Thorium and uranium uptake and bioaccumulation by wheat-grass and plantain

Irina Shtangeeva[1]*, Xilei Lin[2], Andreas Tuerler[2], Evgeniya Rudneva[1], Vladimir Surin[1] and Richard Henkelmann[2]

[1] St. Petersburg University, Universitetskaya nab., 7/9, St. Petersburg 199034 Russia. shtangeeva@IS15148.spb.edu, agat@bp2956.spb.edu, inenco@mail.neva.ru

[2] Institut für Radiochemie, Technische Universität München, Walther-Meissner-Str. 3, D-85748 Garching. lin@rad.chemie.tu-muenchen.de, tue@rad.chemie.tu-muenchen.de, hen@rad.chemie.tu-muenchen.de

* Corresponding author

Abstract

The paper describes effects of uranium and thorium uptake on two native plant species wheat-grass (*Triticum repens* L.) and plantain *(Plantago major)*. The experiment was performed in a field trial. The plants were watered with solutions of uranium, thorium, and a mixture of the two radio-nuclides and then collected after two days. Concentrations of twenty-five elements in the plants and in the rhizosphere soil were determined by instrumental neutron activation analysis. Both plants accumulated rather large amounts of U and Th but uptake of U was higher than that of Th. The treatments affected concentrations of several elements both in different plant parts and in the soil. Wheat-grass was more affected than plantain. The treatments had significant influence on chlorophyll content in the plant leaves and growth of micro-organisms in the rhizosphere.

Keywords: thorium, uranium, wheat-grass, plantain, element concentrations in the rhizosphere and different plant parts, soil proteins, leaf chlorophyll

1 Introduction

Generally soils and plants contain all naturally occurring radioactive elements, though their concentration in plants may be rather low. The migration of uranium and thorium in the environment is of major environmental concern (AIREY and IVANOVICH 1986; BUCK *et al.* 1996). Fundamental knowledge of biogeochemical cycles of these metals and processes involved in their environmental migration are also of practical importance for power generation, water supply, agriculture, sewage disposal, and environmental protection and remediation. Although there are numerous reports in literature on biogeochemistry of both elements (SHEPPARD and EVEDEN 1988; MAZOR 1992; MORTVEDT 1994; VOIGT *et al.* 2000; YOSHIDA *et al.* 2000; EDMANDS *et al.* 2001; VERA TOMÉ *et al.* 2002; EHLKEN and KIRCHNER 2002; RODRIGUES *et al.* 2002; VERA TOMÉ *et al.* 2003; THIRY *et al.* 2005), the number of publications on uranium prevails. The studies on the fate and transport of thorium in the environment are more limited. However, recently the biogeochemistry of thorium has generated more interest to environmental scientists (HIGGY and PIMPL 1998; ZARARSIZ *et al.* 1997; MORTON *et al.* 2001; SAR and D'SOUZA 2002; MORTON *et al.* 2002; BEDNAR *et al.* 2004; LARSON *et al.* 2005). The authors have recently started the experiments on thorium effects on wheat seedlings (SHTANGEEVA and AYRAULT 2004; SHTANGEEVA *et al.* 2005).

The geochemistry of thorium is simplified by the existence of just one valence state, +4. Since thorium in solution is a highly charged cation it undergoes extensive interaction with water and many anions (WRIGHT 1999) to form complex compounds. Uranium has two valence states: +4 and +6. In soils, uranium typically occurs as hexavalent uranyl aqueous complexes (OHNUKI *et al.* 2005). An understanding of the mobility of U and Th in soils and their transfer to different plants requires a detailed knowledge of U and Th interactions with soil composed of abiotic and biotic components. Despite numerous studies on U and Th content in vegetation, there is little information yet related to the rate of their uptake and storage by different plant species, especially in field conditions. So far little is known about phytotoxicity of thorium and uranium. The chemical toxicity of actinides may be similar to that of heavy metals, however, the ionizing radiation associated with radioactive decay can result in additional toxic effects on a plant. Natural concentrations of U and Th in plants hardly pose any problem for the vegetation (BOWEN 1966). The effects may certainly be significant when the radionuclide concentration exceeds micromolar levels in the biomass. In this case the higher Th and U concentrations could affect certain biochemical and physiological processes in the plants.

The aim of this research was to estimate the ability of two widespread plant species – wheat-grass and plantain – to accumulate U and Th, and to assess the effects of the radionuclides on soil biota, plant nutrition and some physiological characteristics of the plants.

2 Materials and methods

A field experiment was carried out in the beginning of May 2005. Four small (1 m × 1.5 m) sites were used for the trial. Plants (wheat-grass and plantain) were watered with solutions of $Th(NO_3)_4$ (test 1), $(UO_2)(NO_3)_2$ (test 2) and a mixture of nitrates of U and Th (test 3). Concentrations of U and Th in the solutions were 60 mg L^{-1}. In test 3 the same amounts of Th and U were added simultaneously. Each site was watered with 1 L of the solution. The control (test 4) plants were watered with ordinary water. Each test was performed in five replicates. After two days, the plants and soil from the roots surface were collected. The soil was classified as Ferric Podzol (FAO-UNESCO 1988) with a loam texture. The plant samples were washed carefully just after sampling while they keep turgor to remove dust and smallest particles of soil from the surface of leaves and especially from roots. The plant and soil samples were dried at room temperature to constant weight and analyzed by instrumental neutron activation analysis. This analytical technique allows for determination of a wide range of elements in different environmental samples. The element detection limits are rather low. This gives us possibility to analyze all environmental samples in their natural state, without special sample preparation for element determination. Therefore, we can reduce the analytical errors arising during the process of sample pretreatments and thus, increase quality of analytical data. The samples were irradiated at FRM-II reactor of Munich Technical University for 18 hours (soils) and 24 hours (plants) in a thermal neutron flux of 1×10^{14} n × cm^{-2} × s^{-1}. The irradiated samples were measured twice within one and three weeks after the end of irradiation. Spectra of the irradiated samples were measured using germanium detectors. The k0-method was used to calculate concentrations of the elements (LIN and HENKELMAN 2004). A spectral photometer-reflectometer was used to study variations in chlorophyll content in leaves of the plants. The analysis was performed immediately after the plant sampling. The accuracy of the determination was 1–2% (KUVALDIN and SURIN 1998). Soil samples were also analysed for protein content. The method of Bradford (BRADFORD 1976) was used to quantify the amount of proteins in the

rhizosphere. Bowen serum albumin standards purchased from SIGMA Chemical Corporation (USA) were utilized to prepare calibration and internal standard solutions. Procedural blanks (0.1 mL of distilled water and 2.5 mL of protein agent) were analyzed to check for any contribution from the reagents. A statistical treatment of experimental data (programme Statistica for Windows 5.5) was used to estimate mean concentrations of elements and differences between groups of samples. Additionally, cluster analysis was carried out to assess effects of the treatments on element behaviour in the plants and soils.

3 Results and discussion

Mean concentrations of elements in soils and in different parts of wheat-grass and plantain are shown in Tables 1 to 3. The treatments significantly affected concentrations of many elements in soils and in plants. As we expected, concentrations of U and Th in the rhizosphere soil of the plants treated with U, Th and U+Th were higher than in the control soil. The treatments also affected concentrations of some other elements in the soils (Table 1). The most significant variations were observed as a result of Th treatment. It is interesting that the element variations in soil were well correlated with variations in the element concentrations in roots and leaves of wheat-grass. For example, a decrease of soil Rb content was followed by an increase of Rb concentration in the plant roots. We also observed a significant increase of K concentration both in roots and in leaves of wheat-grass. We hardly could expect a statistically significant decrease of total amount of K in soil since the amount of K taken by roots of wheat-grass was relatively small (considering the differences between the biomass of roots and the mass of the soil). Nevertheless, taking into account that Rb is a chemical analogue of K, we can suggest that Th treatment stimulated transfer of certain part of soil potassium to a more bioavailable form. The contents of Zn in the rhizosphere soil of U and U+Th treated plants decreased. Simultaneously concentrations of Zn increased in roots of wheat-grass treated with U and Th. Thus, we assume that U and Th treatments could transfer Zn to a more mobile form and stimulate Zn uptake by wheat-grass.

In our work, we considered not just changes in plant U and Th concentrations but also more attention was given to variations in concentrations of other macro- and micro-nutrients in the plants resulting from the treatments. Such variations often ignore, though we think that they may serve as a first sign of further changes in the plant physiological activity.

Wheat-grass demonstrated bigger differences between control plants and plants treated with U, Th, and U+Th compared to the same treatments of plantain. Treatment with U resulted in statistically significant variations in concentrations of seven elements in roots of wheat-grass, while in plantain roots just Na and Sr concentrations were higher than those in the control. Treatment with Th resulted in increased uptake of K, Zn, and Rb by roots of wheat-grass, and no effects were observed in roots of plantain. Similarly the impacts of U and Th were higher on leaves of wheat-grass than on leaves of plantain (Tables 2 and 3). Wheat-grass and plantain belong to two different families – Graminaceae and Plantaginaceae, respectively, and such differences might be expected. If we compare control plants, we can see that concentrations of K, Ca (and its chemical analogue Sr) in roots of control wheat-grass were higher than those in plantain roots, and concentrations of Na and Zn are significantly lower ($P<0.05$). Concentrations of K, Ca, Sr, and Ba in leaves of control wheat-grass are also higher ($P<0.05$) than those in plantain.

Table 1. Mean concentrations of elements (mg kg^{-1}) in soil.
*: differences between control and treated with U, Th, and U+Th samples are statistically significant at $P<0.05$.

Element	Control	+ U	+ Th	U+Th
Na,%	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.1 ± 0.1
K,%	2.4 ± 0.4	2.5 ± 0.2	2.4 ± 0.4	2.2 ± 0.4
Ca,%	1.1 ± 0.2	1.0 ± 0.2	0.9 ± 0.3	1.1 ± 0.4
Sc	8.1 ± 0.7	8.1 ± 0.8	7.0 ± 0.7*	7.2 ± 1.2
Cr	53 ± 5	52 ± 8	50 ± 8	49 ± 7
Fe,%	2.4 ± 0.2	2.3 ± 0.3	2.1 ± 0.2*	2.2 ± 0.4
Co	8.8 ± 0.6	9.0 ± 0.9	8.0 ± 0.7*	8.2 ± 1.5
Zn	135 ± 20	106 ± 21*	136 ± 19	114 ± 18*
As	2.8 ± 0.3	2.8 ± 0.5	2.9 ± 0.5	2.7 ± 0.7
Br	5.0 ± 0.5	5.2 ± 1.2	6.1 ± 0.6*	5.1 ± 1.2
Rb	111 ± 9	115 ± 8	99 ± 9*	104 ± 12
Sr	125 ± 55	143 ± 60	152 ± 63	124 ± 37
Sb	1.1 ± 0.4	1.0 ± 0.6	1.1 ± 0.3	0.8 ± 0.1*
Cs	2.8 ± 0.2	2.7 ± 0.3	2.1 ± 0.4*	2.4 ± 0.6
Ba	604 ± 83	617 ± 56	585 ± 42	573 ± 38
La	32 ± 3	32 ± 5	30 ± 3	40 ± 20
Sm	5.1 ± 0.5	5.2 ± 0.8	4.7 ± 0.5	5.6 ± 1.8
Eu	1.1 ± 0.2	1.0 ± 0.1	1.0 ± 0.1	1.0 ± 0.1
Yb	2.0 ± 0.5	2.0 ± 0.2	1.8 ± 0.3	1.9 ± 0.3
Lu	0.4 ± 0.1	0.39 ± 0.05	0.35 ± 0.05	0.38 ± 0.07
Hf	5.7 ± 1.7	7.1 ± 2.0	6.2 ± 2.5	6.0 ± 1.9
Ta	0.6 ± 0.2	0.7 ± 0.2	0.6 ± 0.1	0.7 ± 0.3
Th	9.6 ± 3.1	8.5 ± 1.7	28 ± 20*	19 ± 8*
U	2.2 ± 0.3	25 ± 21*	2.2 ± 0.4	12 ± 7*

Cluster analysis of the plant samples performed on the basis of element concentrations in the roots and leaves of the plants treated with the radio-nuclides showed that roots of wheat-grass treated with U, Th, and U+Th formed separated groups (Fig. 1a). Roots of the plants treated with Th and U+Th were closer to each other and well separated from roots of the plants treated with U. Such a tendency was also observed in the leaves of wheat-grass (Fig. 1b). We may assume that this resulted from more significant effects of U on the plant as compared to the effects of Th. Besides, simultaneously addition of U and Th could reduce the effects, probably owing to competition between these two metals. In plantain, the differences between different treatments were not so clear (Fig. 1c and Fig. 1d).

Comparison of the data presented in Tables 2 and 3 showed that wheat-grass probably was more affected than plantain. At least the number of statistically significant variations in macro- and micro-nutrient concentrations in roots and leaves of wheat-grass resulting from the treatments was higher than that in plantain. It seems likely that plantain was more tolerant to the treatments than wheat-grass.

If we compare uptake of U and Th by the roots of the plants we can see that U was more preferable taken by the plants compared to Th. This was typical for both plant species and all the treatments. It is known that U may be more mobile in the soil than Th and thus, more bioavailable compared to Th (Morton *et al.* 2002). Although U and Th are chemically and geologically linked (Ivanovich 1991; Evans *et al.* 1997), it is clear that their behaviour in the living systems may be different. Uranium can form complex compounds (Thiry *et al.* 2005), which may be rather easily taken by plants. In soil, Th very quickly transfers into insoluble

form and may be bound tightly onto the surface of soil particles (KATZIN and SONNEBERG 1986). However, it was reported that Th in the rhizosphere can create soluble complexes with humic acids (REILLERA *et al.* 2002). In this form plants can rather easily uptake Th.

Table 2. Mean concentrations of elements (mg kg^{-1}) in roots and leaves of wheat-grass.
[a] - concentrations of the elements are shown in μg kg^{-1}.
*- differences between control and treated with U, Th, and U+Th plants are statistically significant at $P<0.05$.

	Control		+ U		+ Th		U+Th	
El.	Roots	Leaves	Roots	Leaves	Roots	Leaves	Roots	Leaves
Na	2460±390	612±194	1820±200*	550±152	2050±370	514±65	2750±350	614±442
K,%	1.1±0.4	2.8±0.7	1.3±0.2	3.0±0.2	2.3±0.3*	4.0±0.4*	1.2±0.4	3.6±0.03
Ca,%	0.42±0.10	0.47±0.06	0.40±0.12	0.54±0.08	0.39±0.10	0.40±0.06	0.38±0.14	0.48±0.09
Sc	0.34±0.01	0.06±0.01	0.52±0.15*	0.06±0.02	0.37±0.16	0.04±0.01*	0.23±0.11	0.06±0.01
Cr	8.0±2.3	3.5±0.6	7.4±2.1	4.2±1.0	9.9±2.8	3.1±0.8	9.1±5.7	2.8±0.3
Fe	1700±237	307±28	1900±430	332±80	1330±450	226±46*	965±313*	313±49
Co	0.96±0.27	0.19±0.07	1.4±0.3*	0.19±0.06	0.78±0.25	0.08±0.02*	0.76±0.23	0.13±0.03
Zn	80±10	49±3	103±13*	49±8	101±17*	50±8	78±17	58±12
Br	3.8±0.9	1.4±1.3	4.1±0.9	1.3±0.4	5.0±1.2	1.1±0.6	18±30	1.2±0.6
Rb	4.4±0.8	4.1±2.4	5.7±1.4	2.9±0.9	6.7±1.0*	2.9±0.4	4.2±1.3	4.7±0.9
Sr	16±2	11±4	10±1	11±4	13±6	13±3	13±3	17±11
Sb	0.42±0.11	0.15±0.02	0.26±0.06*	0.25±0.08	0.31±0.08	0.16±0.03	0.80±0.69	0.19±0.06
Cs	0.67±0.30	0.09±0.02	0.37±0.19	0.11±0.08	0.47±0.15	0.08±0.02	0.41±0.25	0.07±0.02
Ba	30±11	14±3	41±12	14±5	33±13	22±6*	21±8	12±1
La	1.7±0.2	0.59±0.14	3.1±1.9	0.54±0.14	1.5±0.7	0.48±0.09	2.4±0.9	0.43±0.07
Sm	0.27±0.06	0.07±0.01	0.35±0.08	0.05±0.02*	0.23±0.10	0.07±0.02	0.30±0.12	0.06±0.01*
Eu[a]	220±108	20±5	70±23*	20±7	160±106	20±3	80±28*	20±7
Yb	0.18±0.08	0.08±0.02	0.14±0.06	0.12±0.03	0.12±0.07	0.09±0.02	0.10±0.05	0.08±0.02
Lu[a]	40±16	20±6	10±11*	30±7	30±11	20±4	30±5	20±3
Hf	0.60±0.04	0.53±0.10	0.57±0.06	0.61±0.13	0.80±0.47	0.52±0.14	0.67±0.16	0.38±0.06*
Ta	0.09±0.03	0.03±0.01	0.05±0.02	0.02±0.01	0.07±0.02	0.03±0.01	0.05±0.02	0.02±0.01
Th	0.43±0.04	0.14±0.01	0.8±0.4	0.19±0.05	13±6*	8.2±7.8*	1.8±0.8*	8.2±3.8*
U	0.16±0.19	0.14±0.08	162±96*	29±11*	0.31±0.20	0.13±0.06	3.2±2.7*	4.9±1.7*

A decrease in the chlorophyll content is one of the injury factors of exposure of plants to different metals (ERNST 2000). Chlorophyll content of wheat-grass and plantain leaves was affected significantly by the treatments with Th and especially U. Treatments with U and Th resulted in an increase of the coefficient of reflection (CR) of light by the plant leaves in spectral channel 0.38–0.63 μm (Fig. 2a). An increase of CR in this channel means that chlorophyll content in the plant was decreased. This indicates that after the treatment with radio-nuclides concentration of chlorophyll in the leaves was lower compared to the control plants and the decrease was most significant in the plants treated with U (the analysis was performed only for plantain). This data is in good agreement with previously published experimental results which demonstrated a decrease of leaf chlorophyll content resulting even from low doses of uranium (AERY and JAIN 1997; JAGETIYA and PUROHIT 2006). HAFEZ and RAMADAN (2002) suggested that the decrease in chlorophyll biosynthesis may be explained by replacement of Mg^{2+} ions by $(UO_2)^{2+}$. Uranium toxicity may relate to the disruption of the first step in glycolysis through replacing magnesium by uranyl in the enzyme (VAN HORN and HUANG 2006).

Table 3. Mean concentrations of elements (mg kg^{-1}) in roots and leaves of plantain.
[a] - concentrations of the elements are shown in μg kg^{-1}.
*- differences between control and treated with U, Th, and U+Th plants are statistically significant at $P<0.05$.

	Control		+ U		+ Th		U+Th	
El.	Roots	Leaves	Roots	Leaves	Roots	Leaves	Roots	Leaves
Na	1300 ± 220	953 ± 475	1670 ± 250*	535 ± 233	1220 ± 220	582 ± 191	1630 ± 570	488 ± 255
K%	5.4 ± 0.6	4.0 ± 0.6	6.1 ± 0.6	3.6 ± 0.6	5.9 ± 0.4	3.8 ± 0.5	6.3 ± 1.3	3.5 ± 1.3
Ca%	0.66 ± 0.10	1.6 ± 0.2	0.60 ± 0.09	1.7 ± 0.3	0.67 ± 0.04	2.2 ± 0.6	0.66 ± 0.03	1.9 ± 0.4
Sc	0.36 ± 0.08	0.13 ± 0.07	0.24 ± 0.09	0.09 ± 0.02	0.30 ± 0.07	0.08 ± 0.04	0.35 ± 0.12	0.11 ± 0.02
Cr	5.8 ± 1.2	5.3 ± 0.9	7.7 ± 3.4	5.0 ± 0.7	5.6 ± 1.4	4.7 ± 0.5	9.5 ± 3.6	5.0 ± 2.4
Fe	1870 ± 840	562 ± 239	1140 ± 270	436 ± 52	1030 ± 210	397 ± 135	1170 ± 340	474 ± 93
Co	0.77 ± 0.10	0.39 ± 0.13	0.65 ± 0.11	0.21 ± 0.04*	1.1 ± 0.4	0.38 ± 0.14	0.87 ± 0.22	0.28 ± 0.11
Zn	48 ± 5	49 ± 3	60 ± 14	55 ± 7	72 ± 26	61 ± 10*	54 ± 2	60 ± 6*
Br	4.3 ± 3.1	4.6 ± 6.1	1.9 ± 0.3	1.3 ± 0.4	2.4 ± 1.3	2.2 ± 0.7	2.4 ± 1.1	1.2 ± 0.4
Rb	6.7 ± 2.8	3.9 ± 2.3	4.9 ± 0.9	2.8 ± 0.7	6.6 ± 0.8	3.3 ± 0.6	9.1 ± 2.4	4.4 ± 1.3
Sr	42 ± 7	40 ± 8	67 ± 17*	42 ± 7	58 ± 15	58 ± 19	47 ± 19	59 ± 16*
Sb	0.23 ± 0.04	0.26 ± 0.05	0.24 ± 0.05	0.29 ± 0.23	0.22 ± 0.03	0.57 ± 0.80	0.38 ± 0.16	0.22 ± 0.04
Cs	0.26 ± 0.06	0.09 ± 0.07	0.20 ± 0.08	0.06 ± 0.02	0.27 ± 0.14	0.09 ± 0.01	0.42 ± 0.24	0.07 ± 0.01
Ba	56 ± 18	51 ± 9	51 ± 22	56 ± 6	85 ± 23	69 ± 34	51 ± 4	35 ± 25
La	1.6 ± 0.3	1.1 ± 0.5	1.2 ± 0.3	0.99 ± 0.25	1.5 ± 0.3	1.0 ± 0.3	1.6 ± 0.4	0.95 ± 0.40
Sm	0.20 ± 0.07	0.15 ± 0.07	0.15 ± 0.05	0.12 ± 0.03	0.20 ± 0.04	0.21 ± 0.15	0.22 ± 0.07	0.13 ± 0.05
Eu[a]	60 ± 14	30 ± 7	19 ± 18	30 ± 3	80 ± 28	30 ± 4	22 ± 19	30 ± 1
Yb	0.06 ± 0.02	0.14 ± 0.06	0.07 ± 0.02	0.14 ± 0.05	0.10 ± 0.04	0.12 ± 0.06	0.20 ± 0.11*	0.09 ± 0.07
Lu[a]	20 ± 2	40 ± 18	20 ± 12	40 ± 8	20 ± 8	30 ± 8	40 ± 20	40 ± 20
Hf	0.56 ± 0.21	0.76 ± 0.15	0.63 ± 0.11	0.82 ± 0.14	0.59 ± 0.16	0.70 ± 0.11	0.81 ± 0.12	0.80 ± 0.44
Ta	0.04 ± 0.01	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.01	0.08 ± 0.09	0.03 ± 0.01	0.07 ± 0.02*	0.07 ± 0.07
Th	0.38 ± 0.08	0.25 ± 0.13	0.27 ± 0.09	0.27 ± 0.15	4.4 ± 7.9	159 ± 193	3.2 ± 4.5	44 ± 33*
U	0.11 ± 0.08	0.09 ± 0.01	35 ± 30*	8.6 ± 7.7*	0.22 ± 0.15	0.68 ± 0.74	5.81 ± 0.8	23 ± 17*

Micro-organisms produce into soil extracellular compounds abundant with proteins (WRIGHT and UPADHYAYA 1996). Determination of rhizosphere proteins is supposed to be an accurate indirect method to assess soil microbial biomass because of a relatively high protein content in microbial cells (BAATN 1998). Our results showed that total amount of proteins in the rhizosphere of the plants treated with these radio-nuclides increased (Fig. 2b and 2c). This indicates that an addition of U and Th can enhance growth of soil micro-organisms. Furthermore, it was found that the higher amount of proteins in the rhizosphere of plantain observed the higher amount of U was taken by the plant roots and translocated to leaves. On the other hand, there was no such a correlation registered for wheat-grass.

Micro-organisms appear to be very sensitive and predictive tools in soil health monitoring. In particular, micro-organisms play an important role in regulating the mobility of U in soil (TICKNOR 1994; FOWLE *et al.* 2000; FRANCIS *et al.* 2004). However, in most previous experiments the negative effects on plant nutrition and growth of soil micro-organisms were observed. This inconsistence between published materials and our experimental results may hardly be explained by nitrate component of $(UO_2)(NO_3)_2$ because in this case we would observe absolutely the same effects from Th and from U.

The general response of plants to toxic heavy metals is to induce the synthesis of metal-binding compounds (RAUSER 1999; CLEMENS 2001; HALL 2002). In particular, it was shown that concentration of leaf soluble proteins may be significantly increased as a result of higher concentrations of uranium in soil (JAIN and AERY 1997; JAGENTIYA and PAROHIT 2006).

Based on the results of this experiment we can conclude that both Th and especially U are able to induce significant changes in plant nutrition and physiological activity of plants and soil biota. The effects are species-specific. Among the two plant species plantain was more resistant to the treatments than wheat-grass.

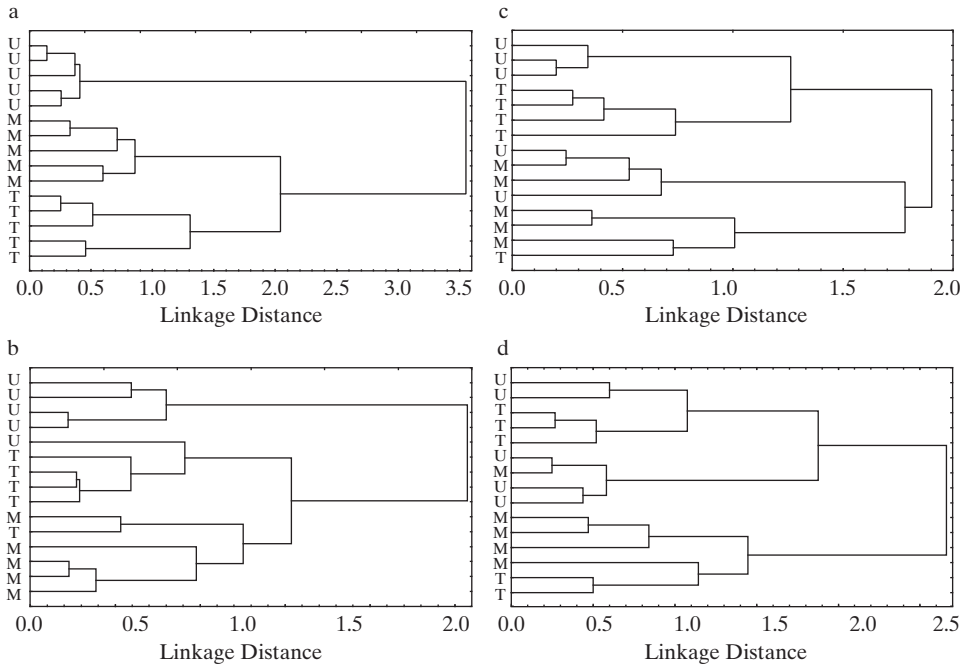

Fig. 1. Cluster analysis (Ward's method) of element concentrations in roots (a) and leaves (b) of wheat-grass and in roots (c) and leaves (d) of plantain. U, T, and M – the plants were treated with U, Th, and mixture of U and Th, respectively.

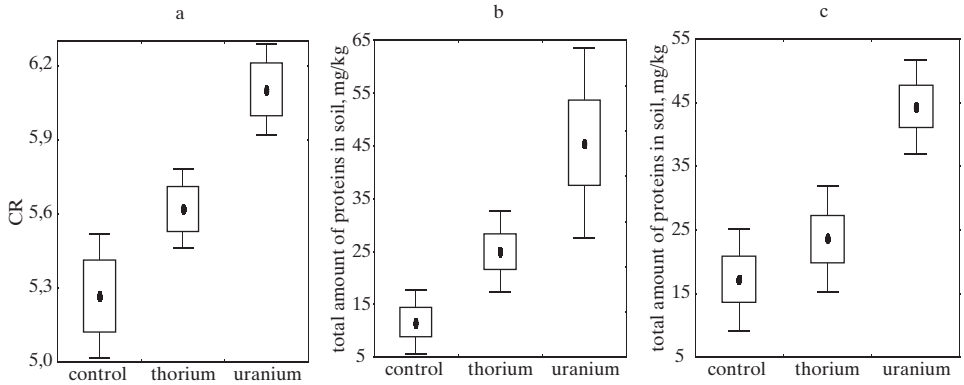

Fig. 2. Coefficient reflection of light (CR) in spectral channels 0.38–0.63 μm which correspond to chlorophyll content in plants (a) and total amount of proteins (mg kg $^{-1}$) in the rhizosphere soil of plantain (b) and wheat-grass (c).

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