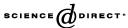


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# Soil to plant transfer of <sup>238</sup>U, <sup>226</sup>Ra and <sup>232</sup>Th on a uranium mining-impacted soil from southeastern China

S.B. Chen<sup>a,b</sup>, Y.G. Zhu<sup>a,\*</sup>, Q.H. Hu<sup>c</sup>

<sup>a</sup>Research Center for Eco-environmental Sciences, Chinese Academy of Sciences,

18 Shuangqing Road, Beijing 100085, PR China

<sup>b</sup>Institute of Natural Resources and Regional Planning, Chinese Academy of
Agricultural Sciences, 12 Zhongguanchun Road, Beijing 100081, PR China

<sup>c</sup>Chemical Biology and Nuclear Science Division, Lawrence Livermore National Laboratory,
PO Box 808, MS L-231, Livermore, CA 94550, USA

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#### Abstract

Both soil and plant samples of nine different plant species grown in soils from southeastern China contaminated with uranium mine tailings were analyzed for the plant uptake and translocation of  $^{238}$ U,  $^{226}$ Ra and  $^{232}$ Th. Substantial differences were observed in the soil—plant transfer factor (TF) among these radionuclides and plant species. Lupine (*Lupinus albus*) exhibited the highest uptake of  $^{238}$ U (TF value of  $3.7 \times 10^{-2}$ ), while Chinese mustard (*Brassica chinensis*) had the least  $(0.5 \times 10^{-2})$ . However, in the case of  $^{226}$ Ra and  $^{232}$ Th, the highest TFs were observed for white clover (*Trifolium pratense*)  $(3.4 \times 10^{-2})$  and ryegrass (*Lolium perenne*)  $(2.1 \times 10^{-3})$ , respectively.  $^{232}$ Th in the tailings/soil mixture was less available for plant uptake than  $^{226}$ Ra or  $^{238}$ U, and this was especially evident for Chinese mustard and corn (*Zea mays*). The root/shoot (R/S) ratios obtained for different plants and radionuclides shown that Indian

<sup>\*</sup> Corresponding author. Tel.: +86 10 6293 6940. E-mail address: ygzhu@mail.rcees.ac.cn (Y.G. Zhu).

mustard had the smallest R/S ratios for both  $^{226}$ Ra (5.3  $\pm$  1.2) and  $^{232}$ Th (5.3  $\pm$  1.7), while the smallest R/S ratio for  $^{238}$ U was observed in clover (2.8  $\pm$  0.9). © 2005 Elsevier Ltd. All rights reserved.

Keywords: Uranium; Thorium; Radium; Tailings-contaminated soil; Soil-plant transfer

#### 1. Introduction

The radioactive waste (e.g. tailings) produced by uranium mining activities contains a series of long-lived radionuclides, such as uranium (U), radium (Ra), and thorium (Th) isotopes. Over the years only some work on radioactive food contamination in the environment and its transfer or pathway mechanism to plants, animals and human population has been reported (Mitchell, 1974; Till and Moore, 1988; ICRP, 1993; Gaso et al., 2000); data are still very sparse in this research area, especially about the environmental radiological effect of uranium-mining activities in China.

Food consumption is the main source of human exposure to radioactive elements, which leads to internal radiation doses (Repin et al., 1998; Gaso et al., 2000). Santos et al. (2002) reported that the estimated annual effective dose, due to the ingestion of vegetables (leafy vegetables, fruit, root, bean and rice) and their derived products (sugar, coffee, manioc flour, wheat flour, corn flour and pasta) by the adult inhabitants of Rio de Janeiro City with the long-lived natural radionuclides (<sup>232</sup>Th, <sup>238</sup>U, <sup>210</sup>Pb, <sup>226</sup>Ra and <sup>228</sup>Ra), reached 14.5 μSv. Taking into account the data for water and milk, the dose value increases to  $29 \,\mu\text{Sv}$ . In China, little record of radioactive contamination of the environment has been reported. A great deal of effort has been made in establishing baseline radioactivity levels in the different environments in the country. Therefore, the knowledge of natural radionuclide concentration levels and their mobility in the environment is of great interest in several scientific fields. It is also important to understand the behavior of natural radionuclides in the environment (e.g., mobility, transfers, translocation), because such information can be used as the associated parameter values for radiological assessments (Mortvedt, 1994; Tome et al., 2003). Migration and accumulation of contaminants (including radionuclides) in the soil—plant system is complex, and assessment models commonly utilize a soil—plant concentration ratio, referred to as a transfer factor (TF), to estimate the transportation of radionuclides through the food chain. This ratio describes the amount of radionuclide expected to enter a plant from soil. As discussed by Bettencourt et al. (1988), factors such as soil characteristics, climatic conditions, type of plants, part of the plant concerned, physico-chemical form of the radionuclides and the interfering element can all influence the TF values. For example, the availability of calcium and potassium in soil for uptake will affect the uranium, thorium and radium content of the plant. Other soil factors such as illite clays of alluvial soil, which trap potassium in its crystal lattice, and the contents of phosphate that forms insoluble compounds with thorium, have been observed to reduce radionuclide availability to plants.

There are considerable differences in the uptake and translocation of long-lived radionuclides among different plant species. Up till now, several investigations on

mobilization of natural radionuclides (such as <sup>238</sup>U and <sup>226</sup>Ra) in different compartments (soil, plant, and water), as well as the transfer between them, have been performed at different uranium mining sites around the world (Petterson et al., 1993; Krizman et al., 1995; Fernandes et al., 1996). However, there is no information about the transport of <sup>238</sup>U, <sup>226</sup>Ra and <sup>232</sup>Th from soil to plant in temperate to tropical climate eco-systems in southeastern China. The objective of this work was to investigate the uptake and soil-to-plant transfer factors of radionuclides (<sup>238</sup>U, <sup>226</sup>Ra and <sup>232</sup>Th) in uranium mining-impacted soils in southeastern China, where the uranium mine tailings had been used as landfill materials. Slightly elevated concentrations of these radionuclides have been detected in some of the soils, vegetables and in the derived foodstuffs. However, very little information is available about the source of pollution. Therefore the aim of the present investigation was to determine the accumulation of <sup>238</sup>U, <sup>226</sup>Ra and <sup>232</sup>Th by some local vegetables and other common crops. For this purpose, this investigation selected the soil, as well as the tailings that were used as landfill materials, in the uranium mining area.

### 2. Material and methods

# 2.1. The soil sample

A field soil (0–20 cm in depth), characterized as red soil (haplic udic ferrosols), one of the typical soil types in southern China and the tailings near a uranium mine in Jiangxi province, southeast of China were collected and used in this study. The soil and the tailings were passed through a 2-mm nylon sieve before mixing and analysis. To prepare soil—tailings mixtures, the tailings were thoroughly mixed with the soil in the ratio 1:10 (referred to as Soil I) and 1:5 (Soil II) according to the weight. The mixture was chosen to roughly represent two scenarios of contamination at different locations near the tailing site according to preliminary survey prior to this pot experiment. The properties of the soil, tailings and soil—tailings mixtures were determined according to standard methods recommended by the Chinese Society of Soil Science (Lu, 1999); some selected physiochemical properties and the concentrations of <sup>238</sup> U, <sup>226</sup> Ra, <sup>232</sup>Th and <sup>235</sup>U are presented in Table 1.

### 2.2. The plant species

Nine plant species, including local vegetables, were selected in this investigation. The species were comprised of broad bean (*Vicia faba*.), Chinese mustard (*Brassica Chinensis*), India mustard (*Brassica juncea*), lupine (*Lupinus albus*), corn (*Zea mays*), chickpea (*Cicer arietinum*), tobacco (*Nicotiana tobacum*), ryegrass (*Lolium perenne*), and clover (*Trifolium pratense*). Nitrogen (N), phosphorus (P) and potassium (K) were applied as essential nutrients in the form of solution to each pot at the rate of 0.2 g N kg<sup>-1</sup> soil as (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, 0.15 g P<sub>2</sub>O<sub>5</sub> kg<sup>-1</sup> as CaHPO<sub>4</sub> and 0.125 g K kg<sup>-1</sup> as KCl. Nutrient solution was mixed thoroughly with the soil/tailing mixture prior to

Table 1
Selected characteristics and the specific activities of radionuclides in the soil—tailings mixtures before the pot experiment

Parameter	pH $(H_2O)$	CEC (Cmol kg <sup>-1</sup> ) <sup>a</sup>	Organic	Available (mg kg <sup>-1</sup> )			$Bq (kg^{-1})^a$	$Bq (kg^{-1})^a$				
			matter (g kg <sup>-1</sup> )	N	P	K	<sup>238</sup> U	<sup>226</sup> Ra	<sup>232</sup> Th	<sup>235</sup> U		
Sample	7.68	12.6±1.9	11.2	18.9	16.9	28.7	_	_	_	_		
Tailings	6.42	$8.1 \pm 2.2$	2.3	5.2	14.7	40.3	$10246 \pm 894$	$46457 \pm 2239$	$1428 \pm 162$	$899 \pm 88$		
Soil I	7.56	$11.2 \pm 1.1$	9.5	16.2	16.8	35.7	$2253 \pm 251$	$9011 \pm 895$	$312 \pm 10$	194±9		
Soil II	7.11	$9.8 \pm 1.6$	9.2	15.5	17.2	36.1	$3159 \pm 415$	$12994 \pm 1362$	$605 \pm 41$	$358 \pm 13$		

<sup>&</sup>lt;sup>a</sup> Mean  $\pm$  standard deviation (SD) (n=9).

potting. The soil-tailings mixtures were then placed into plastic pots (2 kg soil per pot) and saturated with deionized water to equilibrate for 3 weeks before the pregerminated seeds were sown. In the ryegrass and clover treatments, there were 20 plants in each pot while other treatments had four plants in each pot. All treatments were arranged in a randomized design with four replicates for each treatment. Over the period of the experiment (April to July), these pots were placed in a greenhouse (ambient light intensity ranging from 500 to 1100  $\mu$ mol m<sup>2</sup> s<sup>-1</sup>) with a controlled temperature at  $28\pm1$  °C during the daytime and  $24\pm1$  °C during the night, and pots were watered to field capacity with deionized water according to loss by weighing.

# 2.3. Sample preparation

After 3 months of growth, the shoots and roots of the plants were sampled and washed with water; soil samples from each pot were also collected. All these samples were dried at 70 °C for 48 h until they reached a constant mass, then ground to pass through a 60-mesh sieve for radiochemical analysis. Samples with dry masses <5 g were placed in sealed cylindrical containers (69 mm in diameter, 20 mm in height) and activated carbon was added to inhibit radon from escaping. All samples were stored for at least 45 days to ensure that <sup>238</sup>U and its daughter products (<sup>214</sup>Bi and <sup>214</sup>Pb, etc.) were in secular equilibrium with <sup>226</sup>Ra prior to gamma counting. All samples were stored for at least 45 days to ensure that <sup>238</sup>U and its daughter products (<sup>214</sup>Bi, <sup>222</sup>Rn and <sup>214</sup>Pb, etc.) were in secular equilibrium with <sup>226</sup>Ra prior to gamma counting.

### 2.4. Determination of the radionuclides

The plant and soil samples were analyzed by gamma-spectrometry using a welltype hyper-purity germanium detector (HP-Ge detector, HPGe-gc-3018-γdetector, Canberra Ltd., USA), with 34.0% relative efficiency and a resolution of 2.0 keV at  $E_r = 1.33$  MeV. This low-level radioactive system was shielded by 15 cm of lead, with an integral background count rate in the range from 30 keV to 2.7 MeV. For the determination of the full-energy peak efficiency, a set of calibration sources from Chinese Isotope Co., Ltd. were prepared, which contained all nuclides of the <sup>238</sup>U and <sup>235</sup>U chains in secular equilibrium. The background alpha and beta activities were also counted in the low-background anti-coincidence proportional detector and the density of the samples was calibrated according to the standard sample (soil and plant leaves) provided by Chinese Isotope Co., Ltd. <sup>226</sup>Ra was analyzed through its progeny, namely <sup>222</sup>Rn and its gamma-emitting daughters. Furthermore, <sup>214</sup>Bi, and <sup>208</sup>Tl were used for the measurements of <sup>238</sup>U and <sup>232</sup>Th, respectively. All samples were counted for at least 22 h; the relative error of the measured activity ranged from 0.16 to 5.0% for different radionuclides and various concentrations, with a common tendency of increasing error with decreasing concentrations.

The radioactivity concentration of each radionuclide was calculated using the following equation (IAEA, 1989):

$$C_i = A/(E \times T \times P \times W)$$

where  $C_i$  is the specific activity of each radionuclide in the plant (Bq kg<sup>-1</sup>), A is the count of each radionuclide, E is the detector efficiency of the specific  $\gamma$ -ray, P is the absolute transition probability of the specific  $\gamma$ -ray, T is the time (s) and W is the mass of the sample (kg). The absolute efficiency calibration was performed using mixed standard gamma source (Ref. no. GS07-07406) from Chinese Isotope Co., Ltd.

### 2.5. Transfer factors

Transfer factors (TFs), which are the ratios of specific activities in plant parts and soil (in Bq kg<sup>-1</sup> dry weight plant part divided by Bq kg<sup>-1</sup> dry weight soil) can be used as an index for the accumulation of trace elements by plants or the transfer of elements from soil to plants (Yanagisawa et al., 1992; Whicker et al., 1999). The corresponding TFs of different plant parts, relating the specific activity of a given radionuclide (<sup>238</sup>U, <sup>232</sup>Th and <sup>226</sup>Ra) for every plant part in Soil I and Soil II were calculated after harvesting.

## 3. Results and discussion

## $3.1.^{238}U$

The observed mean concentration of specific activity of <sup>238</sup> U (Bq kg<sup>-1</sup> dry weight) and the TFs for <sup>238</sup>U of the plant shoots in the Soil I and Soil II are shown in Table 2 and Fig. 1, respectively. From Table 2, it can be seen that the specific activity of <sup>238</sup> U for the plants grown in Soil II were generally higher than that in Soil I. The mean specific activities of <sup>238</sup>U ranged from 15 to 118 and from 108 to 1167 Bq kg<sup>-1</sup> for the shoots and roots, respectively. However, the TFs for different plants are consistently larger in Soil I with lower concentration of <sup>238</sup>U in soils. The TFs for the plant shoots and roots grown in the soils ranged from 0.005 to 0.037 and from 0.042 to 0.39, respectively. This was generally in agreement with reported values for plants grown in contaminated soils (IUR, 1994; Tome et al., 2003). Statistical analysis revealed the differences of uranium transfer from the soils to plants (p > 0.05) (Fig. 1). For these plants growing in soils, differences between the uranium TF values would be expected due to the different characteristics of the plants. However, relatively small variations were found between these plants. Among the plant species, the highest TFs (0.037 and 0.037 for two tailings-contaminated soils, Soil I and Soil II, respectively) for <sup>238</sup> U were found for lupine shoot. In contrast, Chinese mustard shoots exhibited the lowest TFs (0.006 and 0.005) on the Soil I and Soil II. Among these nine plant species with their natural metabolic differences, the difference in mean <sup>238</sup>U TF values were found to vary by a factor of about 7.

Table 2

Plants	Soil I						Soil II				
	<sup>238</sup> U		<sup>226</sup> Ra		<sup>232</sup> Th		<sup>238</sup> U		<sup>226</sup> Ra		<sup>232</sup> Th
	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot

$^{238}U$		<sup>226</sup> Ra		<sup>232</sup> Th	<sup>238</sup> U		<sup>226</sup> Ra		232	
Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Sh

Specific activities of  $^{238}$ U,  $^{226}$ Ra and  $^{232}$ Th (Bq kg $^{-1}$  dry weight) for different plant species grown in Soil I and Soil II (mean  $\pm$  SD; n=4)

U		Na		111		U		Na		1
Shoot	Root	Sho								

	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot
Pisum arvense L.	$38 \pm 10 \text{ cd}$	637±20 b	$96 \pm 12 \text{ cd}$	971±96 c	$0.17 \pm 0.02$ c	1.9±0.6 c	53±4 bc	$729 \pm 16 \text{ c}$	123±8 de	1273 ± 132 b	0.20±

	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
Pisum arvense L.	$38 \pm 10 \text{ cd}$	$637 \pm 20 \text{ b}$	96±12 cd	971±96 c	$0.17 \pm 0.02$ c	1.9±0.6 c	53±4 bc	729±16 c	123±8 de	1273±132 b	$0.20 \pm 0.0 \text{ b}$	$2.0 \pm 0.3 \text{ cd}$
Brassia chinensis	$15 \pm 2 e$	$122 \pm 14 e$	$67 \pm 8 \text{ d}$	$540 \pm 52 \text{ de}$	$0.08 \pm 0.01 d$	$1.12 \pm 0.23$ de	16±1 e	$149 \pm 21 e$	84±4 e	$949 \pm 190 \text{ bc}$	$0.08 \pm 0.01 \text{ b}$	$1.2 \pm 0.3 \text{ cd}$
Brassia juncea L.	$21 \pm 2$ de	$108 \pm 22 e$	$65 \pm 3 d$	$342 \pm 42 e$	$0.13 \pm 0.04$ cd	$0.65 \pm 0.20$ e	$27\pm8$ de	$134 \pm 56 \text{ e}$	$88 \pm 13 \text{ e}$	$427 \pm 37 \text{ c}$	$0.13 \pm 0.04 b$	$0.66 \pm 0.14 d$

 $83\pm29~a$   $538\pm89~c$   $155\pm17~bc$   $1000\pm76~c$   $0.18\pm0.03~c$   $1.71\pm0.26~cd$   $118\pm35~a$   $832\pm21~b$   $208\pm21~c$   $1300\pm128~b$   $0.22\pm0.02~b$   $2.04\pm0.30~c$ Lupinus L.  $733 \pm 51$  cd  $0.13 \pm 0.05$  cd  $1.72 \pm 0.50$  cd  $30 \pm 3$  de  $141 \pm 13$  e  $82 \pm 9$  e  $1126 \pm 160$  bc  $0.14 \pm 0.03$  b  $1.90 \pm 0.30$  cd Zea mays  $26\pm 2 \text{ de}$   $126\pm 18 \text{ e}$   $67\pm 3 \text{ d}$  $58 \pm 9 \text{ b}$   $879 \pm 95 \text{ a}$   $96 \pm 6 \text{ cd}$   $1033 \pm 120 \text{ c}$   $0.17 \pm 0.04 \text{ c}$   $1.79 \pm 0.15 \text{ c}$   $68 \pm 15 \text{ b}$   $1167 \pm 62 \text{ a}$   $114 \pm 16 \text{ e}$   $1228 \pm 212 \text{ b}$   $0.18 \pm 0.02 \text{ b}$   $2.07 \pm 0.18 \text{ c}$ Cicer L.

Nicotiana 25+3 de 239+6 d 102+8 cd 953+94 c  $0.15 \pm 0.01$  cd  $1.73 \pm 0.38$  cd  $29 \pm 4$  de  $282 \pm 43$  d  $145 \pm 28$  d  $1424 \pm 175$  b  $0.19 \pm 0.07$  b  $2.36 \pm 0.60$  c tobacum L. 7 cd  $155 \pm 37 \text{ e}$   $263 \pm 17 \text{ b}$   $5189 \pm 493 \text{ a}$   $0.85 \pm 0.31 \text{ a}$   $8.82 \pm 1.90 \text{ a}$ 

Lolium	$30\pm8$ cde	134±21 e	$196 \pm 63 \ b$	$3877 \pm 236 \text{ a}$	$0.67 \pm 0.08$ a	$5.52 \pm 0.41$ a	$41 \pm 7$ cd	$155 \pm 37 \text{ e}$	$263 \pm 17 \text{ b}$	$5189 \pm 493 \text{ a}$	$0.85 \pm 0.31~a$	$8.82 \pm 1.90$ a
multiflorum lam												
Trifolium pratense	$47 \pm 8 \text{ bc}$	$125 \pm 17 \text{ e}$	$308 \pm 16 \text{ a}$	$2292 \pm 38 \text{ b}$	$0.54 \pm 0.09 \text{ b}$	$3.69 \pm 0.47 \text{ b}$	$63 \pm 10 \text{ b}$	$198 \pm 4 \text{ de}$	$411 \pm 25 \text{ a}$	$4776 \pm 126 \text{ a}$	$0.70 \pm 0.05$ a	$5.90 \pm 1.18 \text{ b}$

Trifolium pratense	$47\pm8$ bc	$125 \pm 17 \text{ e}$	$308\pm16~a$	$2292 \pm 38 \text{ b}$	$0.54 \pm 0.09$ b	$3.69 \pm 0.47 \text{ b}$	$63 \pm$
multiflorum lam							

Column with the same letters in the same part of plant are not significantly different at p < 0.05.

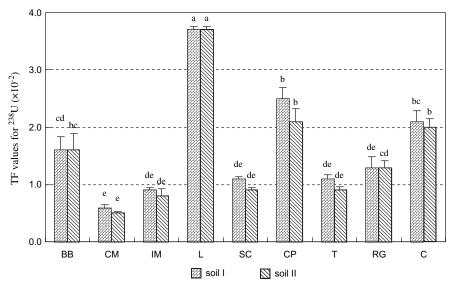


Fig. 1. TF values for  $^{238}$ U of various plant shoots grown in Soil I and Soil II; bars with the same letters in the same soil–tailings mixture are not significantly different at p < 0.05; BB, broad bean; CM, Chinese mustard; IM, Indian mustard; L, lupine; SC, sweet corn; CP, chickpea; T, tobacco; RG, ryegrass; C, clover.

# 3.2. <sup>226</sup>Ra

The mean specific activities of <sup>226</sup>Ra ranged from 65 to 411 and from 342 to 5189 Bq kg<sup>-1</sup> (dry weight basis) for the shoots and roots, respectively (Table 2). The TF values for <sup>226</sup>Ra of the plant shoots in Soil I and Soil II were shown in Fig. 2. For the plants grown on the soils, the TF values for <sup>226</sup>Ra were in the same order-ofmagnitude as those observed for <sup>238</sup>U. The TFs for the plant shoot ranged from 0.006 to 0.034, with sweet corn and Indian mustard having the relatively lower TF values (<0.008) for <sup>226</sup>Ra in the shoot among these plants studied. However, both shoot and root of clover had relatively higher TF values (>0.03) for <sup>226</sup>Ra (data not shown) than other plants. Different <sup>226</sup>Ra uptake response among the plants may be caused in part by metabolic rate differences between plant species and cultivations. The mean TF data for total <sup>226</sup>Ra are, in general, in agreement with values documented in the literature. For example, Ng (1982) reported data ranging from 0.00007 to 0.75 for various plant species. For vegetables growing in areas of high natural radioactivity, TF values were reported from 0.001 to 0.06 by Vasconcellos et al. (1987) and from 0.01 to 0.07 by Bettencourt et al. (1988). Fig. 2 shows a tendency, with the shoot TF values for <sup>226</sup>Ra higher in Soil I than those in Soil II. However, for Chinese mustard, sweet corn, and tobacco, the <sup>226</sup>Ra TFs for the roots grown in Soil II were higher than in Soil I. This phenomenon indicated that plantspecific effects seemed to be of considerable importance in mobilizing the radionuclides in the soil for root uptake and shoot translocation.

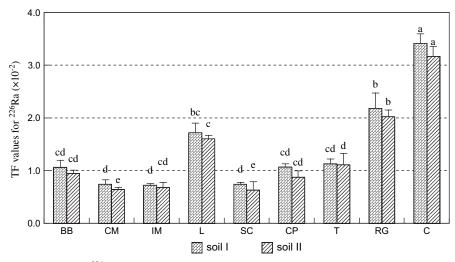


Fig. 2. TF values for <sup>226</sup>Ra of various plant shoots grown in Soil I and Soil II; refer to Fig. 1 caption.

# 3.3. <sup>232</sup>Th

Table 2 and Fig. 3 present the corresponding specific activities and geometric mean TF values of  $^{232}$ Th observed in this study across all plants. The mean specific activities of  $^{232}$ Th ranged from 0.08 to 0.85 and from 0.65 to 8.82 Bq kg $^{-1}$  for the shoots and roots, respectively. In contrast to  $^{238}$ U and  $^{226}$ Ra, the shoot TF values of  $^{232}$ Th, ranging from 0.13 to 2.14 ( $\times 10^{-3}$ ), was one order-of-magnitude lower than those of  $^{238}$ U and  $^{226}$ Ra. As shown in Table 2, the shoot uptake of  $^{232}$ Th by ryegrass

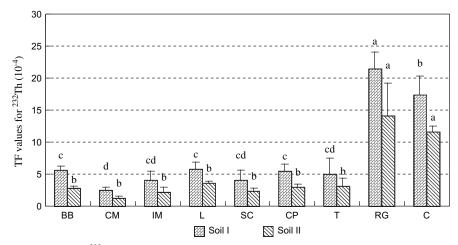


Fig. 3. TF values of <sup>232</sup>Th for various plant shoots grown in Soil I and Soil II; refer to Fig. 1 caption.

(0.67 and 0.85 Bq kg<sup>-1</sup>) and clover (0.54 and 0.70 Bq kg<sup>-1</sup>) were at least three to four times greater than other plants in the soils. This is also reflected in the plant shoot TF values (Fig. 3), along with thee lowest TF (0.13×10<sup>-3</sup>) for Chinese mustard. The comparative uptake of the radionuclides by plants is affected by numerous chemical and physical biological conditions in the soil and plant species. The combined effects of these conditions, as well as the individual chemical properties of the radionuclides, tend to affect their uptake by plants. Pinder et al. (1990) showed that corn kernels exhibited low accumulation of Pu isotopes relative to other parts of the corn plant, and Schreckhise and Cline (1980) reported that legumes accumulated more radioactivity than grasses. The TFs for <sup>232</sup>Th were also consistently higher in Soil I than that in Soil II (Fig. 3), which also implied that plant TFs for <sup>232</sup>Th increased with decreasing specific activities in the soils.

#### 4. Discussion

The rankings of transfer factors (TFs) by different plant shoots for each radionuclides were as follows:  $L>CP\sim C>BB>RG\sim SC\sim T\sim IM\sim CM$  (see Fig. 1 for the abbreviations of the plant species) for  $^{238}$ U, C>RG~L>T~ for  $^{226}$ Ra and  $RG > C > L \sim BB \sim CP \sim T \sim SC \sim$  $CP \sim BB \sim CM \sim SC \sim IM$ IM > CM for <sup>232</sup>Th. Our observed ranges of TF values for <sup>232</sup>Th tended to be about one order-of-magnitude lower than that for 238U and 226Ra. In all cases, ryegrass and clover exhibited relative higher uptake for <sup>226</sup>Ra and <sup>232</sup>Th than other plants. As for <sup>238</sup>U, lupine and chickpea had significantly higher activity concentrations than other plants. In general, the comparative uptake of <sup>238</sup>U, <sup>226</sup>Ra and <sup>232</sup>Th by different plants is affected by numerous physical, chemical and biological conditions of the soil. The combined effects of these conditions, as well as the individual chemical properties of the nuclides, tend to affect its uptake by plants. For example, retention of radionuclides onto the soil particles will affect their availability for plant uptake. Martínez-Aguirre et al. (1995) reported that Th exhibited a much lower mobility than U, which is consistent with our observations that <sup>232</sup>Th has smaller TF values. The magnitude and range of TFs of <sup>238</sup>U, <sup>226</sup>Ra and <sup>232</sup>Th found in this study appeared to be generally similar to values obtained in other studies where root uptake was the primary mechanism of accumulation (IAEA, 1994; IUR, 1994; Bettencourt et al., 1988; Frissel and Koster, 1988; Köhler et al., 2000).

However, the overall transfer factor values, obtained for a given radionuclide from the corresponding activity in a plant did not immediately yield quantitative information on the translocation of this radionuclide from root to the shoot. Such information can, however, be obtained by defining a root to shoot concentration ratio (R/S ratios), as the specific activity of radionuclide in plant root divided by that in plant shoot. The R/S ratio values of  $^{238}$ U,  $^{226}$ Ra and  $^{232}$ Th for different plants are presented in Table 3. From Table 3, we found that Indian mustard had the smallest R/S ratios both for  $^{226}$ Ra ( $5.3\pm1.2$ ) and  $^{232}$ Th ( $5.3\pm1.7$ ) in the two contaminated soils. These R/S ratios data quantitatively demonstrated a considerably easier shoot

Table 3 Root to shoot concentration ratios (R/S Ratios) of  $^{238}$ U,  $^{226}$ Ra and  $^{232}$ Th for different plants grown on the Soil I and Soil II; Mean  $\pm$  SD (n=4), column with the same letters in the same part of plant are not significantly different at p < 0.05.

Plants	Soil I			Soil II					
	<sup>238</sup> U	<sup>226</sup> Ra	<sup>232</sup> Th	<sup>238</sup> U	<sup>226</sup> Ra	<sup>232</sup> Th			
Pisum arvense L.	15.3±2.5 a	10.7±3.5 b	11.0±4.1 abc	13.8±1.9 a	$10.7 \pm 0.9$ bcd	$11.4 \pm 3.0 \text{ abc}$			
Brassia Chinensis.	$8.2 \pm 0.8 \text{ bc}$	$8.1 \pm 0.7 \text{ bcd}$	14.4±3.7 a	$9.4 \pm 1.3 \text{ b}$	$11.7 \pm 6.2 \text{ bc}$	$14.7 \pm 2.4 \text{ a}$			
Brassia juncea L.	$5.3 \pm 1.8 \text{ cde}$	$5.3 \pm 1.2 \text{ d}$	$5.3 \pm 1.7 \text{ d}$	$5.5 \pm 1.2 \text{ cd}$	$5.4 \pm 2.7 \text{ d}$	$5.5 \pm 2.4 d$			
Lupinus L.	$7.0 \pm 2.8 \text{ bcd}$	$6.5 \pm 0.7 \text{ cd}$	$9.7 \pm 1.8 \text{ bc}$	$7.6 \pm 2.6 \text{ bc}$	$6.6 \pm 2.4 \text{ cd}$	$9.6 \pm 1.6 \text{ bcd}$			
Zea mays	$4.8 \pm 0.4 \text{ de}$	$11.0 \pm 1.4 \text{ b}$	$13.6 \pm 1.3 \text{ ab}$	$4.8 \pm 0.5 \text{ cd}$	14.0 ± 4.3 b	$14.2 \pm 2.8 \text{ ab}$			
Cicer L.	$15.3 \pm 2.3 \text{ a}$	$10.8 \pm 2.6 \text{ b}$	$11.0 \pm 3.1 \text{ abc}$	$16.2 \pm 2.4 \text{ a}$	$11.1 \pm 3.6$ bcd	$11.6 \pm 2.1 \text{ abc}$			
Nicotiana tobacum L.	$9.8 \pm 1.2 \text{ b}$	$9.5 \pm 1.9 \text{ bc}$	$11.2 \pm 2.1 \text{ abc}$	$9.9 \pm 2.4 \text{ b}$	$10.5 \pm 3.2 \text{ bcd}$	$13.3 \pm 5.6 \text{ abc}$			
Lolium multiflorum lam	$4.5 \pm 0.6$ de	$19.9 \pm 5.7 \text{ a}$	$9.3 \pm 0.9 \text{ cd}$	$3.8 \pm 0.4 d$	$20.0 \pm 4.1 \text{ a}$	$11.2 \pm 3.7 \text{ abc}$			
Trifolium pratense	$2.8 \pm 0.9 \text{ e}$	$7.5 \pm 0.9 \text{ bcd}$	$7.1 \pm 2.1 \text{ cd}$	$3.2 \pm 0.6 \text{ d}$	$12.3 \pm 0.8$ bc	$8.5 \pm 1.9 \text{ cd}$			

translocation of  $^{226}$ Ra and  $^{232}$ Th by Indian mustard than other plants. As for  $^{238}$ U, the smallest R/S ratios were observed for clover (2.8±0.9). On the contrary, the largest R/S ratios (15.3±2.5, 19.9±5.7 and 14.4±3.7 for  $^{238}$ U,  $^{226}$ Ra and  $^{232}$ Th) were found in chickpea, ryegrass and Chinese mustard, respectively. These results indicated that  $^{226}$ Ra and  $^{232}$ Th in ryegrass and Chinese mustard root and  $^{238}$ U in chickpea root were obviously less available for shoot (edible part) translocation.

Because these species are directly involved in the human food chain, information on the concentration level and transfer of radionuclides from tailings will provide important data for the environmental risk assessment at such sites.

#### 5. Conclusions

A radiological study was performed to obtain transfer factors of  $^{238}$ U,  $^{226}$ Ra and  $^{232}$ Th for nine plant species on soil contaminated with uranium mine tailings from the southeastern region of China. The difference in relative mobility of uranium, radium and thorium isotopes was investigated by the division of the specific activity (Bq kg<sup>-1</sup>) ratios between plant and soil samples. The results indicated that the root uptake of  $^{238}$ U,  $^{226}$ Ra and  $^{232}$ Th from the soil contaminated by uranium mine tailings was plant-specific. In general, the TFs across all plant species for the three radionuclides were in the following order:  $^{238}$ U  $\sim$   $^{226}$ Ra >  $^{232}$ Th. Calculation of root to shoot specific activity ratio was a useful way to quantitatively compare the root-to-shoot translocation of a particular radionuclide. In this study, clover absorbed smaller amounts of  $^{238}$ U, but translocated the greatest percentage amount of  $^{238}$ U to shoots; the same tendency for  $^{226}$ Ra and  $^{232}$ Th was observed for Indian mustard.

Based on these results, it was possible to compare those radionuclides on the availability for root uptake and its translocation to shoot.

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