

Accumulation properties of Norway spruce (*Picea abies*) for different radionuclides

Ewa Tomankiewicz,
Jerzy W. Mietelski,
Paweł Gaca,
Sylvia Błażej

Abstract The paper presents results for the ^{137}Cs , ^{90}Sr , ^{40}K activity concentrations and $^{228}\text{Th}/^{232}\text{Th}$, $^{230}\text{Th}/^{232}\text{Th}$ activity ratios in several samples needles from two Norway spruce (*Picea abies*) trees and two soil samples collected in the Tatra Mountains (Poland) area. Activities for artificial ^{137}Cs and ^{90}Sr show moderate values. Statistically different values were found between the mean concentration of ^{90}Sr and ^{137}Cs in current (C) and two years old (C+2) needles of the first tree, whereas for potassium no significant difference was observed. For the second, fallen tree, no significant difference between the mean activity concentration in needles for C+1 and C+2 was found for each radionuclide, but much lower levels of ^{137}Cs contamination were observed. Observed values of the aggregation coefficients for ^{137}Cs and ^{90}Sr are presented.

Key words ^{137}Cs • ^{90}Sr • thorium • spruce tree • the Tatra Mountains • aggregation coefficients

Introduction

In 1987, it was found that radiocesium moves during the growth of the tree Norway spruce (*Picea abies* (L.) Karst, former name *Picea excelsa*) to the youngest needles [17]. The feature of such mobility is called remobilization. To confirm this observation in conditions of Tatra Mountains environment many years after the fallout occurred, the present work was planned. The other aim was to look for any remobilization in a dying tree. To extend the area of study, data on ^{40}K , ^{90}Sr and thorium isotopes were collected as well. We have used needles of two spruce trees – one was a healthy one and the other was broken by wind, but still green. To complete the work, the same radionuclides as for needles were analyzed in soil profiles collected nearby the trees.

Materials and method

Samples

Needles from fresh, current year shots (named C), a one-year old shots (C+1) and two years old ones (C+2) were collected on May 9th, 2003 from a single Norway spruce tree which stands in the Dolina Sucheju Wody, a valley in the Tatra Mountains (southern Poland) at an altitude of 1100 m above the sea level (a.s.l.), longitude 20°02' E, latitude 49°17' N. In the paper it is called the first tree or the standing tree. Another tree used for sampling (“the second one” or “the fallen one”), was the one which was entirely fallen down (not broken trunk) by wind in November 2002, but had still

E. Tomankiewicz✉, J. W. Mietelski, P. Gaca, S. Błażej
The Henryk Niewodniczański Institute
of Nuclear Physics, Polish Academy of Sciences,
152 Radzikowskiego Str., 31-342 Kraków, Poland,
Tel.: +48 12 662 83 92, Fax: +48 12 662 84 58,
E-mail: ewa.tomankiewicz@ifj.edu.pl

Received: 10 October 2005

Accepted: 29 December 2005

green needles during sampling in the some day of May 2003. It grew at an altitude of 1060 m a.s.l., longitude 20°06' E, latitude 49°18' N. That one did not have current year shots, so only C+1 and C+2 were collected. The trees were about 30–35 years old, the growing one was approximately 9 m tall and the fallen one was 13.9 m tall. From each tree, samples were collected at three different levels: below the top, from the middle and at the bottom of the tree canopy, from each level separately from north and south side of each tree. This second tree was planted in 1968 as a two-year old tree. The original orientation of the fallen tree was determined by observation of mosses present on the bark.

Sampling was completed by taking the samples of two profiles of the soil-litter nearby the trees. The soil profiles (including litter) were collected as cores taken with a plastic tubes, pressed into the soil. After drying, the profiles were sliced into 2 or 3 cm thick samples and homogenized by grinding. Samples of needles were dried at 105°C overnight and then also ground. Initial depth of the profiles were 12 and 30 cm, for the first and the second site, respectively. The difference was caused by a difficulty of taking a deeper core on the first site due to the stony soil. During drying the cores shrank. They were now 10 cm and 24.5 cm long, for the 1st and 2nd tree, respectively. All depths used in the paper refer to the dimensions of the shrank cores. The dry masses of each sample were determined. The basic data on samples are summarized in Table 1. The soil-litter samples (called in the paper as “soil” for simplicity) contained a lot of organic matter, as one can notice from the data in the last column of Table 1, where the ratio of ashed mass to dry mass is presented for each sample.

Samples were measured for ^{137}Cs and ^{40}K activities by gamma spectrometry, then a radiochemical procedure was applied to separate Sr and Th fractions to determine their activities (for Sr) or ratios (for Th).

Gamma spectrometric measurements

Samples were measured for ^{137}Cs and ^{40}K activities using a Silena gamma-ray spectrometric system with an HPGe detector of 10% relative efficiency and 1.7 keV (at 661.6 keV) resolution, shielded by 10 cm thick lead walls with 2 mm Cd and 2 cm Cu inner lining. Applied method for calibration of the spectrometer for different sample volume was already described in detail elsewhere [14]. Obtained spectra were evaluated using P.I.M.P. code [12].

Radiochemical procedure

The radiochemical analyses of all samples started with their incineration at 600°C in an oven. Ashes of needles were transferred to 250 ml PTFE beakers and then spiked with a tracer (^{85}Sr). Subsequent wet mineralization in hot mineral acids (HF, HNO_3 , $\text{HCl} + \text{H}_3\text{BO}_3$) was applied following the procedure of IAEA [11] with small our modifications [16]. To remove any possible traces of organic matter, some drops of H_2O_2 , HClO_4

were added very carefully to nitric acid and evaporated to dryness. The final solution for mineralization was 1 M HNO_3 .

During realization of the project, a microwave digestion system was introduced to our laboratory. Therefore, on the contrary to plant samples, the analyzed soil samples were already mineralized using an Ethos microwave oven (Milestone Ltd.), which allows digestion of the samples at 200°C using a pressure up to 10 MPa within special, pressurized PTFE beakers. Since a single microwave beaker could contain no more than 1 g of ash for a single run, each single sample was mineralized in many beakers during one run. To each part of the sample a mixture of 12 ml of conc. (65%) HNO_3 , 4 ml of conc. (32%) HCl and 6 ml of conc. (40%) HF was added. Mineralized portions of one sample were collected into a 250 ml PTFE beakers. An additional, cleaning run was done with the same amount of all acids and then combined with an appropriate sample into the same big beaker. In the case mentioned above, Sr tracers were added where all parts of a given sample were already combined together. Added activity of ^{85}Sr was at a level of 5 Bq (due to the short half-life time, the exact added activity value was different on a given day). We do not have any suitable Th tracer, so for Th only results on isotopic ratios were available. The initial solution (combined together after microwave digestion) was evaporated to dryness on a hot plate. The dry residue was dissolved in concentrated nitric acid, evaporated again, and re-dissolved in concentrated nitric acid, 2 g of boric acid was added to remove any traces of fluorides. Finally, the sample was diluted with deionized water to about 1 M HNO_3 and boiled for 10 min.

All the samples were filtrated using a filter paper and collected to glass beakers. Randomly chosen two soil samples were mineralized in both: classical and microwave ways for comparison, obtained results were consistent, but the microwave shortened the procedure by at least a day. For any way of mineralization, the final solution was set to 200 ml of 8 M HNO_3 . Separation of Th from 8 M HNO_3 solution was done using a Dowex-1 anion exchange resin, then immediately separation of strontium from the same 8 M HNO_3 solution was done using a Sr-resin. Th was removed from the anion-exchange column by 50 ml of 10 M HCl [11].

Strontium was eluted from the Sr-resin column together with some traces of lead (including ^{210}Pb) by 50 ml of 0.01 M HNO_3 , and later Sr and Pb were separated by precipitation of lead iodide [5]. Thorium alpha sources were prepared by the NdF_3 coprecipitation method [11, 16, 18]. Alpha spectra of Th were collected using a Silena AlphaQuattro alpha spectrometer with Canberra PIPS (450 mm²) detectors and ^{90}Sr activity was determined with a Wallac 1414-003 liquid scintillation spectrometer, using Wallac Hi-Safe 3 liquid scintillation cocktail, for the equilibrated ^{90}Sr - ^{90}Y fraction after determination of the chemical recovery of ^{85}Sr with a gamma spectrometer. The recovery was calculated from a relative measurement, i.e. by comparison of count rates for the 514 keV ^{85}Sr line (separated from the interfering 511 keV annihilation line in the spectrometer background) in the final

Table 1. Samples taken for analyses

No.	Sample description	Dry mass of whole sample [g]	Ash mass taken for analyses [g]	Ash to dry mass ratio
1st spruce tree				
1	needles, north side, top (ca. 6 m), C	43.1	1.1	0.025
2	needles, north side, top (ca. 6 m), C+1	21.7	0.6	0.027
3	needles, north side, top (ca. 6 m), C+2	9.6	0.4	0.042
4	needles, north side, middle (ca. 4 m), C	24.8	0.6	0.024
5	needles, north side, middle (ca. 4 m), C+1	17.1	0.6	0.035
6	needles, north side, middle (ca. 4 m), C+2	10.9	0.4	0.037
7	needles, north side, bottom (ca. 2 m), C	14.8	0.4	0.027
8	needles, north side, bottom (ca. 2 m), C+1	11.5	0.4	0.035
9	needles, north side, bottom (ca. 2 m), C+2	7.8	0.338	0.043
10	needles, south side, top (ca. 6 m), C	17.4	0.5	0.028
11	needles, south side, top (ca. 6 m), C+1	5.8	0.2	0.034
12	needles, south side, top (ca. 6 m), C+2	2.3	0.094	0.039
13	needles, south side, middle (ca. 4 m), C	32.9	0.9	0.027
14	needles, south side, middle (ca. 4 m), C+1	27.0	1.0	0.037
15	needles, south side, middle (ca. 4 m), C+2	14.6	0.6	0.041
16	needles, south side, bottom (ca. 2 m), C	28.8	0.7	0.041
17	needles, south side, bottom (ca. 2 m), C+1	18.4	0.6	0.032
18	needles, south side, bottom (ca. 2 m), C+2	14.0	0.5	0.036
2nd spruce tree				
19	needles, north side, top (ca. 12 m), C+1	54.8	1.2	0.022
20	needles, north side, top (ca. 12 m), C+2	16.5	0.410	0.025
21	needles, north side, middle (ca. 9 m), C+1	28.5	0.653	0.023
22	needles, north side, middle (ca. 9 m), C+2	20.6	0.509	0.025
23	needles, north side, bottom (ca. 6 m), C+1	22.3	0.436	0.020
24	needles, north side, bottom (ca. 6 m), C+2	17.8	0.426	0.024
25	needles, south side, top (ca. 12 m), C+1	40.5	1.09	0.027
26	needles, south side, top (ca. 12 m), C+2	24.3	0.657	0.027
27	needles, south side, middle (ca. 9 m), C+1	22.8	0.520	0.023
28	needles, south side, middle (ca. 9 m), C+2	20.3	0.5	0.025
29	needles, south side, bottom (ca. 6 m), C+1	14.9	0.4	0.027
30	needles, south side, bottom (ca. 6 m), C+2	12.0	0.304	0.025
Soil-litter, site of 1st tree				
	depth [cm]			
31	0–2.0	21.1	6.62	0.31
32	2.0–5.0 (two repetitions)	80.2*	9.77	0.72
			10.0	0.72
33	5.0–7.0 (two repetitions)	53.3*	10.71	0.77
			10.0	0.77
34	7.0–9.5	83.5*	9.48	0.80
35	9.5–12	70.5*	9.87	0.78
Soil-litter, site of 2nd tree				
36	0–1.5	38.8*	6.63	0.52
37	1.5–3.0	56.7*	6.23	0.72
38	3.0–4.5	83.5*	7.99	0.81
39	4.5–6.0	80.7*	7.26	0.85
40	6.0–7.5	103.3*	8.06	0.85
41	7.5–9.5	143.2*	8.18	0.85
42	9.5–11.5	108.8*	8.16	0.86
43	11.5–13.5	119.0*	7.46	0.87
44	13.5–15.5	156.2*	8.32	0.89
45	15.5–17.5	127.9*	8.11	0.89
46	17.5–19.5	179.1*	7.31	0.90
47	19.5–21.5	153.2*	8.19	0.90
48	21.5–24.5	241.5*	7.97	0.90

* Only a certain part of the whole sample taken for radiochemical analyses.

solution with the count rate in the same as spiked Sr tracer amount kept in identical geometrical conditions to the detector. Low energy beta radiation peak (11.4 keV) from ⁸⁵Sr visible on liquid scintillation

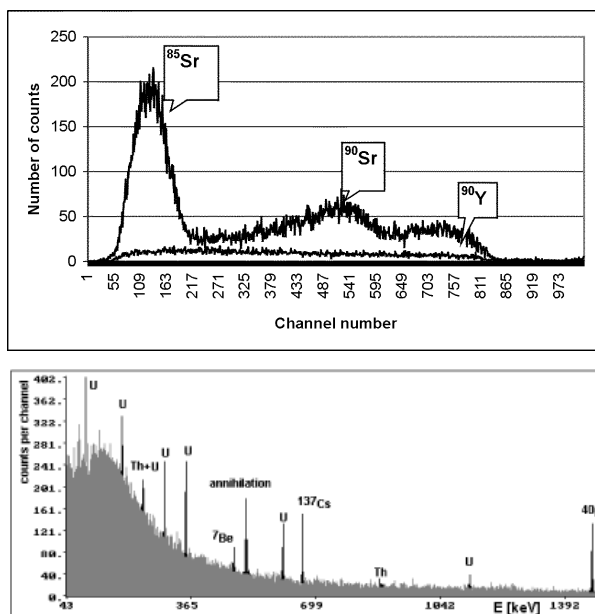


Fig. 1. Examples of the spectra obtained for spruce needle samples (from the tree top): a liquid scintillation beta spectrum of the $^{90}\text{Sr} \rightarrow ^{90}\text{Y}$ fraction (with ^{85}Sr tracer added, background of the spectrometer shown for comparison, sample no. 6, measurement time 21,633 s) and an HPGe gamma-ray spectrum of whole sample no. 19 (measurement time 136,140 s). Please note that beside ^{137}Cs , ^{40}K , background lines from uranium (U) and thorium (Th) series members, the cosmogenic radionuclide ^7Be is present (peak visible at 478 keV).

spectra was not used because of fear of possible chemoluminescence interference in the same energy region. Alpha spectra were evaluated using ALF code [16]. Average recovery of strontium (arithmetic mean) was equal to 0.70 with standard deviation equal to 0.17. Examples of obtained spectra are presented in Fig. 1. In the gamma spectrum, besides lines of ^{137}Cs , ^{40}K , U and Th series members one can notice a ^7Be peak of 478 keV. This cosmogenic radionuclide is present in the ground level air at a level of 3 mBq/m^3 [21] and, therefore, it is commonly observed also in freshly collected leaves or needles.

Quality assurance

The blank samples made of reagents were analyzed after each set of ten samples. Beside the blanks and samples,

the reference material (IAEA Soil-375) was analyzed to ensure the quality of the measurements [7]. A comparison of the obtained results with the certified values is presented in Table 2. The obtained activity concentrations for all the certified radionuclides were close to the reported values with a deviation not exceeding 13%.

To avoid any possible cross contamination, all glass or PTFE beakers were cleaned by washing them upside down in the vapours of boiling concentrated nitric acid for about 1 h.

Results and discussion

Radiocesium ^{137}Cs , radiostrontium ^{90}Sr and potassium ^{40}K in needles

Activity concentrations found for ^{90}Sr , ^{137}Cs and ^{40}K in the examined needles of two spruce trees are displayed in Figs. 2 and 3, for the first and the second examined trees, respectively. Statistical parameters characterizing activities found in the samples of needles are presented in Table 3.

The currently obtained results for spruce needles can be compared with some results obtained earlier. In one of our initial studies only the radiocesium (^{137}Cs and ^{134}Cs) activity was determined [8]. The results reported there for ^{137}Cs activity concentration from Southern Poland ranged (in 1987) from $20 \pm 2 \text{ Bq/kg d.w.}$ (dry weight) to $410 \pm 11 \text{ Bq/kg d.w.}$, and those for Finland (in 1988) from $34 \pm 4 \text{ Bq/kg d.w.}$ to $875 \pm 21 \text{ Bq/kg d.w.}$ The results of different radionuclide activity in the needles of spruce or pine coming from three locations in Poland (but not the Tatra Mountains), presented in our last papers [13, 15] do not differ much from the obtained now for the spruce from the Tatra Mountains. The activities of ^{137}Cs were similar or even higher for spruce needle samples from countries not affected strongly by the Chernobyl accident like, for example, Austria [19, 20], Sweden [4, 6] or Italy [1]. Much higher values of radiocesium and radiostrontium were found close to the Chernobyl NPP, like those reaching MBq's level reported, for example, in papers [2, 3]. Therefore, the general observation about the activities of artificial radionuclides measured here is that ^{137}Cs and ^{90}Sr seem to not exceed the expected levels, with maximum values equal to about 140 Bq/kg d.w. for ^{137}Cs and 80 Bq/kg d.w. for ^{90}Sr . Radiocesium

Table 2. Results for the IAEA Soil-375 reference materials [7] compared with certified values

Nuclide	Dry mass [g]	Measured value [Bq/kg]	Certified value [Bq/kg]	95% CL
Soil 375				
^{137}Cs	88.7	$5399 \pm 64^*$	5280	5200–5360
^{40}K	88.7	453 ± 45	424	417–432
^{137}Cs	28.2	$5350 \pm 47^*$	5280	5200–5360
^{40}K	28.2	480 ± 48	424	417–432
^{90}Sr	1.154	$104 \pm 9^*$	108	101–114

* Corrected for decay to the reference date (31 December 1991).

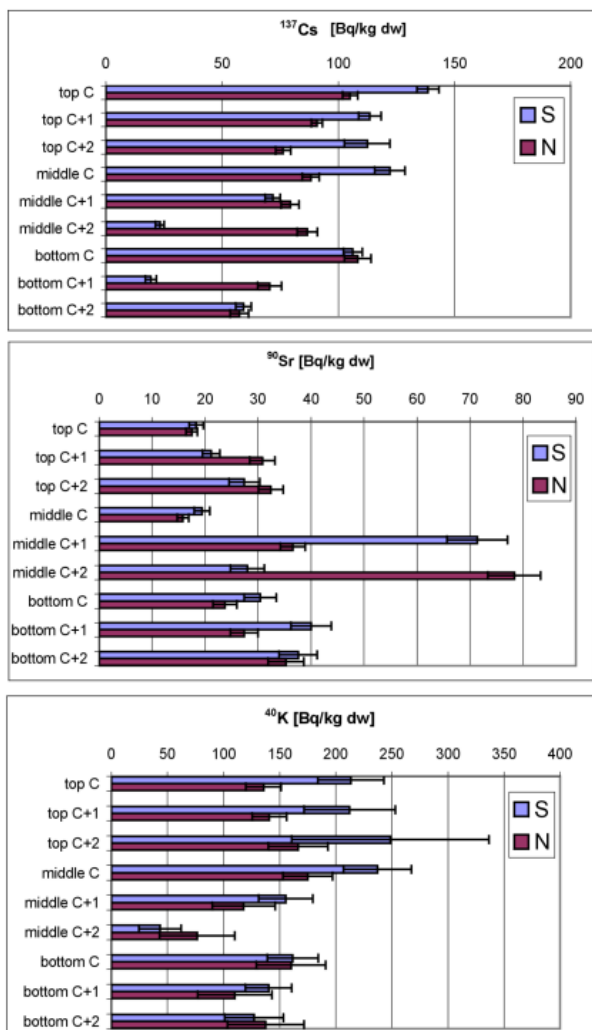


Fig. 2. Activity concentration for (from the tree top to the bottom): ¹³⁷Cs, ⁹⁰Sr and ⁴⁰K found in the first investigated spruce tree, for north and south sides of the tree.

levels in the fallen, second tree are significantly, an order of magnitude, lower than in the first tree.

Results presented here seem to indicate no difference between the needles, which grow on the south or the north part of the tree. One might expect a difference due to the presumed difference in water vaporization rate. Nevertheless, a large variety of results for needles from each of the trees can be noticed. The most interesting is the difference between ¹³⁷Cs and ⁹⁰Sr

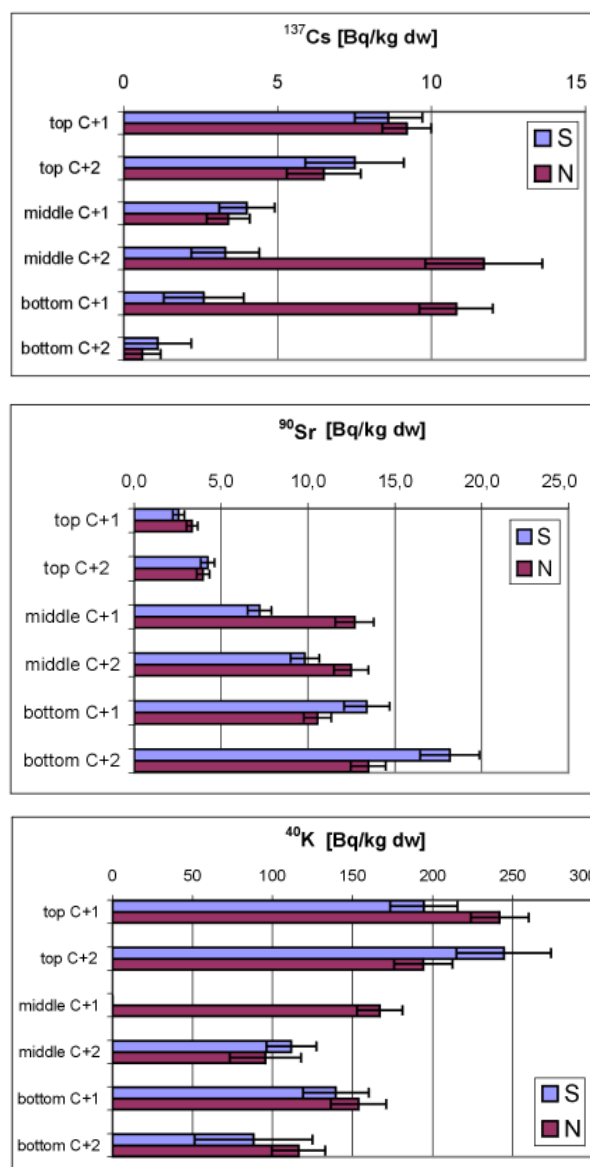


Fig. 3. Activity concentration for (from the tree top to the bottom): ¹³⁷Cs, ⁹⁰Sr and ⁴⁰K found in the second investigated spruce tree, for north and south sides of the tree.

activity in the needles of different age. Radiocesium seems to accumulate in the freshest needles, whereas radiostrontium accumulates in the older ones. To prove this a one-way Analysis of Variance (ANOVA) statistical test was applied to compare mean values for

Table 3. Statistical parameters for activity concentration in examined spruce needles

	[Bq/kg d.w.]								
	⁹⁰ Sr			¹³⁷ Cs			⁴⁰ K		
	C	C+1	C+2	C	C+1	C+2	C	C+1	C+2
1st tree									
Mean	20.8	37.9	39.8	111.5	74.2	69.2	181	146	133
SD	5.4	17.7	19.3	17.1	31.2	30.3	38	36	72
2nd tree									
Mean		8.3	10.4		6.4	5.1		145	142
SD		4.7	5.6		3.5	4.3		92	63

the first tree using GraphPad InStat software. To perform this test, all distributions should be Gaussian (what was confirmed by Kolmogorov-Smirnov tests done by this software) and the standard deviation should not differ significantly (assumption was tested by the method of Bartlett). For radiostrontium, the last assumption was not fulfilled, and in this case a non-parametric ANOVA (Kruskal-Wallis) test was applied. For the second tree, only two classes ($C+1$ and $C+2$) were available for each radionuclide, therefore another statistical test, the unpaired t-test was applied using the same software. It was found that for the first tree, statistically different were the mean concentrations of ^{90}Sr and ^{137}Cs only between C and $C+2$ and for potassium there was no significant difference at all. For the second tree, no significant difference between the mean activity concentration in needles $C+1$ and $C+2$ was found for each radionuclide.

Observed behaviour of cesium isotopes can be explained by their remobilization to the youngest (C)

needles during the growth of the tree. Such a feature was already recognized and confirmed [2, 3, 17, 19, 20] for radiocesium and for some trace metals as well ([17] – see also references therein). Accumulation of ^{90}Sr in the older needles was already known [2, 3], but not so widely confirmed. Strontium apparently follows the calcium distribution pattern in the tree. Moreover, low levels of ^{137}Cs in the second, fallen tree suggest a kind of mechanism, which removes cesium from dying needles.

Soil-litter samples

The activity concentrations of radiocesium ^{137}Cs and radiostrontium ^{90}Sr in the soil samples collected nearby the investigated trees are displayed in Fig. 4. Accordingly to the soil type map of the Tatra National Park [9], a general soil type on the first tree site is podzol or ranker and on the second tree site it is cambisol. One

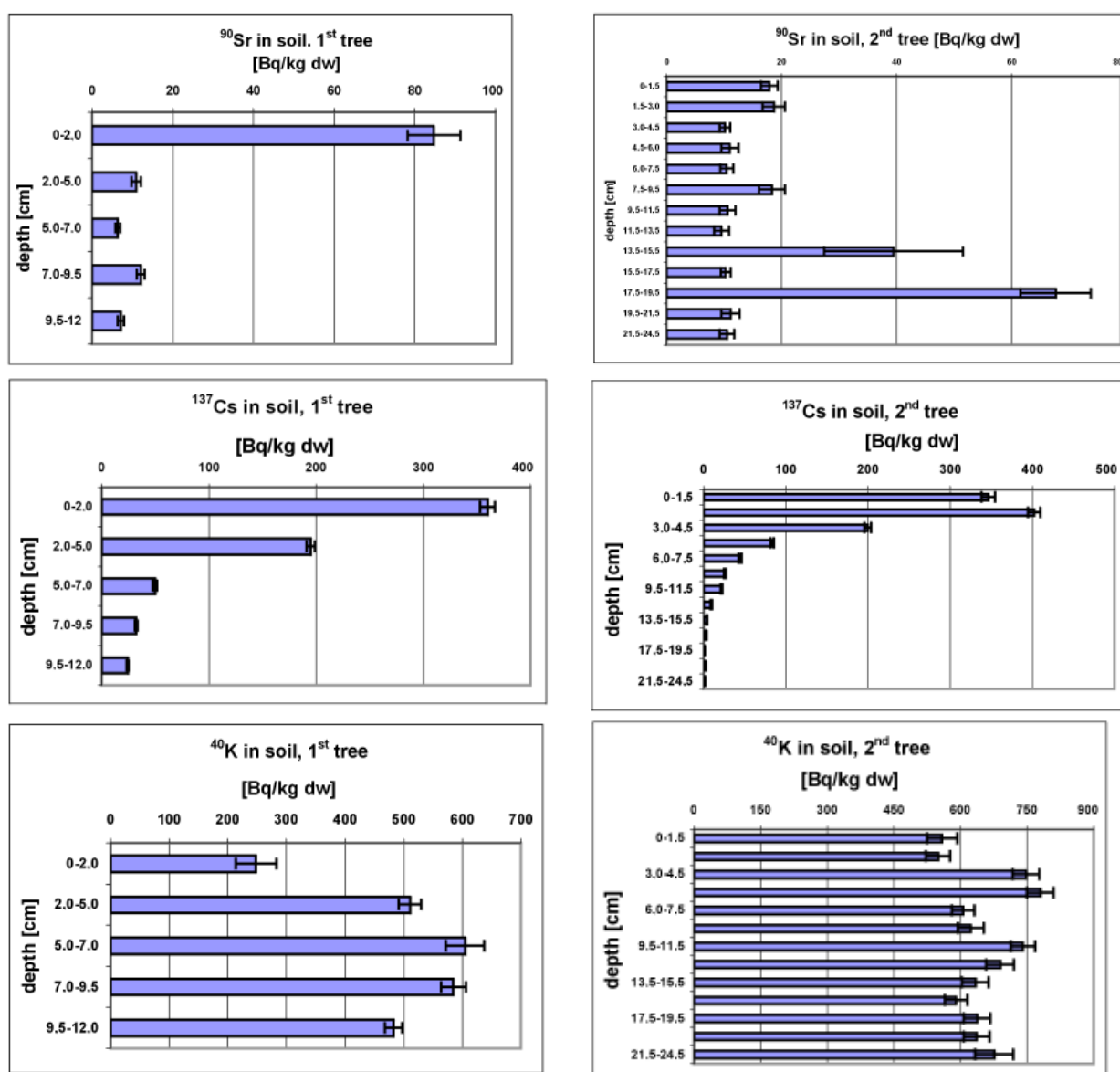


Fig. 4. Depth distribution of activity concentration for (from the tree top to the bottom): ^{90}Sr , ^{137}Cs and ^{40}K for the two investigated soil-litter profiles, nearby the first and second investigated tree.

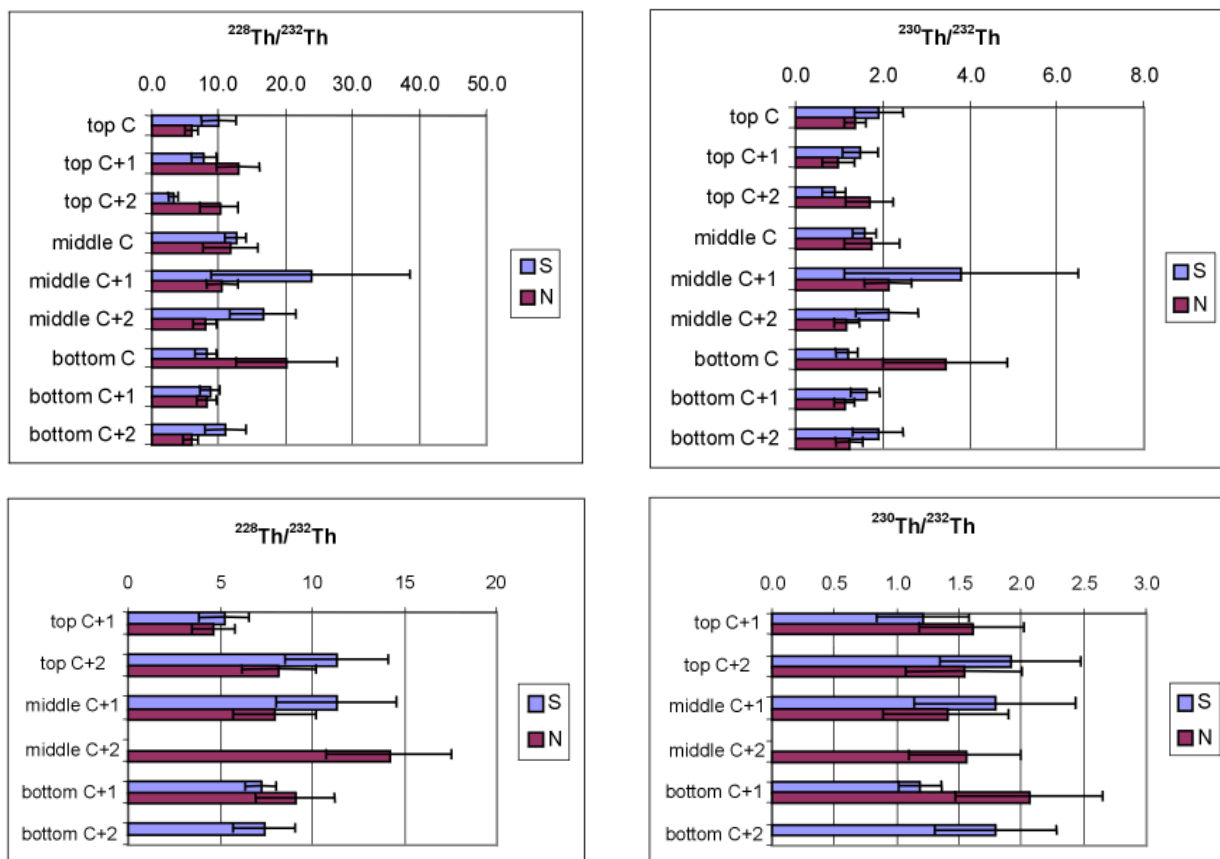


Fig. 5. Thorium activity ratios (^{228}Th to ^{232}Th and ^{230}Th to ^{232}Th) for the analyzed spruce needle samples, the first tree and second tree top and bottom, respectively.

can notice that radiocesium seems to be accumulated in top layers of soil-litter system, and mildly decreases with increasing depth. The maximum value for radiocesium has a maximum at about 400 Bq/kg d.w. in both cases falling to about 20 Bq/kg d.w. at the depth of about 10 cm. Radiostrontium has not so clear pattern. Its activity concentration seems to be almost constant at several becquerels with some unexpected, three or four times higher values for a single layer.

The total inventory for ^{137}Cs in all the examined layers of soil on the first site was $3570 \pm 80 \text{ Bq/m}^2$ and on the second site it was $8630 \pm 260 \text{ Bq/m}^2$ (95.8% of it in the first 10 cm). Analogous results for ^{90}Sr were $523 \pm 46 \text{ Bq/m}^2$ and $3840 \pm 545 \text{ Bq/m}^2$, for the first and second sites, respectively. However, it should be stressed here, that on the second site (which was sampled deeper) the inventory in the first 10 cm was only $950 \pm 58 \text{ Bq/m}^2$.

The described above values for the cumulated deposition of ^{137}Cs are within the range of the values found for the first 10 cm soil depths at the Tatra Mountains area [10]. No radiostrontium ^{90}Sr was measured earlier in soils on the Polish (northern) side of Tatra Mountains. Obtained maximum values for cumulated deposition of ^{137}Cs are about 2.5 times higher than the average deposition for appropriate latitude belt from the global fallout [21]. Important part of radiocesium, but no radiostrontium, came definitely also from the Chernobyl fallout, but identification using $^{134}\text{Cs}/^{137}\text{Cs}$ ratio is not available any longer due to the decay of ^{134}Cs .

If one would assume that the tree crown gives dry biomass [19] input at the level of about 1.7 kg/m^2 , the correction to the value of cumulated deposition of radionuclides, caused by their content in the needles is not very high, likely below 10%.

Similarity and differences for thorium isotopic ratios

There is no difference in $^{230}\text{Th}/^{232}\text{Th}$ activity ratio between the needle samples (Fig. 5). All results are within the uncertainty at a level of 1.5. However, the same ratios for both soil profiles are lower (Fig. 6), about 0.6 for the 1st tree and 0.8 for the 2nd one. This suggests little higher mobility of ^{230}Th (a member of the uranium series) than ^{232}Th (a member of the thorium series) in the environment, what leads to little more favourable uptake of ^{230}Th by the tree. If one would look at ^{228}Th to ^{232}Th activity ratios (both members of the Th series) in the tree needles (Fig. 5) or in the soil (Fig. 6) it can be noticed that this ratio is much higher (about 10 times) for the needles than for the soil samples, where it is about 1. This means indicates which radionuclide is preferably incorporated into the tree by the root uptake, it is likely ^{228}Ra rather than ^{228}Th . ^{228}Ra decays (via ^{228}Ac) to ^{228}Th . The decay apparently occurs within the tree, therefore the accumulation properties of this isotope reflect the behaviour of two elements: radium and thorium.

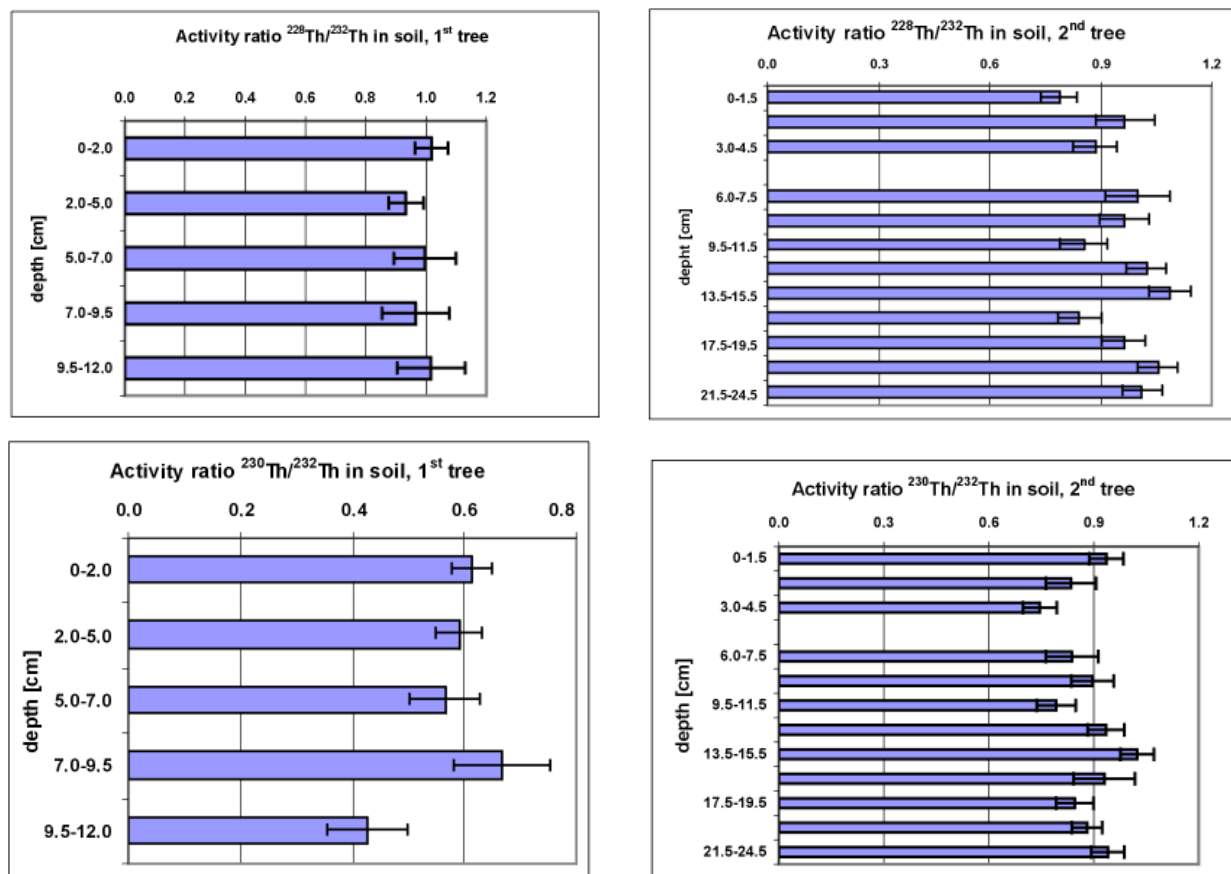


Fig. 6. Thorium activity ratios (^{228}Th to ^{232}Th and ^{230}Th to ^{232}Th) for the analyzed soil profiles.

Aggregation coefficients

Measured activities enable calculating the so-called aggregation coefficients (AC) for ^{137}Cs and ^{90}Sr between the soil and the tree as the ratio of the average activity concentration in needles (in Bqs per kg of dry mass) to cumulated deposition in the top 10 cm of soil (in Bqs per m^2 of area). We used the cumulated activities only for the first 10 cm, since this makes two sites comparable. Obtained data are presented in Table 4.

Conclusions

A variety of radionuclide activity concentrations within each examined tree has been found. This shows how the sampling procedure can be critical to the proper assessment of contamination of a given area using plant samples.

Table 4. Mean aggregation coefficient for the transfer from the top 10 cm of soil for a given radionuclide to the spruce needle of a given age [m^2/kg d.w.]

	^{90}Sr			^{137}Cs		
	C	C+1	C+2	C	C+1	C+2
1st tree	0.040	0.072	0.076	0.031	0.021	0.019
2nd tree		0.009	0.011		0.0008	0.0006

The remobilization of radiocesium to the youngest needles within a spruce tree was observed. A removal of radiocesium from dying tree seems to be noticed. Radiostrontium follows the pattern of calcium behaviour in the tree, cumulating in the older needles.

Results for Th isotopes activity ratios showed that there is a small difference in the mobility between ^{232}Th and ^{230}Th , and a huge difference between the ^{228}Th and ^{232}Th activities, so one can conclude that radium governs the observed differences here.

Acknowledgment This work was supported by the Grant no. 3 P04G 06323 from the State Committee for Scientific Research. The authors are thankful to Dr Z. Krzan, Deputy Head of Tatra National Park, for his great support and help.

References

- Baldini E, Bettoli MG, Tubertini O (1987) Chernobyl pollution in forest biogeocenoses. *Radiochim Acta* 41:199–201
- Buzinny MG, Kuchma MD (1998) Accumulation of ^{90}Sr and ^{137}Cs in plants of exclusive zone of Chernobyl NPP and its application for estimation of migration possibilities of radionuclide burials. In: Chernobyl-98. Scientific-practical conference, 30–31 March 1999, Kiev, Ukraine. Book of abstracts, p 61
- Buzinny M, Los' I, Shepelevich K (2000) The distribution of ^{137}Cs and ^{90}Sr in the biomass of pine trees planted in

- 1987–1988 in the near zone of the Chernobyl Nuclear Power Plant. *Appl Radiat Isot* 52:905–910
- Fawaris BH, Johanson KJ (1994) Radiocesium in soil and plants in a forest in central Sweden. *Sci Total Environ* 157:133–138
 - Gaca P (2004) Concentration of ^{90}Sr in the natural environment of Poland. PhD Thesis, Gdańsk University, Gdańsk (in Polish)
 - Högbom L, Nohrstedt H-Ö (2001) The fate of ^{137}Cs in coniferous forests following the application of wood-ash. *Sci Total Environ* 280:133–141
 - IAEA (2000) Analytical Quality Control Services. Reference materials catalogue 2000–2001. IAEA, Vienna
 - Jasińska M, Kozak K, Mietelski JW, Greszta J, Barszcz J (1990) Radioactive contamination of the forest of southern Poland and Finland. *J Radioanal Nucl Chem Lett* 146:1–13
 - Komornicki T, Skiba S (1996) Soils. In: Mirek Z (ed.) Nature of the Tatra National Park. Tatra National Park, Zakopane–Kraków, pp 215–229
 - Kubica B, Mietelski JW, Gołaś J *et al.* (2002) Concentration of ^{137}Cs , ^{40}K , ^{238}Pu , $^{239+240}\text{Pu}$ radionuclides and some heavy metals in soil samples from two main valleys from Tatra National Park. *Pol J Environ Studies* 11:537–545
 - LaRosa JJ, Cooper E, Ghods-Esphahani A *et al.* (1992) Radiochemical methods used by the IAEA's Laboratories at Seibersdorf for the determination of ^{90}Sr , ^{144}Ce and Pu radionuclides in the environment samples collected for the International Chernobyl Project. *J Environ Radioact* 17:183–209
 - Mietelski JW (1989) P.I.M.P. – A user-friendly computer code for gamma ray spectra evaluation on PC. Report IFJ 1435/S. Institute of Nuclear Physics, Kraków (in Polish)
 - Mietelski JW (2003) Nuclear spectrometry applied to study on bio-availability of radionuclides from “fuel-like hot particles” in forest environment. Report IFJ 1921/B. Institute of Nuclear Physics, Kraków (in Polish)
 - Mietelski JW, Jasińska M, Kozak K, Ochab E (1996) The method of measurements used in the investigation of radioactive contamination of forests in Poland. *Appl Radiat Isot* 47:1089–1095
 - Mietelski JW, Szwajko P, Tomankiewicz E *et al.* (2004) ^{137}Cs , ^{40}K , ^{90}Sr , $^{238,239+240}\text{Pu}$, ^{241}Am and $^{243+244}\text{Cm}$ in forest litter and their transfer to some species of insects and plants in boreal forests – three cases study. *J Radioanal Nucl Chem* 262:645–660
 - Mietelski JW, Waś B (1995) Plutonium from Chernobyl in Poland. *Appl Radiat Isot* 46:1203–1211
 - Ronneau C, Cara J, Apres D (1987) The deposition of radionuclides from Chernobyl to a forest in Belgium. *Atmos Environ* 21:1467–1468
 - Sill CW (1987) Precipitation of actinides as fluorides or hydroxides for high resolution alpha spectrometry. *Nuclear Chem Waste Mgmt* 7:201–215
 - Strebl F, Gerzabek MH, Bossew P, Kienzl K (1999) Distribution of radiocesium in an Austrian forest stand. *Sci Total Environ* 226:75–83
 - Strebl F, Gerzabek MH, Karg V (1995) Plant transfer factors in forest ecosystems. Report OEFZS-4746 Seibersdorf
 - UNSCEAR (1977) Ionizing radiation sources and biological effects. Report to the General Assembly with annexes. UN, New York