PHYTOEXTRACTION OF THORIUM FROM SOIL AND WATER MEDIA

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Abstract. Remediation of ecosystems that have been exposed to radionuclides is of great importance for many countries. At present the remediation efforts using existing technologies are rather expensive. Phytoremediation can serve as a perspective method for rehabilitation of the radioactive contaminated soils and wastes. Among other radio-nuclides, limited information is available on screening and selection of plants for thorium uptake. In our work short-term pot experiments in a greenhouse have been performed to study the phytoextraction of thorium by wheat seedlings grown in soil and different water media artificially contaminated with thorium. Addition of a small amount of thorium to the media resulted in a significant increase of thorium concentration both in roots and leaves of the wheat seedlings. The uptake of Th by roots depended of the media where the plants grew: it was more significant in water-grown plants. The rate of Th translocation from roots to leaves was approximately the same regardless of the growth medium. The bioaccumulation of Th in the wheat resulted in the removal of Th from the soil and water. During the short-term vegetation test concentration of Th in all the media decreased: in water – 2–5 times, in soil – 1.7 times. Th accumulation in the wheat seedlings affected concentrations and relationships between other elements in the plants. More significant changes were found in the wheat grown in doubly distilled water and in nutrient solution. The most affected part of the plants was the root system.

Keywords: thorium, phytoextraction, soil, water media, wheat

1. Introduction

Remediation of ecosystems, that have been exposed to radionuclides, is of great importance for many countries. Since the effective start of the 'atomic energy era' with the construction of the first nuclear reactor in Chicago in 1942, there has been a series of additions to various soil radionuclides as a result of human activities of both cold war production of weapons and robust manufacturing, during the time when environmental matters and sustainable developments were not fully understood. The most known radioactive contaminated sites in the former Soviet Union are nuclear complexes in Siberia (Tomsk-7 and Krasnoyarsk-26), River Techa in the Ural, nuclear testing ground in Semipalatinsk (Kazakhstan) and the zone near the Chernobyl reactor. The total number of sites contaminated with radionuclides in the United States amount to thousands. The releases of radioactive wastes and different nuclear accidents were also reported for some European countries (Luykx

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and Frissel, 1996). Till now, many sites remain contaminated with no remediation in sight because it is too expensive to clean them up with available technologies.

Phytoremediation is a very promising technique for rehabilitation of the radioactive contaminated lands (Dushenkov *et al.*, 1997; Entry *et al.*, 1996). Unfortunately, main disadvantage of the phytoremediation technique is a long time required for clean up metal contaminated soils. For example, McGrath and coauthors (1998) reported that it would take nine years to reduce zinc concentration in soil from 440 to 300 μg g^{-1} using plants-hyperaccumulators. Therefore, the primary aim of the phytoremediation studies is to find suitable ways to enhance the rate of metal and radio-nuclide removal from contaminated soils and wastes.

The data on distribution of natural radioactive elements in terrestrial and aqueous plants has been demonstrated in many scientific publications (Ehlken and Kirchner, 2002; Mazor, 1992; Morton *et al.*, 2001; Mortvedt, 1994; Sheppard and Eveden, 1988; Voigt *et al.*, 2000). Among other radionuclides, limited information is available on the screening and selection of plants for thorium uptake (Misdag and Bourzik, 2002; Morton *et al.*, 2002; Raju and Raju, 1999; Sar and D'Souza, 2002; Tomй *et al.*, 2002; Zararsiz *et al.*, 1997). The levels of Th concentration in native plants are usually very low. It is rather common that the Th content in plants is near to the detection limits of many analytical techniques. On the basis of available literature, we may expect that due to the ability of the solid phase of soil to adsorb Th^{4+} ions the bioavailability of Th in soil may be rather low (Morton *et al.*, 2002; Sheppard and Eveden, 1988). On the other hand, it is known that tetravalent thorium is able to form complexes with organic molecules that roots and mycorrhizal fungi produce into the rhizosphere (Choppin, 1988). According to current hypotheses (Campanella and Roger, 2000), the complexes seem to be more soluble and mobile than the ions themselves. Therefore, the element-organic complexes may be easier absorbed by roots and translocated to other parts of a plant.

Because of numerous factors that affect the movement of elements through soil to roots, an effect of ion concentrations in the growth medium on uptake and kinetics of the ions in plant have often been studied in hydroponic systems. In particular, it was shown that Th^{4+} has an ability of strong complexing with a dissolved organic matter, an important ligand pool in natural water systems (Katzin and Sonnenberg, 1986). Due to this complexing, the uptake of Th in water-grown plants may be enhanced (Guo *et al.*, 1997). However, it is clear that soil and water (including various nutrient solutions) differ widely in bioavailability of nutrients and the ability to supply plants with macro- and trace elements. For example, plant tissue concentrations of radio-nuclides have rarely shown a linear relationship to radionuclide concentrations in soil (Morton *et al.*, 2002), while in water-grown plants linear correlation between concentration of the element in water and accumulation of the element in roots is rather a common phenomenon (Salt *et al.*, 1999).

The purposes of this research were (i) to study the potential of Th phytoextraction from different media (soil and water), (ii) to assess change in the Th content in the media, where the plants were grown, and (iii) to estimate an effect of Th bioaccumulation on concentrations of other elements and relationships between the elements in different parts of the plants.

2. Materials and Methods

The choice of appropriate plant species is an important stage of the phytoremediation research. The plants should be able to tolerate and accumulate high levels of metals in their harvested parts, have a rapid growth rate and potential to produce large biomass in the field. During the last twenty years, the development of phytoremediation was mainly based on the use of plants-hyperaccumulators (Baker *et al.*, 2000; McGrath *et al.*, 2000). Although the metal-accumulating plants have a good potential, it seems that crops may be more promising because of their greater biomass production. One of the alternative ways is to find large-biomass crops capable of increasing metal mobilization within the rhizosphere. Among others, wheat has a great potential for phytoremediation of metal and radionuclide contaminated soils. The wheat can uptake rather large amounts of metals and produce sufficiently high biomass, even in negative environmental conditions (this can result in the removal of more metals per planting). It was also shown that root exudates of the wheat generally are able to mobilize more metals from soil as compared to hyperaccumulators (Zhao *et al.*, 2001). For our experiments we chose wheat *Triticum vulgare (vill) Horst*. Since the young seedling stage is the most metal-sensitive stage for plants (Bajji *et al.*, 2002), it would be interesting to assess possible effects of Th exposure on the plant between the very beginning (after seed germination) and the first stages of the plant growth.

The experiments were performed in September 2000 in a naturally illuminated greenhouse. Two hundred and forty seeds of wheat *Triticum vulgare (vill) Horst* were obtained from a microbiological department of St. Petersburg Technical University. The seeds were germinated for six days on a moist filter paper at room temperature. Uniform germinated seedlings were divided into four equal parts and transferred to pots filled with soil (2 kg in each pot) and jars filled with different growth media: doubly distilled water, water taken from a spring and nutrient solution of Hoagland (3 L of water in a jar). The modified Hoagland's solution had the following composition: K as KNO_3 at 334 μM, Ca as $Ca(NO_3)_2$ at 68 μM and Mg as $MgSO_4 \cdot 7H_2O$ at 82 μM. The spring was situated in a park, 25 km from St. Petersburg, far away from roads and other possible sources of pollution. The soil was taken from a site near the spring out of a top (0–10 cm) soil horizon. Thorium nitrate was added to one part of the pots with soil and jars with water (50 μg kg^{-1} of Th was added to the water media and 75 mg kg^{-1} of Th was added to the soil). The other part of the pots and jars served as a control. Water in the jars was aerated throughout the whole experiment. The soil was watered daily. The plants were harvested three times – within two, four and seven days after planting. Water and soil (from the surface of roots, a zone of intense biological and chemical activity) were taken simultaneously with the plants. After sampling, water was placed in plastic bottles and kept in a fridge at a temperature of 4 °C. The soil was air-dried until it reached a constant weight. In order to remove dust and small particles of soil from the surface of leaves and roots, all plants were carefully rinsed by water immediately after sampling and also dried at room temperature up to a constant weight.

Instrumental neutron activation analysis was used to determine the concentrations of 26 elements (Na, K, Ca, Sc, Cr, Fe, Co, Zn, As, Br, Rb, Ag, Sb, Cs, Ba, La, Sm, Eu, Tb, Yb, Lu, Hf, Ta, Au, Th and U) in the soil (total concentrations of the elements) and in roots and leaves of the plants. Each plant sample represented a mean of three replicate pots and consisted of at least six plants harvested at the same time. The samples were irradiated for 17 hr in a thermal neutron flux of 1×10^{14} n cm^{-2} s^{-1} in a CEA/Saclay (France) nuclear reactor OSIRIS. The k0-method was used to calculate concentrations of the elements (Piccot *et al.*, 1997). Concentrations of Na and K in water samples were determined by liquid ion chromatography (DIONEX DX-120, with conductimetric detector). ICP-MS was used to determine the concentrations of 24 elements (Li, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Mo, Cd, Sb, Cs, Ba, La, Eu, Dy, Pb and U) in water samples. Before analysing, one half of each water sample was filtered through ester cellulose 0.22 μm syringe filter. The other part of the sample was analysed in its natural state, without filtration. The analysis was performed by a VG Plasma Quad PQ2+ ICP-MS instrument (VG Elemental, Winsford, Cheshire, U.K.) at the joint LPS-BRGM laboratory at Saclay. A multivariate statistical treatment of the experimental data was made in order to reach a better understanding of the bioaccumulation of thorium and other elements and to provide the way of estimating a contribution of specific factors that may have an effect on element interactions at the border plant root/surrounding medium. The statistical treatment included a calculation of mean concentrations of elements and analysis of variances to estimate statistically significant differences between groups of samples. Additionally, a cluster analysis (CA) and a principal component analysis (PCA) were carried out. The data for the PCA and CA were normalized to the unit concentration in order to avoid misclassifications, caused by different order of magnitudes of variables (Statistica for Windows 5.5 Software package).

3. Results and Discussions

3.1. Distribution of Thorium in Plants and Growth Media

Data on concentrations of Th in soil, water media, roots and leaves of the plants grown in soil and water are presented in Table I. Th content in leaves of all control plants was fairly similar regardless of the growth medium. Concentration of Th in

TABLE I

Mean concentrations of Th in plants (mg kg^{-1}) and in media where the plants were grown (μg L^{-1} in water solutions and mg kg^{-1} in soil) and ratio of Th concentrations in the plants, grown in Th enriched media to those in the control

Growth media	Control	Exp. (+ Th)	Exp./Control
Leaves			
Doubly distilled water	0.15±0.08	2.02±1.25	13.3*
Spring water	0.12±0.12	1.75±1.74	13.3*
Nutrient solution	0.13±0.11	1.64±1.35	17.3**
Soil	0.10±0.03	1.45±1.25	18.6**
Roots			
Doubly distilled water	0.08±0.07	2248 ±1333	28960***
Spring water	0.25±0.45	1974 ±823	4270***
Nutrient solution	0.68±1.09	1085 ±443	1819***
Soil	0.71±0.61	49.3±4.6	69.2***
Media			
Doubly distilled water	<0.087	5.47±4.83	
Spring water	<0.087	2.56±1.52	
Nutrient solution	<0.087	0.14±0.07	
Soil	7.0±2.9	39.1 ±11.6	

*, **, *** – Differences between control plants and plants grown in Th contaminated media were statistically significant at $P < 0.5$, $P < 0.01$ and $P < 0.001$, respectively.

roots of the control plants was not so constant as in leaves. The lowest Th concentration was observed in roots of the plants grown in doubly distilled water (it was even lower than that in the leaves). However, only differences in concentrations of Th in roots of the plants grown in doubly distilled water and in roots of the plants grown in soil were statistically significant ($P < 0.01$). An addition of Th to the growth media resulted in a significant increase of Th content both in leaves and, especially, in roots. The most noticeable accumulation of Th was found in roots of the plants grown in doubly distilled water. It seems that deficiency in all elements in the medium was a contributory factor for an enhanced uptake of Th in case of increasing the concentration of Th in the medium. The ratios of the concentrations $Th_{exp.}/Th_{cont.}$ were different in the leaves and in the roots. Besides, the $Th_{exp.}/Th_{cont.}$ ratios depended on the growth medium. Meanwhile, Th accumulation has not affected the biomass of the plants. After seven days, the length of the leaves of the wheat seedlings in all experiments and in the control was comparable. This

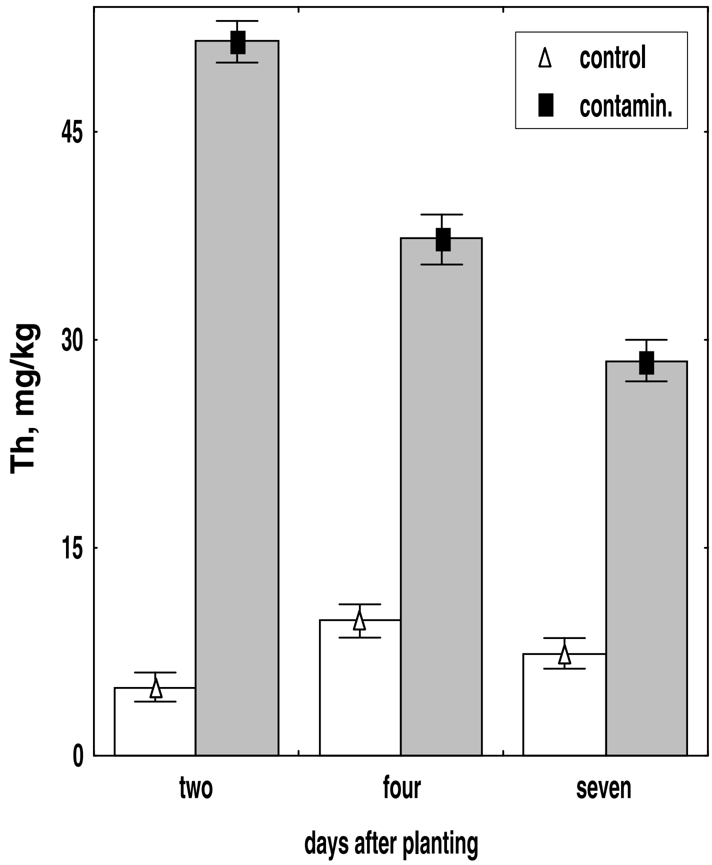

Figure 1. Dynamics of the Th concentration in clean (control) and artificially contaminated with Th soil within two, four and seven days after addition of Th to the soil.

indicates that Th was not very toxic for the plants. However, for our experiments we used rather short-term Th exposure. We may not exclude that physiological and biochemical consequences of longer radiolitic and chemical Th stress would not appear in further stages of the plant growth.

3.2. Variations in Th content in soil and soil-grown plants

In the course of the short-term vegetation test concentration of Th in the artificially contaminated soil decreased ~1.7 times (Figure 1). It is known that in contrast to aqueous systems, soils have an intimately associated solid-phase component that strongly buffers metal solubility (Sauve *et al*., 1998). As was reported (Katzin and Sonnenberg, 1986), all radionuclides due to their high complexing ability can bind tightly to solid surfaces. An addition of Th to soil might result in a rapid absorption of Th by an organic matter of the soil and Th adsorption on the surface of the soil particles and thus, transfers Th to a insoluble and non-available state for the plants. We may assume that the observed decrease of Th content in the soil was caused primarily by metabolic activity of the wheat seedlings. It was shown that root exudates play a decisive role in solubilization and mobilization of nutrients in soil (Aulakh *et al.*, 2001; Kirk *et al.*, 1999). Roots excrete a variety of organic acids and thus, create in the rhizosphere specific micro-environment, which may greatly differ from that in the bulk soil. The organic root exudates are able to enhance acquisition of nutrients by plant. For example, it is known (Katzin and Sonnenberg, 1986) that only a small part of Th, bound to a solid phase, can be dissolved by nitric and hydrochloric acids, while a large part of Th can be dissolved by oxalic acid. In this connection, it is necessary to note that many fungi dwelling on plant roots excrete just oxalic acid (Piimpel and Parkinar, 2001). Concentration of Th in roots of the experimental plants increased approximately to the level of Th content in the artificially contaminated with Th soil. A significant (18.6 times) increase of Th concentration in the leaves indicates that Th was easily translocated from the roots to upper parts of the wheat seedlings. Therefore, we may conclude that the decrease of Th content in the rhizosphere resulted solely from an uptake of Th by the plants.

3.3. Variations in Th content in water

Similar variations in Th concentration were observed in the experiments with wheat seedlings grown in water supplemented with Th (Figure 2). In all the media Th concentration in non-filtered water was higher than that in filtered water. As for the other elements, it was found that concentrations of some elements in filtered water differed from those in non-filtered water. For example, no statistically significant differences between concentrations of all elements studied in filtered and non-filtered doubly distilled water were registered. Concentrations of Sr in non-filtered and filtered nutrient solution of Hoagland were 84.2 and 80.3 μg kg^{-1}, respectively. The difference was statistically significant ($P < 0.05$). The Mn content in filtered spring water (0.21 μg kg^{-1}) was also lower, compared to the concentration of Mn in non-filtered water (0.38 μg kg^{-1}). It is surprising that the concentration of Cu in spring water increased after filtration from 0.76 μg kg^{-1} (in non-filtered water) to 0.98 μg kg^{-1}. In both latter cases (Mn and Cu in spring water) the differences were statistically significant ($P < 0.01$).

The simplest explanation of higher Th concentration in non-filtered water is, that a large part of Th in the water may be potentially bound to a dissolved organic matter. A number of studies reported that many trace elements can be strongly complexed in water by natural ligands (Di Toro *et al.*, 2001; Vasconcelos and Leal, 2001). As we mentioned above, the ability of Th^{4+} to form complex compounds in aqueous media is marked feature of the ions. As is seen from Figure 2, the differences between concentrations of Th in filtered and non-filtered water also depended on the type of the aqueous solution. At a first glance it is rather unclear why in spite of an equal amount of Th added to all water media at the beginning of

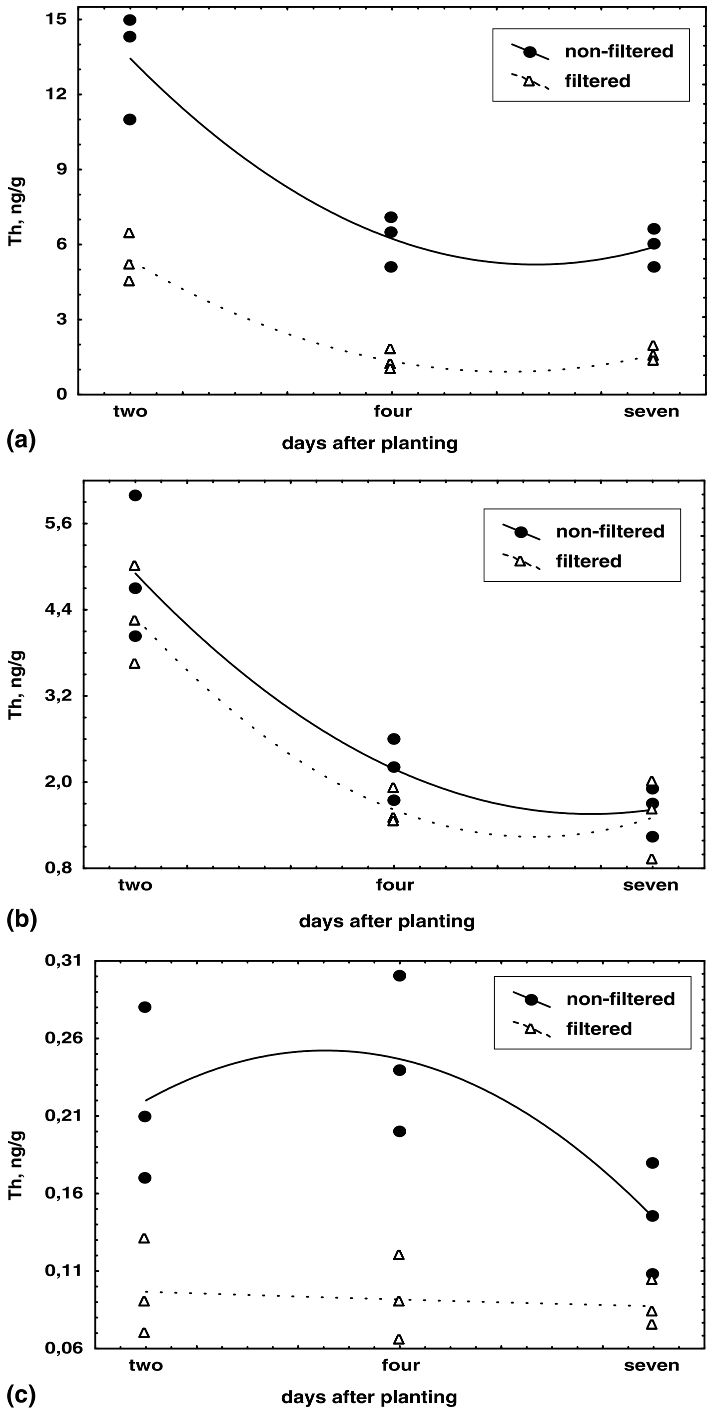

Figure 2. Variations in the concentration of Th in filtered and non-filtered doubly distilled water (a), spring water (b) and nutrient solution of Hoagland (c), as a result of seedling growth in the media.

the experiment, Th content in Hoagland's solution decreased at a higher extent than in doubly distilled and spring water. This phenomenon, however, may be explained by the fact that in the nutrient solution Th may form insoluble complexes with sulphates and precipitate on the glass wall surface of the jars. More important is that the level of Th content in the plants grown in the nutrient solution was rather high (approximately equal to that in the plants grown in the other water media). On the one hand, it seems reasonable that a quantity of Th absorbed by plants should be linearly dependent on the concentration of this element in water. But on the other hand, there is the departure from the linear dependence at low concentrations of radionuclides in medium (Murin, 1960). In this case radionuclides usually show increased adsorption.

3.4. Dynamics of Th content in growth media and in different parts of plants

Dynamics of Th content in the experimental growth media and in different parts of the plants grown in the media, is shown in Figure 3. With time the concentration of Th, both in roots and in leaves of the plants, grown in doubly distilled water and in spring water increased, while Th content in the waters decreased. It is important that the increase of Th concentration in the media was accompanied by an increase of Th content in leaves of the experimental plants. This indicates that Th was actually removed from the water. It was reported that even dead plant tissues could adsorb large amounts of certain metals from the water where the plants were placed (Schneider and Rubio, 1999). However, this is a simple biosorption process. Although it has been commonly assumed that Th movement through plant tissues is limited by adsorption onto cell walls (Sheppard and Eveden, 1988), in this study it seems that specific complexation and chelation processes resulting in increased mobility and bioavailability of Th take place. As one can see, a translocation of Th to the upper parts of plant was also increased.

It is known that cell walls may have a negative charge due to an arrangement of carboxyl and phosphate groups of protein (Neis, 1999). It has also been stated that Th^{4+} shows a strong tendency to form complexes with organic acids (Katzin and Sonnenberg, 1986). Thus, owing to the electrostatic attraction between the charged functional groups and organically bound Th^{4+} the ordinary rate of Th transport across the lipid membranes of the cells may rise. As a result of the increased membrane permeability, concentration of Th may increase not only in roots, but also in the leaves of plants. Lastly, it has been proposed that differences in a solution composition may have a marked effect on the permeability of cell membranes by altering the surface electrical potential on the membrane (Zhang *et al.*, 2001). This may explain the observed differences in the uptake of Th by wheat seedlings grown in the different water media.

A more complicated situation was observed in the experiments with soil and nutrient solution of Hoagland: an explanation of Th transport in both latter cases

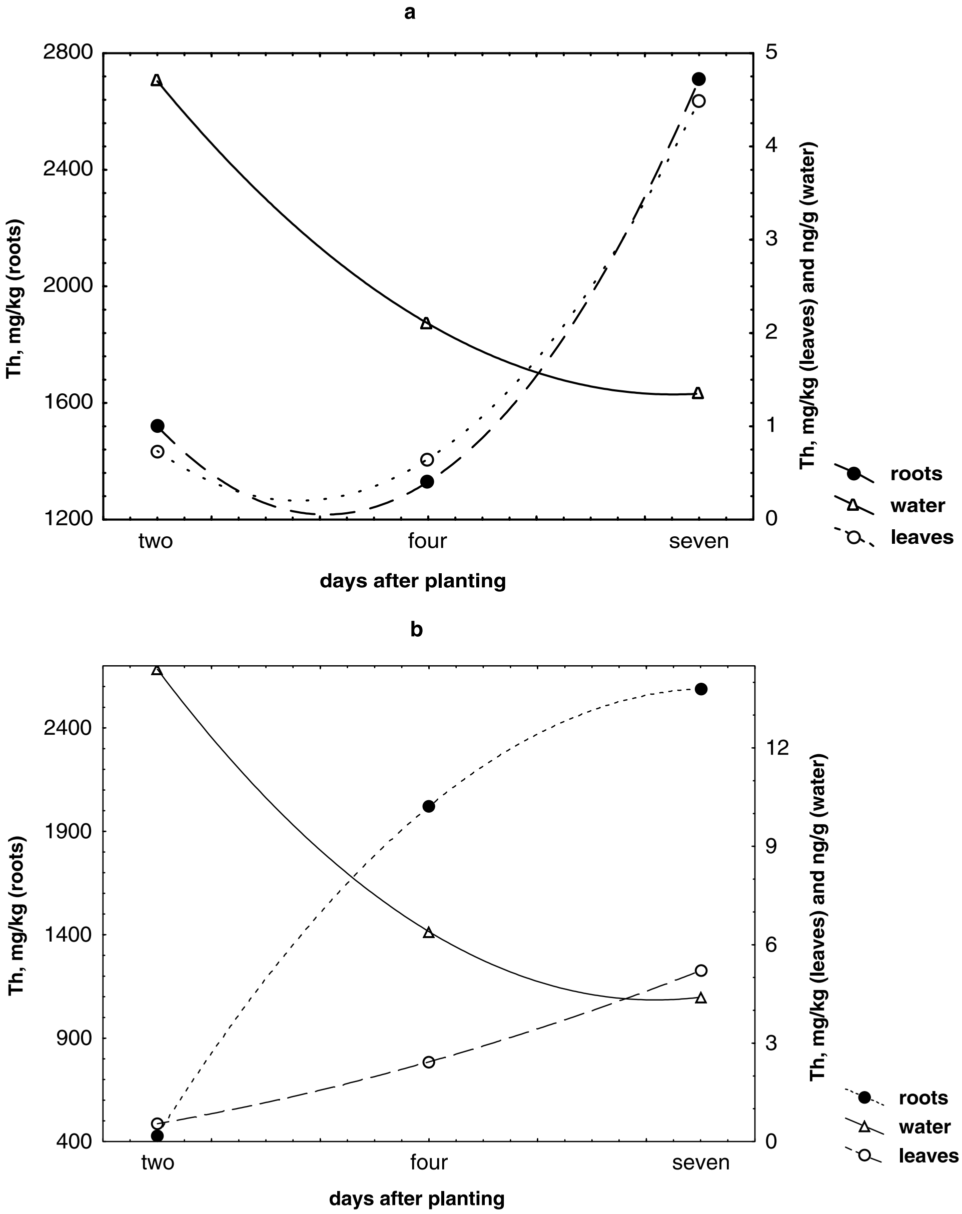

Figure 3a-b. Variations in the concentration of Th in different parts of plants, grown in spring water (a) and doubly distilled water (b), and the changes in Th concentration in the growth media.

was rather problematical. Here, an initial increase of Th concentration in roots was followed by a decrease (approximately 1.5 times). It seems that in this case the distribution of Th in the contact zone (root – medium) tended to equilibrium. By this time, in Hoagland's solution, Th was either absorbed by plants or precipitated

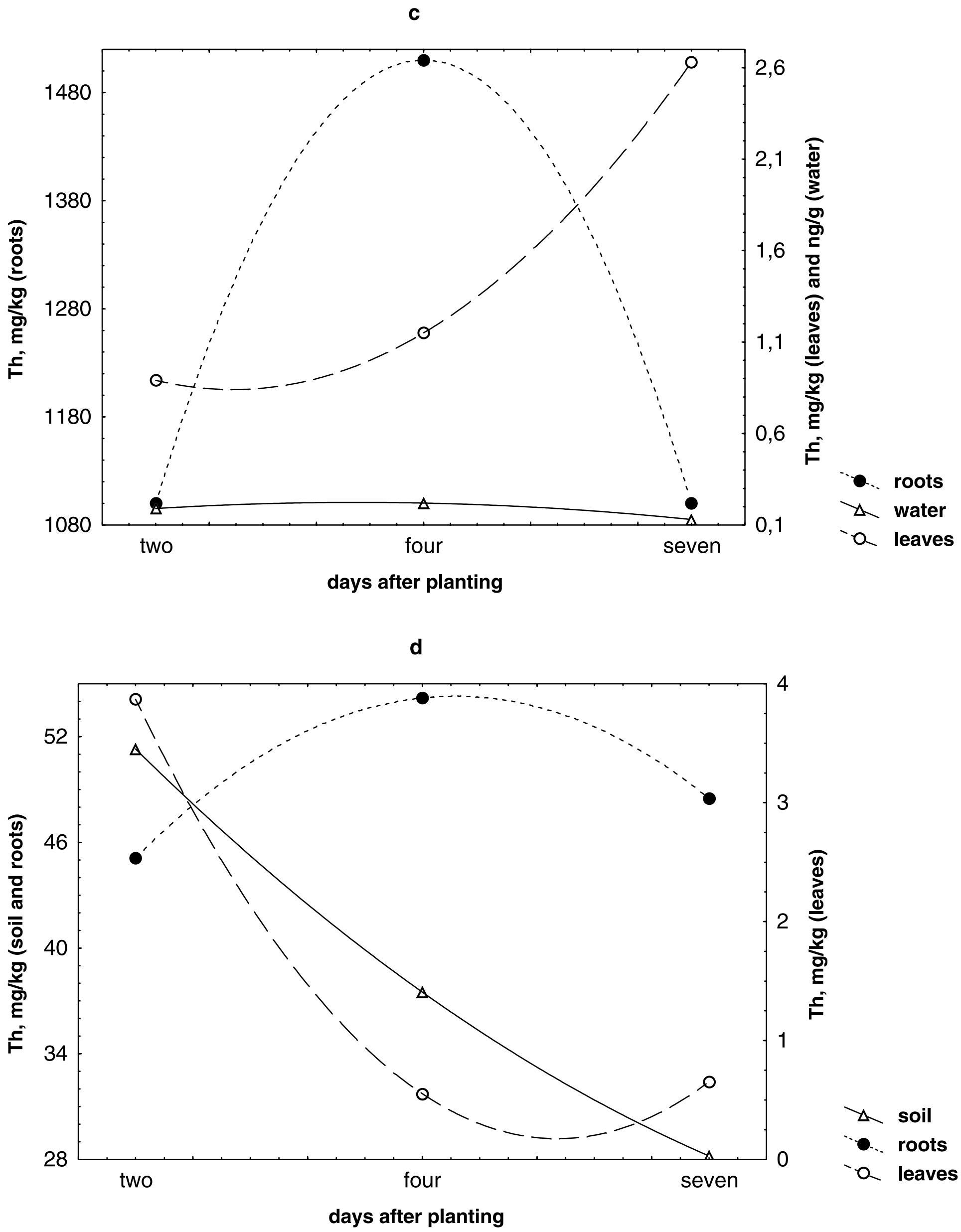

Figure 3c-d. Variations in the concentration of Th in different parts of plants, grown in nutrient solution of Hoagland (c) and soil (d), and the changes in Th concentration in the growth media.

on the walls of the jars. A similar situation might take place in soil. Root and fungus exudates had been already unable to dissolve the rest of Th bound to a solid phase of the soil. Besides, surface adsorption of metals on cell walls (metabolism independent biosorption) is frequently a reversible process causing no damage to the biomass. Therefore, plants could regulate the level of Th content in both directions – either increasing or decreasing it – in order to maintain intracellular concentration of Th within certain range. For example, in contrast to all other media, rapid accumulation of Th in the leaves of soil-grown plants was succeeded by Th efflux. After a 2-day growth of the plants in the soil, supplemented with Th, the concentration of Th in the leaves was several times higher than that in the control plants. Then, the Th concentration in the leaves fell back to about the same level as in the control. It is difficult to tell at the present, whether the decrease of Th content in leaves of the soil-grown plants resulted from vaporization of Th from the leaves jointly with transpired water. Maybe there was another reason for such a behaviour of Th in the soil-grown plants. Nevertheless, the short-term vegetation test demonstrated an actual decrease of Th concentration in soil and water.

3.5. Effect of Th on distribution of other elements in wheat seedlings

It would also be of interest to estimate how Th accumulation in the wheat seedlings influenced concentrations of other elements in different parts of the plants. Minor variations in elemental composition were observed in the soil-grown seedlings, though even then concentration of Sb in leaves and concentrations of Hf and Cr in roots of the plants grown in Th contaminated soil were higher ($P < 0.01$) than in the control plants grown in ordinary soil. As compared to the experiment with soil, in the plants, grown in spring water, concentrations of several elements (Co, Ag and Au in leaves and Sc in roots) decreased. As to the plants grown in the two other media (doubly distilled water and nutrient solution of Hoagland), the most affected part of the plants was a root system. Concentrations of Co, Zn, Ag, Sb, Cs and Au in the roots of plants grown in the contaminated with Th nutrient solution were statistically significant higher, and Rb content was lower ($P < 0.01$) than the values obtained for the control plants, grown in the solution. Nevertheless, not any significant effect on elemental composition of leaves of the seedlings was seen. Lastly, after adding Th to doubly distilled water, concentrations of Sc, Zn and Cs in leaves and concentrations of Fe, Co, Rb and Cs in roots of the plants grown in the water were statistically significant lower than those in the control plants.

Figure 4 shows the results of the principal component analysis of the experimental data. Two first PCs explained 48% of the total variance of the system. Roots of the control plants, grown in soil and in spring water, were clearly separated from the roots of the control plants grown in doubly distilled water and in the nutrient solution of Hoagland. The PC1 (29%) was responsible for the separation. Positive loading values in the PC1 were obtained for Cr, Sc and La, negative – for Co. The PC2 (19%) was responsible for the separation of roots of the control plants and plants grown in Th contaminated media. The best separation was observed between roots of the wheat seedlings, grown in clean and contaminated doubly distilled water and in Hoagland's solution, while roots of the plants, grown in

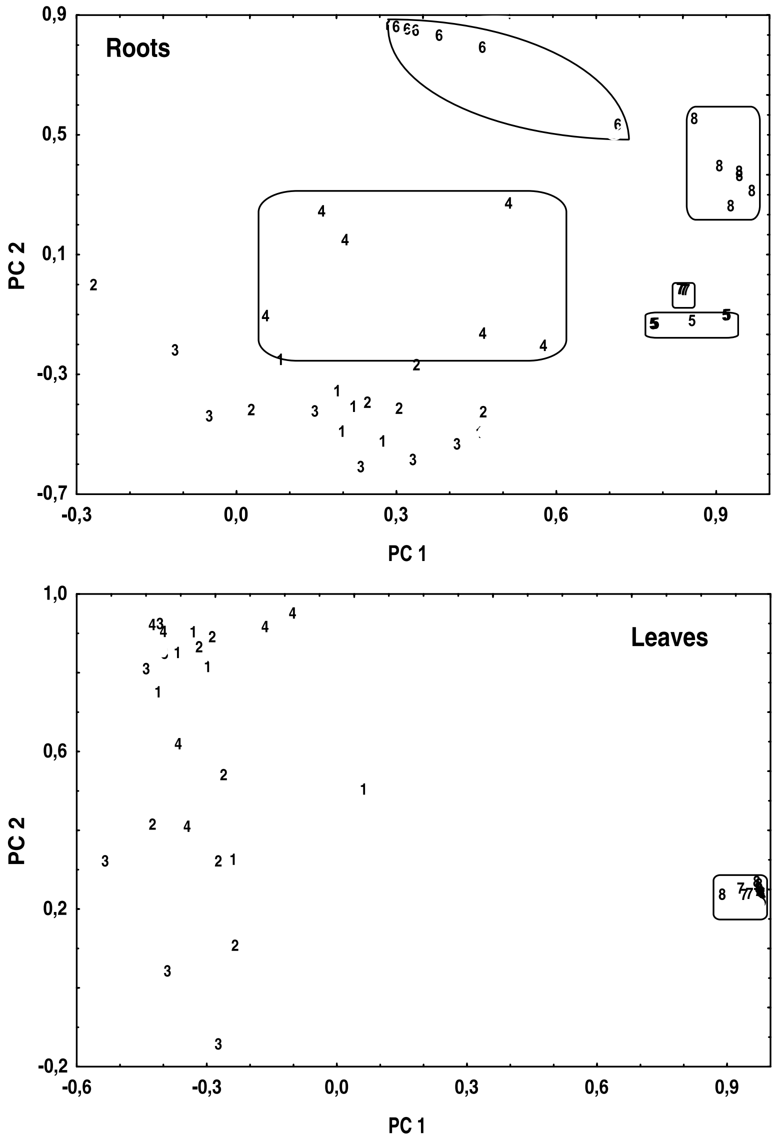

Figure 4. Score plot of the first and second principal components. Plants were grown in control soil (1), in Th contaminated soil (2), in control spring water (3), in Th contaminated spring water (4), in control doubly distilled water (5), in Th contaminated doubly distilled water (6), in control nutrient solution (7), and in Th contaminated nutrient solution of Hoagland (8).

spring water and especially in soil, were not separated very well. Although one might expect that Th could affect on the differences between the control plants and plants grown in Th contaminated media, just Rb and Ba highly correlated with the second PC. It is interesting that the leaves of plants, grown in different conditions, were separated depending only on the medium where the plants grew. The first

PC (42%) was responsible for the separation, and Cr, Co and La (just as it was in case of the roots) were highly correlated with the PC1. Moreover, a group of leaves of the plants, grown in doubly distilled water, was found to be very closely to a group of leaves of the plants grown in Hoagland's solution, while groups of 'soil' and 'spring' leaf samples were closer to each other and were separated from the two other groups. Perhaps, it was a specific response of the plants to growth conditions (an artificial environment for the two first groups compared to more natural conditions for the two last groups, especially keeping in mind that the soil was taken near the spring).

It would also be interesting to compare the relationships between different elements in roots and in leaves of the plants grown in the clean and contaminated media. The results of cluster analysis (hierarchical clustering, Ward's method) showed both similarities and differences in the relationships between elements in different groups of the plants. In particular, in all control plants grown in soil (roots and leaves alike) Sc highly correlated with Fe, and both these elements had statistically significant correlation with Th. Once the plants were placed in soil supplemented with Th, the correlation between Sc and Fe remained, while the relationships of the elements with Th were destroyed (especially in leaves). It seems that, the only similar correlation observed in different parts of the plants is the correlation between Sc and Fe. All other relationships between elements were special for just roots or just leaves. To illustrate, there was a significant correlation between K and Rb in the leaves of plants, grown in different media. However, there were no statistically significant relationships between potassium and other elements in roots of all plants. This may indicate that K^+ behaves rather differently in the leaves and roots. Besides, in the leaves of all wheat seedlings, was a observed significant correlation between Co and La. In roots, correlation La–Cr and Na–Co–Zn was observed in all plants, no matter where the plants were grown. An addition of Th to the media resulted in the change of correlation between elements in different parts of the wheat seedlings. Most relationships, typical for the control plants, failed. We may assume that the changes in the relationships between elements may serve as a first sign of harm caused to the experimental plants.

4. Conclusions

Wheat seedlings are able to accumulate large amounts of thorium. After one week growth of the seedlings in soil and water, artificially contaminated with thorium, the concentration of this metal in roots increased significantly (several thousand times in plants grown in water and 70 times in soil-grown plants). Concentration of Th in leaves also increased approximately 15 times, regardless of the medium where the plants were grown. Biomass of the seedlings, grown in thorium contaminated soil and water, was similar to the biomass of the control plants. However, concentrations of some trace elements in the seedlings did change, compared to those in the control plants. Phytoextraction of Th resulted in decrease of Th content in the growth media.

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