c). Differences in the determined activity for samples belonging to different heights above sea level are not significant (0.05 confidence level). However, ANOVA analysis shows that when data are grouped according to the geomorphological unit type, at least one of the mean activity datum corresponding to a geomorphological unit is significantly different from the activity data of the other ones (0.05 confidence level).

A pairwise comparison of the mean activity data for each geomorphological unit was performed using the Tukey test. The results indicate that activity values observed for the OIE geomorphological unit are different from other ones, except for the ^{137}Cs activity, for which no significant differences were observed.

Geostatistical analysis—La Plata activity maps

Figure 3 shows the surface activity map of ^{232}Th, ^{226}Ra, ^{40}K and ^{137}Cs for La Plata soils, obtained applying the Kriging-geostatistical method (Oliver and Webster 1990; Stein 1999). The values in Fig. 3 correspond to the current experimental activities from which the maps were constructed. Normality data distribution was analyzed through frequency plot, skewness and kurtosis values and the Kolmogorov–Smirnov test. The resultant variograms (function derived from the experimental data to describe the degree of spatial dependence of the random variable field) were fitted with the best model (selected from lineal, spherical, Gaussian or exponential). Finally, activity maps were obtained using the ordinary Kriging method and, for each map, contour intervals were determined considering the minimal activity values and the associated errors. The results of Kolmogorov–Smirnov test showed that the activity data of all radionuclides depart from a normally distributed population (within a 0.05 confidence level). Frequency plot (not shown) and kurtosis and skewness values (Table 3) confirm this result.

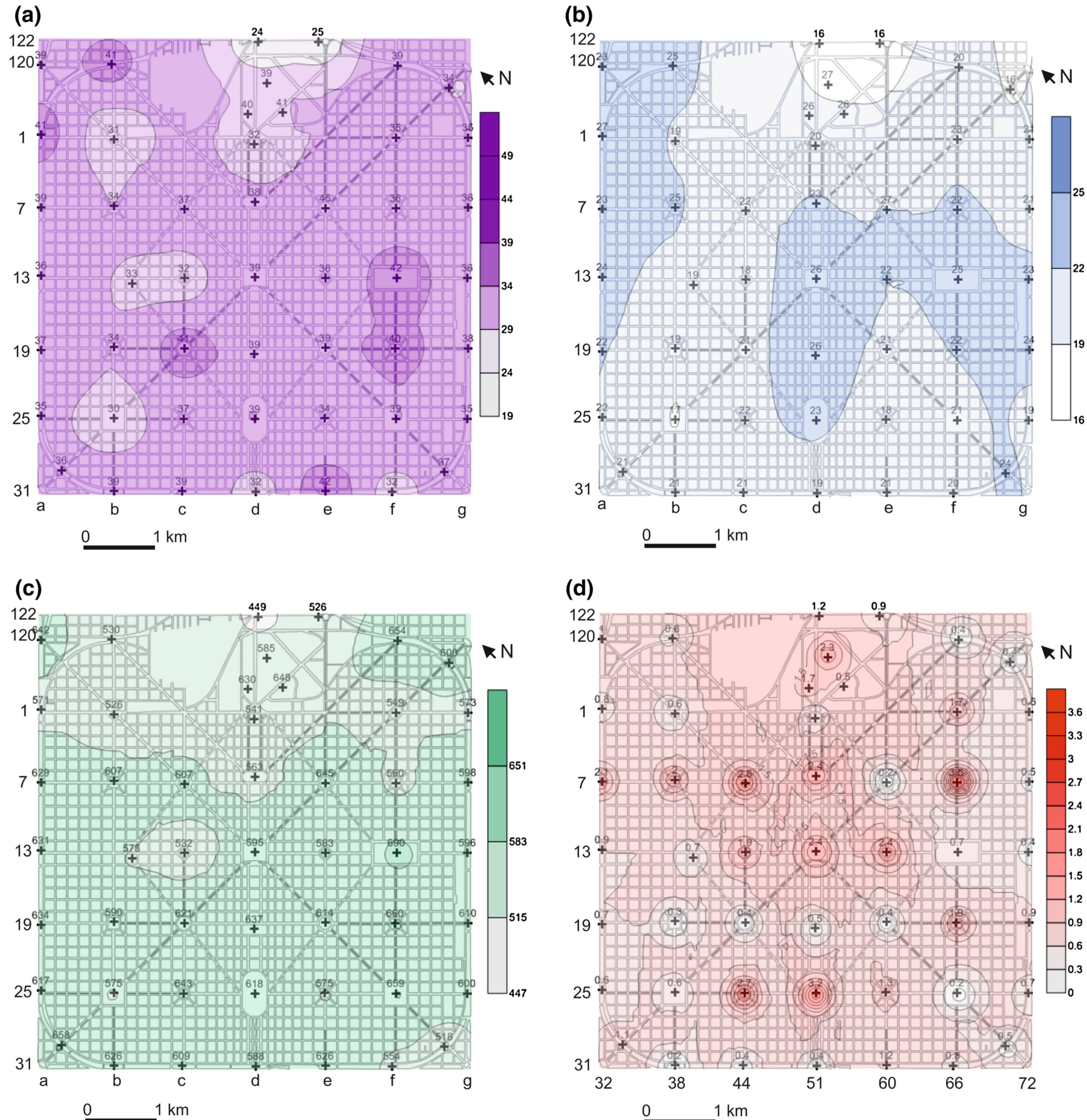

Fig. 3 Estimated distribution of surface activity values (**a**) ^{232}Th, (**b**) ^{226}Ra, (**c**) ^{40}K and (**d**) ^{137}Cs using the Kriging-Geostatistical method. Experimental data from which maps were obtained are also included as well as a cross showing the location of each sampling point

In order to obtain a normally distribution of data, the original data were transformed using logarithmic and square transformations. For natural radionuclides, the transformations were not effective, while ^{137}Cs data displayed normal distribution after logarithmic transformation. Therefore, variograms for natural radionuclides were performed with the original data, while for ^{137}Cs the log-transformed data were used.

Despite the non-normality distribution of natural activity data, the variograms exhibit spatial structure, i.e., the semivariance of the activity data follows a specific behavior with the vector lag, which denotes the separation in distance and direction of any pair of values of the regionalized variable. Attempts to fit the variograms using Gaussian or Exponential models clearly indicate that ^{232}Th, ^{226}Ra and ^{137}Cs variograms are better represented by

Table 3 Skewness and kurtosis values for original and transformed (log and square) data

Radionuclide	Original data		Log transformation		Square transformation	
	s	*k*	*s*	*k*	*s*	*k*
^{232}Th	−0.86	1.29	−1.34	2.63	−1.10	1.89
^{226}Ra	−0.06	−0.49	−0.37	−0.28	−0.22	−0.41
^{40}K	−0.65	0.74	−0.96	1.57	−0.81	1.11
^{137}Cs	1.03	−0.01	0.57	−0.85	0.57	−0.76

Gaussian functions, while exponential functions display a better fit to the ^{40}K variogram.

Figure 3 shows that the better agreement within experimental and simulated data corresponds to the ^{137}Cs activity map: only a single value differs significantly from the predicted one (B3 sampling point, 0.5 Bq/kg in the park zone). However, the activities of natural radionuclides show slight discrepancies between the experimental and predicted data for some sampling points.

In some cases, although the experimental data and the predicted values are not in the same contour level, the differences seem to be irrelevant regarding the contour interval width, the proximity of the involved contour levels and the experimental errors associated with the measured activity value. This can be observed in the ^{226}Ra map for the 7and32, 19and32, 19and53, 13and53, 7and60, 25and60 sampling points and in the ^{40}K map for the 31and32, 25and66 and 120and66 sampling points.

Another discrepancy between the experimental natural activity values and the predicted ones was observed in the park zone (B1, B2 and B3): the predicted values are significantly lower than the measured ones. This might be attributed to the fact that the activity gradient that exhibits the park to 122th street is different from the prevalent one in the rest of the studied area, probably because of the relative lower natural radionuclide activity values measured at the 122th street samples (near B1, B2 and B3). Moreover, the ANOVA and Tukey tests show that the natural radionuclide activities measured at 122th street (old inner estuary geomorphological unit) are significantly different from the mean values determined in the remaining geomorphological units. Consequently, the variogram from which the map is obtained cannot represent correctly the experimental data. An extension of the studied region

Table 4 ^{232}Th, ^{226}Ra, ^{40}K and ^{137}Cs activity values, in Bq/kg, determined in soils at Lima region

Soil code	^{226}Ra	^{232}Th	^{40}K	^{137}Cs
AT1	22 ± 3	39 ± 5	678 ± 70	<0.2
AT2	29 ± 4	45 ± 5	683 ± 70	0.9 ± 0.2
AT3	27 ± 3	40 ± 5	612 ± 63	2.5 ± 0.3
AT4	28 ± 4	35 ± 5	573 ± 59	2.0 ± 0.2
AT5	21 ± 3	39 ± 5	583 ± 63	1.7 ± 0.4
AT6	28 ± 4	44 ± 5	661 ± 69	1.8 ± 0.3

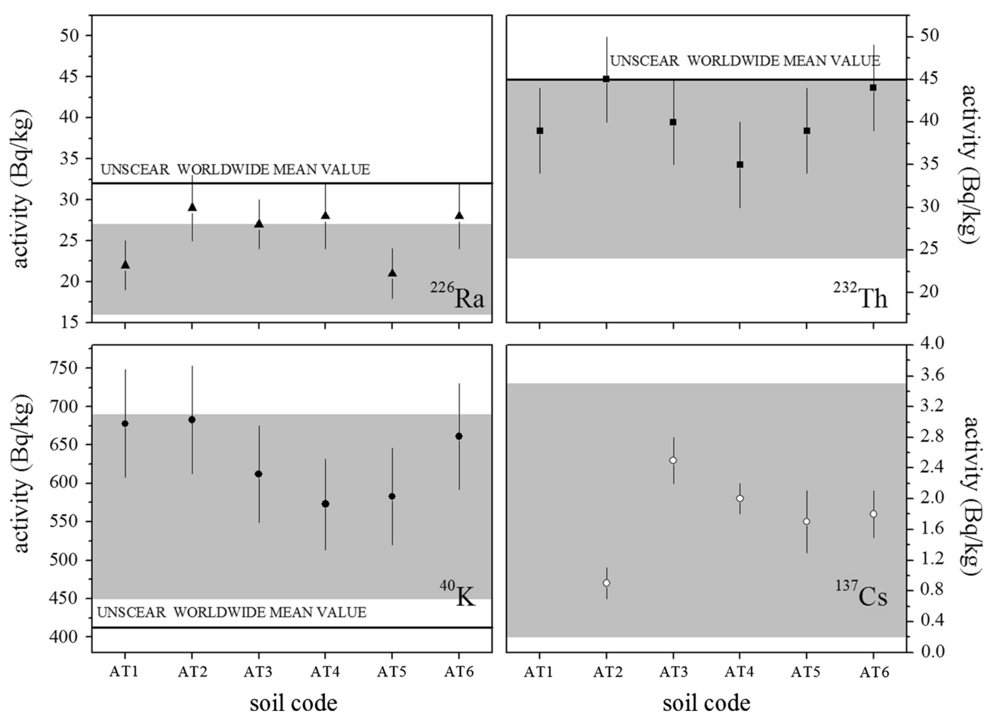

Fig. 4 Activity values determined in superficial soils at Lima. *Grey band* represent the interval of activity values determined in soils at La Plata, while the *line* denotes the worldwide mean value reported by UNSCEAR (2008)

Table 5 External dose calculated from natural activity values (ACED) and external doses measured with the Geiger Müller detector (D_G), considering a 20 % of time spent outdoors, for the two studied regions

La Plata

Streets		32 St.	38 St.	44 St.	53 St.	60 St.	66 St.	72 St.	Park zone	
122 St.	ACED	NS	NS	NS	0.050 ± 0.004	0.054 ± 0.004	NS	NS	NS	
	D_G				0.21 ± 0.05	0.23 ± 0.04				
120 St.	ACED	0.074 ± 0.006	0.071 ± 0.005	NS	NS	NS	0.073 ± 0.005	0.065 ± 0.005	0.076 ± 0.006	B1
	D_G	0.20 ± 0.05	0.23 ± 0.05				0.23 ± 0.05	0.21 ± 0.05	0.23 ± 0.04	
1 St.	ACED	0.074 ± 0.006	0.060 ± 0.005	NS	0.062 ± 0.005	NS	0.067 ± 0.005	0.068 ± 0.005	0.074 ± 0.006	B2
	D_G	0.23 ± 0.05	0.21 ± 0.04		0.24 ± 0.05		0.23 ± 0.03	0.21 ± 0.04	0.23 ± 0.04	
7 St.	ACED	0.074 ± 0.006	0.070 ± 0.005	0.070 ± 0.005	0.071 ± 0.005	0.081 ± 0.006	0.067 ± 0.005	0.069 ± 0.005	0.076 ± 0.006	B3
	D_G	0.19 ± 0.4	0.21 ± 0.04	0.21 ± 0.04	0.23 ± 0.04	0.23 ± 0.04	0.23 ± 0.05	0.19 ± 0.07	0.21 ± 0.04	
13 St.	ACED	0.072 ± 0.004	0.065 ± 0.005	0.063 ± 0.004	0.74 ± 0.005	0.069 ± 0.005	0.080 ± 0.005	0.070 ± 0.005		
	D_G	0.23 ± 0.04	0.21 ± 0.05	0.21 ± 0.05	0.23 ± 0.05	0.21 ± 0.05	0.23 ± 0.05	0.19 ± 0.05		
19 St.	ACED	0.072 ± 0.006	0.066 ± 0.005	0.074 ± 0.005	0.076 ± 0.006	0.071 ± 0.005	0.076 ± 0.006	0.073 ± 0.006		
	D_G	0.25 ± 0.04	0.23 ± 0.05	0.23 ± 0.04	0.25 ± 0.07	0.21 ± 0.05	0.23 ± 0.04	0.21 ± 0.05		
25 St.	ACED	0.070 ± 0.005	0.061 ± 0.005	0.072 ± 0.006	0.073 ± 0.005	0.065 ± 0.005	0.074 ± 0.006	0.062 ± 0.005		
	D_G	0.21 ± 0.05	0.23 ± 0.04	0.23 ± 0.05	0.21 ± 0.05	0.23 ± 0.04	0.25 ± 0.05	0.23 ± 0.05		
31 St.	ACED	0.072 ± 0.005	0.072 ± 0.005	0.072 ± 0.005	0.064 ± 0.005	0.075 ± 0.005	0.063 ± 0.005	0.067 ± 0.005		
	D_G	0.23 ± 0.05	0.25 ± 0.05	0.21 ± 0.005	0.25 ± 0.05	0.23 ± 0.05	0.23 ± 0.05	0.23 ± 0.05		

Lima

	AT1	AT2	AT3	AT4	AT5	AT6
ACED	0.077 ± 0.005	0.084 ± 0.006	0.076 ± 0.005	0.071 ± 0.005	0.07 ± 0.005	0.082 ± 0.006
D_G	0.28 ± 0.05	0.23 ± 0.04	0.25 ± 0.05	0.28 ± 0.05	0.26 ± 0.05	0.26 ± 0.05

would be needed to improve the variogram for the whole data set.

These maps are part of the radiologic baseline necessary to evaluate future potential radiological pollution and, to the best of the authors' knowledge, La Plata is the first Argentine city in which the baseline of gamma-emitters in soils has been determined.

Activity values around Lima

Table 4 and Fig. 4 show the ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs activities determined in soils at Lima. Figure 4 also displays worldwide mean activity values and the activity ranges for soils at La Plata reported here.

^{226}Ra and ^{232}Th activities are lower than the worldwide activity reported by UNSCEAR (2008), while ^{40}K activity values are higher than the corresponding worldwide activity value, as in La Plata soils. Regarding ^{137}Cs, the similarity for La Plata and Lima activity values suggest that the source of ^{137}Cs in the soils around the nuclear power plants is due only to the nuclear weapons tests performed in the southern hemisphere and not to any nuclear local source. ^{60}Co, a potential element that can be found around the nuclear power plant, could not be detected within the sensitivity of the spectrometer used in the present study.

Considering the experimental uncertainties, the activity values for Lima soils are within the range of those determined for La Plata. These values can be used as a reference in future investigations, especially to assess possible contaminations, after the power plants reach full operation.

Dose: in situ measurements and calculated soil contributions

Table 5 summarizes the total outdoors external dose (DG) measured by Geiger Müller counters at each public space in La Plata, considering an outdoors factor of 20 %. The determined DG varies from 0.19 to 0.25 mSv/year; all values are lower than the average external dose of 0.28 mSv/year reported by UNCEAR (2008). Figure 5a shows that the DG values obtained at Lima are similar to those determined at La Plata and the average external dose reported by UNSCEAR (2008).

The annual committed effective dose for adults because of natural radionuclides existing in soil (ACED) has been calculated for each public space, considering also a 20 % of time spent outdoors (UNSCEAR 2008), according to:

$$\text{ACED (mSv)} = 10^{-9} \times 24 \times 365 \times 0.2 \times \sum_i f_i \times C_i \times A_i \quad (1)$$

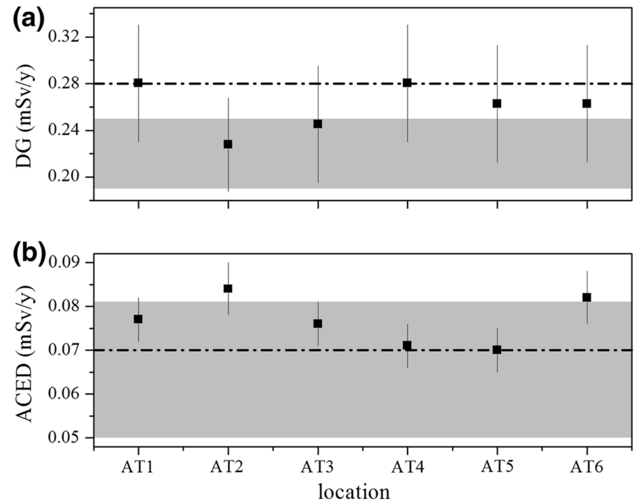

Fig. 5 DG and ACED values determined at Lima region. *Gray band* denote the range of values found at La Plata. The *dash dot line* represents the worldwide values reported by UNSCEAR (2008)

where A_i is the activity value of the ith-radionuclide and f_i and C_i are the conversion factors for Bq/kg to nGy/h and for Gy to Sv, respectively. The dose conversion factors f_i used for ^{238}U and ^{232}Th series and for ^{40}K activity were, 0.462 (nGy/h)/(Bq/kg), 0.604 (nGy/h)/(Bq/kg) and 0.0417 (nGy/h)/(Bq/kg), respectively (UNSCEAR 2008). The C_i coefficients used to convert the absorbed dose in air to ACED were 0.709 Sv/Gy for ^{40}K, 0.695 Sv/Gy for the ^{232}Th chain and 0.672 Sv/Gy for the ^{238}U series (UNSCEAR 2000).

Table 5 summarizes the calculated ACED values for both mapped regions. In La Plata, the ACED values vary from 0.050 to 0.081 mSv/year with a mean value of 0.070 mSv/year and a standard deviation of 0.006 mSv/year. The result found here is in agreement with the average annual committed effective dose (0.07 mSv/year) reported by UNSCEAR (2008). ACED values around Lima range from 0.07 to 0.084 mSv/year (mean value of 0.077 mSv/year and a standard deviation of 0.006 mSv/year), showing no significant differences with those obtained for La Plata (gray band in Fig. 5b). Therefore, the present investigation indicates that the nuclear facilities in the neighborhood of Lima are not affecting the regional ACED value.

Conclusions

The activity maps obtained from ^{232}Th, ^{226}Ra, ^{40}K and ^{137}Cs activities of surface soils at La Plata public spaces are the first ones reported for an Argentine city.

The activities determined for ^{226}Ra and ^{232}Th in surface soils at La Plata are lower than the worldwide average value, while those of ^{40}K are higher than the average reported by UNSCEAR, exhibiting the same trend as the unperturbed soils of the region.

The Pearson correlation coefficients between natural activities, considering the whole dataset for La Plata soils (both perturbed and unperturbed) are higher than the Pearson coefficients obtained only for unperturbed soils. The established positive correlations among all radionuclides result more reliable than in the previous study.

The ^{137}Cs activities for La Plata and Lima are lower than the determined previously for the unperturbed soils around La Plata. The determined ^{137}Cs activities indicate that there is no other ^{137}Cs source in addition to the nuclear weapons tests performed in the southern hemisphere.

The total outdoors dose values reported here for La Plata inhabitants lie between 0.19 and 0.25 mSv/year. All values are lower than the total average external dose (0.28 mSv/year) reported by UNSCEAR. The activity levels and dose values at Lima are similar to La Plata, which indicates that the nuclear facilities have not modified the distribution of radionuclides in soils.

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