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Tracing Environmental Radionuclides (^{40}K, ^{226}Ra, ^{210}Pb And ^{137}Cs) In Soil Under Coniferous Stands In The Czech Republic

Corresponding Author

Ryoko Fujiyoshi
Division of Quantum Science and Engineering,
Graduate School of Engineering,
Hokkaido University, Kita 13, Nishi 8,
Kita-ku, Sapporo 060-8628, (JAPAN)
Tel: +81 11 706 6674, Fax: +81 11 706 6675,
E mail: fuji@qe.eng.hokudai.ac.jp

Co-Authors

Yoshihiro Satake, Takahiro Sato, Takashi Sumiyoshi, Sadashi Sawamura
Division of Quantum Science and Engineering, Graduate School
of Engineering, Hokkaido University, Kita 13, Nishi 8,
Kita-ku, Sapporo 060-8628, (JAPAN)

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ABSTRACT

Depth profiles of environmental radionuclides (^{40}K, ^{226}Ra, ^{210}Pb, ^{137}Cs) in forest soil provide information on the "in situ" situation occurring or having been occurred within a soil horizon of interest. Degree of soil homogeneity could appear on variability of depth profiles of lithogenic nuclides (^{40}K and ^{226}Ra). The level of ^{40}K activity concentration is reflected by the underlying lithology. Change in its concentration with soil depth in the upper portion may suggests biological activity like root uptake of this nuclide. Fallout nuclides like ^{137}Cs and a part of ^{210}Pb did not always show the surface enrichment, which would be caused by bioturbation, surface runoff and/or canopy effect of the stands as well as anthropogenic intervention. Mean values of annual burial rate of ^{137}Cs may roughly be estimated for several soils giving exponential decrease in activity concentration with depth within the upper 20 cm layer of the soil. The values were about 1-2 mm/y independent of the soil type. Similar values were also obtained from the ^{210}Pb profiles at the same sites.

KEYWORDS

Radionuclides;
Forest soil;
Depth profile;
Soil homogeneity;
Bioturbation.

INTRODUCTION

Soil contains a variety of environmental radionuclides of different origin and chemical properties. Anthropogenic nuclides such as ^{137}Cs and ^{90}Sr have been focused to evaluate radiological impacts on general public especially due to the accident in the nuclear power plant at Chernobyl in Russia on April 26 1986. Actually, the accident released significant quantities of radioactive gases, aerosols and finely fragmented nuclear fuel particles into the upper atmosphere, which inevitably lead to various forms of these nuclides into soil surfaces as a pulsed source through dry fallout and wet deposition[1,2]. It is therefore believed that spatial and vertical distribution of these nuclides varies to a great extent depending on their origin as well as on climatic and topographical situation in a pertinent location. The effects of topography on the spatial distribution of radiocesium were investigated by Albers et al.[3] to elucidate underlying reasons for variability of this nuclide in soils and also in the above-ground vegetation. Radiocesium is also known as a useful tracer for quantifying erosion rates for periods up to 35 years.

In addition to the anthropogenic nuclides, there is another type of nuclides with a decay series, such as ^{238}U, ^{232}Th and ^{235}U, and a long-lived ^{40}K in soil. These are lithogenic nuclides which contribute to main external source of irradiation to the human body. Many studies have already been carried out to estimate dose rate due to terrestrial gamma radiation from these nuclides. Evans et al.[4] investigated naturally occurring radionuclides in soil profiles to determine the feasibility of a radio-pedogenic index based on comparison of radiological properties between sola and C horizons. They used ^{228}Ac and ^{214}Pb as the ^{232}Th progeny and the ^{238}U progeny, respectively. According to them, the ratio between ^{228}Ac/^{214}Pb is useful to estimate if secular equilibrium has been preserved within a horizon of interest. They also referred to ^{226}Ra which is particularly useful because of its established analogy to Ca present in most soils and serving as an essential plant nutrient.

The present authors have investigated depth profiles of several environmental radionuclides (^{40}K, ^{226}Ra, ^{210}Pb, ^{137}Cs) in temperate forest soils under coniferous stands to elucidate behavior of these radionuclides of different origin and chemical properties in forest soils in the Czech Republic. The results will be compared with those obtained previously for German soils to elucidate behaviors of these nuclides and further to estimate underground biological activities.

MATERIALS AND METHODS

Site description and soil sampling

Soil sampling was carried out in September 2004 from several coniferous stands in the Czech Republic by the courtesy of Dr. Tomas Paces of Czech Geological Survey. The sites (Lysina, Pluhuv Bor and Nacetin) were located in west to northwest part of the Czech Republic (Figure 1)[8].

Lysina (54°03′N, 12°40′E) is situated in the western part of the Czech Republic in the mountain region of the Slovkov Forest[8]. The stand is predominantly covered with Norway spruce (Picea abies). The altitude of the site is between 829 and 949 m a.s.l. Mean annual temperature is 5°C and mean annual precipitation is 900 mm. The bedrock is coarse-grained leucogranite with only trace amounts of biotite. The dominant soil is podzolic brown forest earth. The mean stand age is 45 years old.

Pluhuv Bor situated in western Bohemia (54°04′N, 12°46′E) is covered with Norway spruce monoculture[8]. The bedrock is underlain by serpentinite consisting primarily of antigorite. The serpentinite at Pluhuv Bor contains greater amounts of K_2O (ten times) and Na_2O (six times) and lower amount of Al_2O_3 (one-forth) than 'average' serpentinite. The dominant soils are eutrophic brown soils and peaty gleys.

Figure 1: Location map of the sampling sites (Lysina, Pluhuv Bor and Nacetin) in the czech republic

The Nacetin site is located at 50°35′N, 13°15′E, on the border between the Czech Republic and Federal Republic of Germany[9]. The site is covered with spruce stands. The soil is classified as Cambic Podzols to dystric Cambisols and their texture is sandy loam.

Individual soil samples were collected by hand every 5 cm from the uppermost to a depth of about 50 cm in a pit (1m×1m) depending on 'in situ' geology. Special care was taken to note any changes in soil outlook during soil sampling. Collected samples were oven-dried at 45°C at least 24 hr or longer until a constant weight was reached at a laboratory of the Czech geological survey. Dried samples in plastic bags were transported to our laboratory in Hokkaido university, where they were disaggregated, sieved through a 2 mm mesh sieve and kept in plastic bottles for further analyses.

The amount of soil organic matter was estimated by the weight loss on ignition at 450°C for 24 hours.

Leaching experiments were performed to know the amount of potassium dissolved in the aqueous solution after washing bulk soils with pure water. The amount of potassium (K^+) leaching out from a soil was evaluated electrochemically using a potassium ion selective electrode (Orion Model 93-19BN, Orion, USA) and an ion meter (Orion 920A, Orion, USA)[5].

Radioactivity measurement

Radioactivity was measured for the nuclides (^{40}K, ^{226}Ra, ^{210}Pb, ^{137}Cs) by gamma spectrometry with two types of HPGe detector (GEM-25185-P and GMX10P, EG&G ORTEC, USA). Standard reference materials were purchased from the International Atomic Energy Agency (IAEA Soil-6, IAEA-312 and IAEA-327) to evaluate the activity concentration of individual samples from counting data obtained with the same geometry under identical operating conditions. Both energy and efficiency calibration was carried out periodically for each nuclide, as well as background check. Precision of the measurement was estimated by considering pertinent photo-peak areas for both samples and the standards. All of the analytical values except for those on ^{210}Pb were crosschecked by measuring activity for individual samples with the different detectors. TABLE 1 summarizes the minimum detectable activity (MDA) of each nuclide and the standard error (S.E.) of counting rates for a sample (approx. 100g) in a container (100 cm^3) for 48 h counting time by using a HPGe detector (GM×10P).

TABLE 1: Minimum detectable activity (MDA) and standard error (S.E.) of the activity concentration of each nuclide in a typical soil sample (100 g, 2 day counting time, HPGe detector)

Nuclide	MDA (Bq)	S.E (±%)
^{40}K	0.63	1.9-6.0
^{137}Cs	0.31	5.1-10.1
^{210}pb	0.59	2.5-5.9
^{226}Ra	0.33	3.4-11.4

Elemental analyses

Major and minor elements contained in soil were determined by X-ray fluorescence spectrometry (JSX 3220, JEOL, Japan).

Calibration curves were prepared for several elements including potassium using thirteen standard

TABLE 2: Major elemental composition of the soil under coniferous stands (Lysina, Nacetin and Pluhuv Bor) in the czech republic

Location	Depth (cm)	Concentration					
		MgO	Al_2O_3	SiO_2	K_2O	CaO	Fe_2O_3
		(Mass %)					
Lysina	-5-0	ND*	10.5	61.0	4.9	2.9	10.0
	0-5	ND	16.1	69.8	7.0	ND	4.6
	5-10	ND	17.2	71.3	7.3	ND	3.2
	10-15	ND	17.4	68.4	6.7	ND	5.4
	15-20	ND	18.5	63.8	5.9	ND	8.7
	20-25	ND	16.3	72.9	7.3	ND	2.4
Nacetin	0-5	ND	10.7	59.2	4.5	0.8	14.7
	5-10	ND	14.1	62.5	5.0	ND	15.3
	10-15	ND	13.2	56.0	4.6	ND	23.3
	15-20	ND	14.6	58.0	5.2	ND	20.0
	20-25	ND	15.8	61.8	5.4	ND	14.8
Pluhuv bor	-5-0	5.9	7.4	62.0	1.6	4.3	15.4
	0-5	9.5	8.8	60.3	1.3	4.8	13.3
	5-10	9.2	9.2	60.5	1.7	4.6	12.6
	10-15	9.5	8.9	59.4	1.6	5.2	13.5
	15-20	8.3	9.4	62.1	2.2	4.2	11.7
	20-25	8.5	9.0	60.9	2.1	4.5	13.2

*** ND denotes the concentration smaller than 0.1 in mass per cent.**

reference materials purchased by geological survey of Japan. A known amount of each sample (about 2 g) was packed in a special container, which was then sealed with a piece of plastic sheet. In order to elucidate speciation of potassium, both residual samples after leaching with water (easily dissolved fraction) and those after heating at 450°C (mineral fraction) were used for the potassium determination. Measurements were carried out under the following instrumental conditions: X-ray tube; Rh crystal, Applied voltage; 30kV, Primary collimator; 4mmϕ, Atmosphere; vacuum. The results of elemental analyses on individual soils were summarized in TABLE 2.

RESULTS AND DISCUSSION

Depth profile of ^{40}K and speciation of potassium

Figure 2 shows depth profiles of ^{40}K activity concentration in the forest soils investigated in this study (Lysina, Pluhuv Bor and Nacetin). It is generally known that activity concentration of ^{40}K is relatively constant with depth within a horizon of interest. This is a reason why the nuclide, ^{40}K, has been regarded as a reference for investigating behavior of anthropogenic radionuclides in soil[3]. It may be true for a soil collected at Pluhuv Bor where the whole bedrock is of serpentinite, consisting primarily of the magnesium-silicates with low potassium content[10]. However, as shown in the figure, the other soils both from Nacetin and from Lysina looked inhomogeneous in ^{40}K distribution with depth.

Figure 3 shows that a positive correlation exists between ^{40}K activity concentration and dry density in any case. Similar results had also been obtained in our previous studies on German soils[5]. Those facts may be explained by considering thats i) most of the soil organic matter exist in the upper portion of the soil, ii) the mineral component of a soil is higher in density than the organic component, and iii) the amount of potassium contained in the mineral fraction is usually much higher than that in the organic fraction of the soil.

Potassium in soil exists in i) crystal lattice of the minerals such as feldspars, micas and secondary-formed clays, ii) exchangeable sites of the weathered products, iii) soil organic matter including living macro (and micro) organisms and secondary formed humic substances, and iv) soil solution as dissolved form (K$^+$). It is therefore supposed that behavior of potassium in soil may not be static with moving (ground) water and also with biological activities like root uptake and burrowing organisms living there.

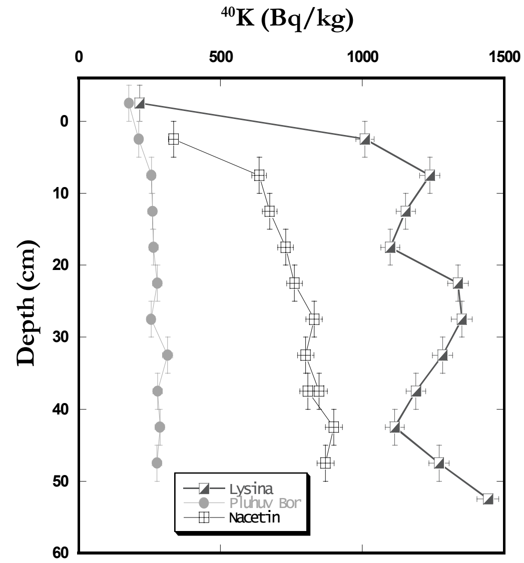

Figure 2: Depth profiles of ^{40}K activity concentration in soil under temperate coniferous stands at Lysina, Pluhuv Bor and Nacetin in the czech republic

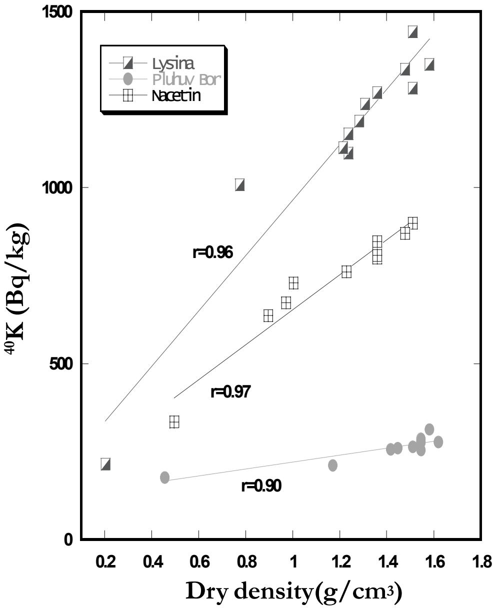

Figure 3: Relationship between ^{40}K activity concentration and dry density

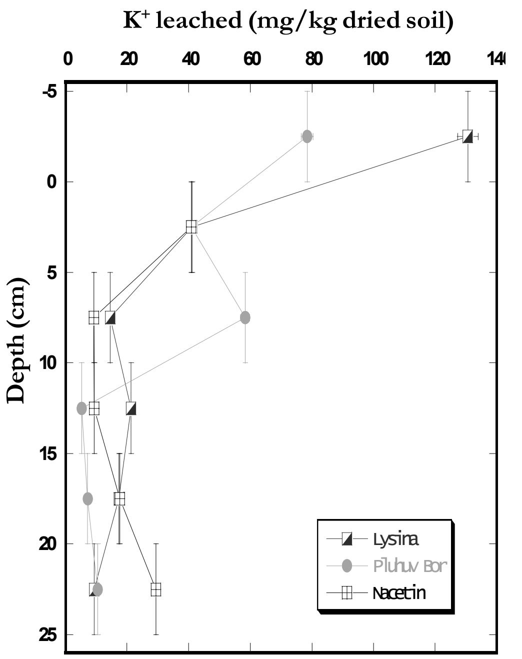

Figure 4: Change in the amount of K^+ ions (mg/kg of dried soil) leached to the aqueous solution plotted against soil depth at three sites in the czech republic

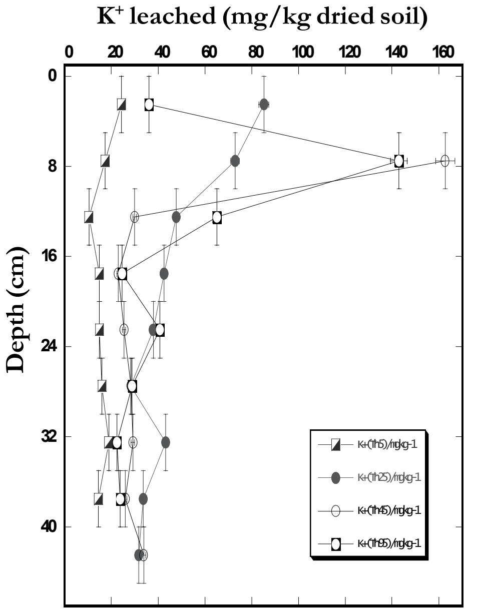

Figure 5: Change in the amount of K^+ ions (mg/kg of dried soil) leached to the aqueous phase against soil depth under coniferous stands of different stand age in Tharandt, Germany

In order to know the amount of potassium (K^+) dissolved easily to the aqueous phase, a leaching experiment was conducted for individual soils using pure water as a leaching reagent.

Figure 4 shows the results in which potassium (K^+) was leaching to a great extent at the upper-most litter layer of each soil. The leaching amount then decreased to be constant at deeper portion of the soil. Potassium in litter may be much labile compared with that in lower mineral fractions.

As a comparison, figure 5 shows the result of leaching experiment for soils under coniferous stands of different age classes in Tharandt, Germany. The amount of potassium leaching in the aqueous phase was similar in value (10~160 mg K^+/kg of dried soil) to those obtained in the Czech soils (Figure 4). The amount was different with different age classes. There exists a depth (~10 cm) at which the leaching amount gave a maximum in the soil at Tharandt-45 and -95 years of age classes. This fact might be associated with underground biological activity, which further suggests a possible seasonal variation of the profiles. In any case, it should be investigated by long-term monitoring of dissolved potassium as well as other chemical forms of this element, i.e., speciation of potassium, in soil.

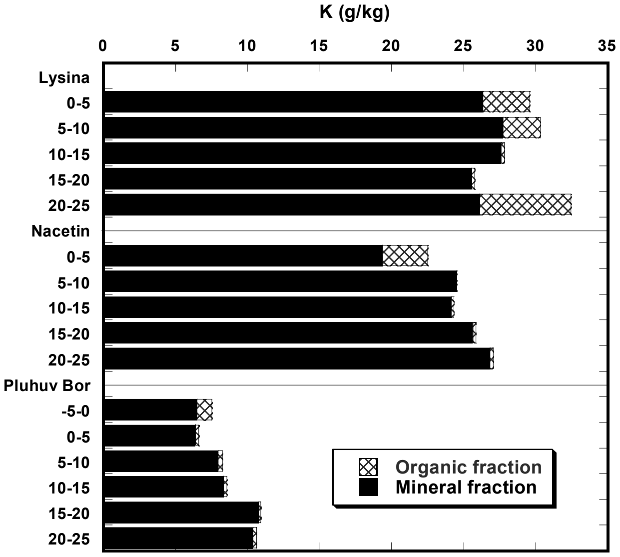

Figure 6: Depth profiles of potassium contained in organic and mineral fractions of the soil at Lysina, Nacetin and Pluhuv Bor

Figure 6 shows depth profiles of potassium contained in mineral and organic fractions of the soil, which was calculated from a set of analytical data on potassium determined for bulk soils as well as those heated at 450°C (TABLE 3). The table also

TABLE 3: Some soil properties (humidity and soil organic matter) and the amounts of potassium (%) contained in organic (Org.) and mineral (Min.) fractions of the soil from Lysina, Nacetin and Pluhuv Bor in the czech republic

Location	Depth	Humidity	SOM	K in Org.*	K in Min.*
	(cm)	(%)	(%)	(%)	(%)
Lysina	0-5	19.0	21.1	1.5	2.6
	5-10	6.7	5.9	4.4	2.8
	10-15	9.0	7.7	<0.1	2.8
	15-20	12.0	9.0	<0.1	2.6
	20-25	6.2	7.7	8.2	2.6
Nacetin	0-5	34.7	57.3	0.5	1.9
	5-10	19.4	18.4	<0.1	2.5
	10-15	19.1	13.5	0.2	2.4
	15-20	18.9	11.4	<0.1	2.6
	20-25	17.3	7.1	<0.1	2.7
Pluhuv bor	-5-0	22.1	43.1	0.2	0.6
	0-5	9.0	8.6	0.3	0.6
	5-10	7.1	4.1	0.8	0.8
	10-15	8.0	4.0	0.5	0.8
	15-20	6.9	2.7	<0.1	1.1
	20-25	5.7	2.1	1.2	1.0

* Possible error of each analytical value was estimated to be lower than ± 7.1 %

lists some soil properties (humidity and soil organic matter) and the amounts of potassium (%) contained in organic and mineral fractions of each soil. As shown in the figure, the amount of potassium in organic fraction is appreciable at the surface portion of any soil, reflecting the amount of organic matter present at each site. At Pluhuv Bor, however, quite small amount was found only at the upper-most layer, which is reasonable by considering that surpentinite contains little potassium, and that the amount of soil organic matter is also small at this site[8].

It is interesting to note in TABLE 3 that percent of potassium contained in one kilogram of mineral fraction is relatively constant except for the surface layer at each site. The same is not true for the potassium in organic fraction as also shown in the table. This may indicate that potassium would exist rather randomly in various forms of soil organic matter.

Depth profiles of ^{226}Ra and ^{210}Pb

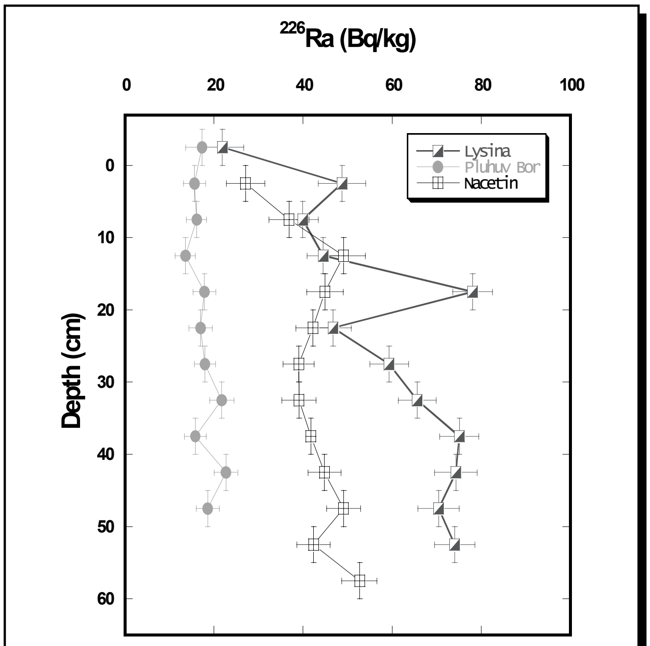

Figure 7: Depth profiles of ^{226}Ra activity concentration in soil under coniferous stands (Lysina, Pluhuv Bor and Lysina) in the Czech Republic

Soil homogeneity within a horizon of interest may be estimated by tracing ^{226}Ra concentration with depth, because radium in soil is originally derived from the underlying bed rock and from its weathered products.

Figures 7 shows depth profiles of ^{226}Ra activity concentrations in soil at three sites. It is obvious that the absolute value of activity concentration depends on local geology[5]. The ^{226}Ra profile obtained at Pluhuv Bor (Figure 7) looks homogeneous with soil depth. A similar pattern was seen in the ^{40}K profile shown in figure 2. It is therefore considered that the soil derived from underlying serpentines would have gradually been altered to clays which result in being homogeneous in texture.

As for geochemistry of radium in soil, Greeman et al.[12] investigated speciation of ^{226}Ra in various soils collected at 12 sites in the eastern United States with a selective chemical extraction plus size fractionation technique. The soils were separated operationally to be six fractions with specific chemical reagents (exchangeable cations, organic matter, free Fe-oxides, sand, silt and clay). They found surface enrichment of ^{226}Ra in most of the soils, which is likely to result from cycling by vegetation. According to them, of the total Ra in an average A-horizon,

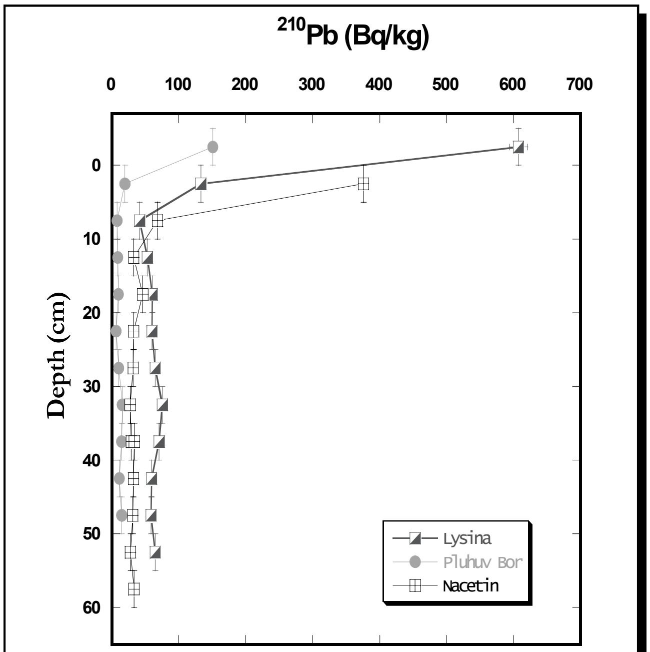

Figure 8: Depth profiles of ^{210}Pb activity concentration in soil under coniferous stands (Lysina, Pluhuv Bor and Lysina) in the czech republic

42% occurs as exchangeable ions and in organic matter. We did not find such a surface enrichment of ^{226}Ra on our bulk soils as suggested by them. But it is likely that similar profiles would be obtained by conducting speciation of this nuclide for our soils.

Depth profiles of ^{210}Pb activity concentration is shown in figure 8 in which surface enrichment of this nuclide appeared down to a depth of about 10 cm[5]. This may be explained by the well-known process that part of ^{210}Pb contained in the surface soil was discharged anthropogenically by dry fallout and/or wet deposition from the atmosphere. Comparing depth profiles for both nuclides (^{226}Ra and ^{210}Pb) makes it possible to estimate mean annual burial rate of the anthropogenic ^{210}Pb (excess ^{210}Pb or ^{210}Pb$_{ex}$) in a soil of interest.

It should be noted that there are several premises to evaluate the value: The first one is to regard the nuclide, ^{226}Ra, being in secular equilibrium with ^{210}Pb (supported ^{210}Pb) which had been derived from the ^{226}Ra (or its progenies like ^{214}Pb) in soil on measurement. The second one is to consider the flux of anthropogenic ^{210}Pb into the soil surface to be constant for certain period of time. The third is that natural ^{210}Pb as a progeny of the ^{222}Rn decay series in the atmosphere would be negligibly small. And the fourth is no serious bioturbation occurring within the profile. It is not likely to find a situation where all the above premises could be satisfied. The present authors tried to get ‘apparent’ burial rates of anthropogenic ^{210}Pb in our soils. TABLE 4 summarizes the results together with those obtained from other locations previously. As shown in the table, the values are not so diverse (about 0.1 to 0.2 cm/y) among the soils collected from quite different places. It should be noted that some of the values in TABLE 4 include large uncertainty because of a lack of the number of samples collected down to a depth of 10 cm.

TABLE 4: Comparative lists of annual burial rate of ^{137}Cs and ^{210}Pb in semi-natural forest soils estimated from their depth profiles

Location and Stand	^{137}Cs (cm/y)	^{210}Pb (cm/y)
Czech Republic*		
Conifer (Lysina)	0.16	0.10
Conifer (Pluhuv Bor)	0.15	-
Conifer (Nacetin)	0.11	0.10
Germany**		
Conifer (Tharandt-25y)	0.15	0.17
Beech (Leinefelde-70y)	0.12	-
(Leinefelde-120y)	0.16	-
(Leinefelde-150y)	0.12	-
Peru***		
Heath	0.21	0.23
Sapporo***		
Deciduous mix (Point 1)	0.11	0.13
Deciduous mix (Point 2)	0.11	0.10

* The results obtained in this study

** In most sites in Germany, values for ^{210}Pb were not included in the table because of no surface enrichment of this nuclide (Tharandt 5y and Tharandt 95y) and of a lack of reliable data points from which the burial rate was calculated (Tharandt-45y, Hainich, Leinefelde 70y, Leinefelde 120y, and Leinefelde 150 y). Uncertainty of the value was estimated to be less than ± 25% for all the soils considering possible errors derived from soil sampling, sample processing and gamma counting.

*** Unpublished data obtained by R. Fujiyoshi

Depth profile of ^{137}Cs

The burial rate may also be estimated from the depth profiles of an anthropogenic nuclide, ^{137}Cs, although all the profiles could not always be suitable for such estimation[5]. Figure 9 shows the ^{137}Cs profiles in the forest soils investigated in this study.

We have found three types of ^{137}Cs depth profile

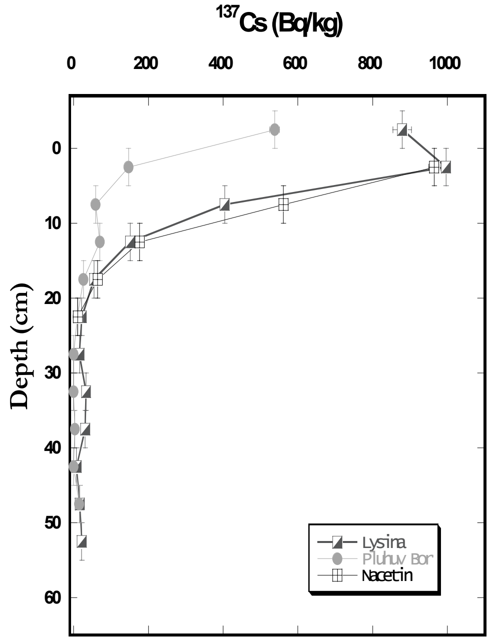

Figure 9: Depth profiles of ^{137}Cs activity concentration in soils under temperate coniferous stands at Lysina, Pluhuv Bor and Nacetin in the czech republic

in various forest soils so far[5]: They are (1) surface enrichment with a maximum at certain depth and then exponential decrease with depth, (2) surface enrichment, exponential decrease and reappearance at deeper portion of the soil, and (3) quite small amount even in the uppermost soil layer. Possible reasons for such different profiles could be speculated as follows: In the type 1 which is a typical example of the ^{137}Cs profiles in the literatures, the nuclide was originally discharged from the atmosphere most probably by the Chernobyl accident in 1986, and possibly by atomic bomb tests in 1960s. It is easy to explain that a pulse-like input of ^{137}Cs to the soil surface results in changing peak of the activity concentration to deeper and broader with time. Contrary to this speculation, the type 1 profile may suggest a property of this nuclide to be strongly associated with certain components, most likely soil organic matter and/or clay minerals in the upper soil layer.

Several explanations would be plausible for the type 2 profile: The first one is that intensive atmospheric fallout of this nuclide occurred twice in the past (1960s and also in 1986). Considering the half-life of ^{137}Cs ($T_{1/2}$=30.0 y), more than half of the portion from atomic bomb tests would have decayed out, but not all. This remaining portion may contribute to the ^{137}Cs reappearance at deeper depth. The second explanation is that high water-level, especially in early spring due to melting snow, causes this nuclide as well as other soluble components to be dissolved to the groundwater. The level decreases with time, but the cesium would still remain there to be associated with some solid soil components like organic matter and clay minerals. The third one is a consequence from underground biological activities, such as root uptake and burrowing macro organisms which would modify the pattern of profile. It is possible to find which one of the above explanations would be the most reasonable if a set of additional information is obtained on seasonal variability of the water level, kind and mass of macro-organisms living there, and depth profiles of soluble components in soil as well as isotopic ratio of ^{134}Cs/^{137}Cs.

The type 3 profile may be derived from surface run-off of this nuclide by heavy rain and/or from canopy effect of coniferous stands. If the speculation is true, any fallout nuclide other than ^{137}Cs should give a similar depth profile to that of the type 3 cesium. Canopy effect may be much important for coniferous stands than for deciduous stands that fall leaves every one year. It should be added that the ^{210}Pb profiles under Tharandt 5 and 95 year-old coniferous stands in Germany may support the above speculation, because there appeared no surface enrichment of ^{210}Pb at both stands[5].

Annual burial rate of ^{137}Cs in soil could therefore be estimated only from a set of data showing the type 1 profile. TABLE 4 summarizes values for ^{137}Cs as well as those for ^{210}Pb in pertinent soils. The burial rates of both nuclides are surprisingly similar in value for such different chemical properties of these nuclides, and for quite different soils of different geology and stand classes. Migration of fallout radionuclides has been studied extensively to understand the behavior of the nuclides after deposition and to predict potential radiological impacts in many places of the world. For example, Schuller et al.[13] investigated global fallout ^{137}Cs accumulation and vertical migration in soils from South Patagonia, Chile. They found no traces of Chernobyl-derived fallout radionuclides in soils. It means that the ^{137}Cs would be originated from the global fallout of atmospheric weapons tests only. About 35 years after the main radioactive fall-out period, ^{137}Cs had infiltrated into the soil to a depth of only 6-14 cm and can be expected to remain in the root zone of steppe grass for many decades. Similar results were also obtained by Arapis and Karandinos[14] who investigated migration of ^{137}Cs in the soil of sloping semi-natural ecosystems in Northern Greece. According to them, the concentration of ^{137}Cs was quite different among the four regions studied, but the vertical migration velocity of this nuclide was in the range from 0.1 to 0.3 cm/y in most contaminated areas. They also found that the bulk of ^{137}Cs deposited after the Chernobyl accident still retained in the upper 5 cm layer of soil.

It is inevitable to make a reliable model for predicting possible consequences of radiological situation in future. Bossew and Kirchner[15] investigated vertical migration of fallout radionuclides (^{106}Ru, ^{110m}Ag, ^{125}Sb, ^{134}Cs, ^{137}Cs and ^{144}Ce) in various soils using modified convection-dispersion equations. The model was fit to a set of 528 profiles in Austria to get apparent convective velocity and apparent dispersion constant. Typical values for the radionuclides focused in their study were 0.1-0.5 cm/y for the velocity, and 0.05-0.5 cm^2/y for the diffusion constant, respectively.

Another study on vertical migration of radionuclides was carried out by Bossew et al.[16] They focused on a glass land site in Chernobyl exclusion zone to obtain apparent downward migration velocity and dispersion coefficient to be 0.14-0.26 cm/y and 0.02 -0.13 cm^2/y, respectively. The burial rates obtained in our study (TABLE 4) may be consistent with those calculated with models.

All the results obtained in this study suggest usefulness of environmental radionuclides for estimating underground environment. Variability of the depth profile of primordial nuclides like ^{40}K and ^{226}Ra suggest a clue regarding that the soil could be considered as a homogeneous phase or not in a horizon of interest. Comparing profiles of fall-out nuclides (^{137}Cs and ^{210}Pb) makes it clear if the soil would have been disturbed physically or biologically. Any consequences from bioturbation will be further examined by direct measurements of the nuclides in biological samples as well as soils including speciation of these nuclides. Importance of bioturbation for radionuclide transportation was demonstrated by Lemans and van Dorp[17] who estimated the amount of dry matter transported by earthworms from deep soil to top soil to be around 2 kgm^{-2}/y.

In any case, long-term monitoring is necessary to elucidate seasonable variability of biological activities including root-uptake by plants and burrowing organisms living there.

It is also necessary to elucidate speciation of the radionuclides associated with various soil components to evaluate biological uptake of the nuclides. As Salbu et al.[18] suggested, key factor contributing to the overall uncertainties in environmental impact assessments are the source term including radionuclide speciation, mobility, biological uptake and accumulation.

Further study is in progress to evaluate underground biological activities using environmental radionuclides in various forest soils.

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