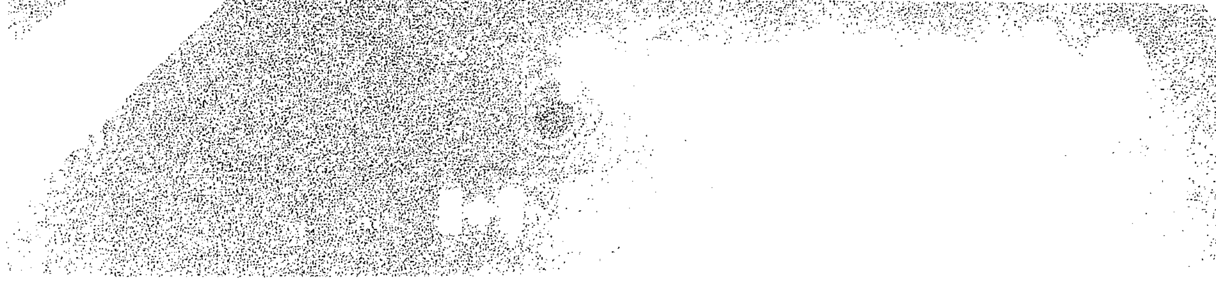

ca9110888

[illegible]

# EFFECT OF SOIL TYPE ON RADIONUCLIDES IN PLANTS: FIELD STUDY

by

Environmental Research Branch
Whiteshell Nuclear Research Est.

Atomic Energy
Control Board

Commission de contrôle
de l'énergie atomique

P.O. Box 1046
Ottawa, Canada
K1P 5S9

C.P. 1046
Ottawa, Canada
K1P 5S9

Canada

INFO-0290

# EFFECT OF SOIL TYPE ON RADIONUCLIDES IN PLANTS: FIELD STUDY

by

Environmental Research Branch
Whiteshell Nuclear Research Est.
Atomic Energy of Canada Limited

A research report prepared for the
Atomic Energy Control Board
Ottawa, Canada

December 1988

Research report

# EFFECT OF SOIL TYPE ON RADIONUCLIDES IN PLANTS: FIELD STUDY:

A research report prepared by the Environmental Research Branch of Whiteshell Nuclear Research Establishment, under contract to the Atomic Energy Control Board.

---

## ABSTRACT

The research was undertaken to provide plant/soil concentration ratio (CR) data for uranium (U), thorium (Th) and lead (Pb) using crops and soils typical of Canada. A clay, a silt, a sand and an organic soil were used and spinach, potatoes, corn, blueberries, wild rice, barley and radish were grown. CR values decreased among the soils in the order sand > silt = clay > organic. CR values were lower in potato flesh than in potato peels, and usually lower in grains than in the associated stems. The geometric mean CR values for U, Th and Pb on a dry plant/dry soil basis were 0.013, 0.0022, and 0.0050, respectively.

## RÉSUMÉ

On a entrepris des recherches pour fournir des valeurs de facteurs de concentrations (FC) d'uranium (U), de thorium (Th) et de plomb (Pb) entre les plantes et les sols à l'aide de cultures et sols typiques du Canada. On s'est servi de sols argileux, limoneux, sablonneux et organiques dans lesquels on a cultivé des épinards, des pommes de terre, du maïs, des myrtilles (bleuets), du riz sauvage, de l'orge et des radis. Les valeurs des FC ont diminué d'un sol à l'autre dans l'ordre sable > limon = argile > organique. Les valeurs de FC ont été plus faibles dans la chair de pomme de terre que dans les pelures et généralement plus faibles dans le grain de céréale que dans la tige associée. La valeur moyenne géométrique du FC d'U, de Th et de Pb entre une plante et un sol secs a été respectivement de 0.013, 0.0022 et 0.0050.

---

## DISCLAIMER

TABLE OF CONTENTS

# EFFECT OF SOIL TYPE ON RADIONUCLIDES IN PLANTS: FIELD STUDY

## A. INTRODUCTION

In a recent review, Sheppard and Evenden (1987) found few plant/soil concentration ratio (CR) data for uranium (U), thorium (Th) and lead (Pb), especially for conditions relevant to Canada. These elements are especially important in the front end of the nuclear fuel cycle. The CR values are important to assess the health impact of industries dealing with U, Th and Pb. The review by Sheppard and Evenden (1987) made several overall points:

1. The major compendiums of CR data compiled by nuclear agencies around the world have neglected to rigorously assess or to even include data for U, Th and Pb.
2. Much of the data that is published is not relevant to Canada. For example, data derived in the arid plains of the southwestern US are not relevant for Canadian soils and plants, and they inevitably are biased by a dust-load transfer of radionuclides.
3. There is an especially-marked deficiency of relevant data for edible plants grown on non-tailings soil materials. For example, there are almost no data for root crops, there are no data for vegetable or fruit crops grown on loam, sand or organic soils, and there are fewer than six values available for the most-represented crop type, the cereals.
4. The few data available are poorly documented and are often derived from translations of Russian papers. This makes it extremely difficult to select values to represent specific Canadian sites, since basic data such as soil type, climatic zone and even crop type may be missing.

The objectives of this project were to measure CR values for U, Th and Pb on four representative Canadian soils and with seven edible plant species. These values would fill gaps in the literature and be especially representative of Canadian conditions. The details of the study were formulated based on the literature review by Sheppard and Evenden (1987). The key features of the study are:

1. The crops were grown outdoors, subject to natural atmospheric and soil conditions.
2. The crops were grown using relevant agronomic practice in terms of planting, soil fertility, etc.
3. The soils represented as broad a range as possible with four soils, including varied levels of texture, pH, organic matter content and carbonate content.
4. The physical and chemical properties of the soils were carefully characterized.

Two experiments were conducted. Experiment A dealt with the effect of four soil types and seven plant species on uptake of U, Th and Pb. It involved one concentration of each of the radionuclides. Experiment B dealt with the effect of soil concentration of each radionuclide and involved one soil and one plant species but several radionuclide concentrations.

## B. METHODS AND MATERIALS

### 1. Experimental Design

The key experiment (A) was designed as an incomplete factorial of four soils and six crops resulting in 12 soil-crop combinations (Table 1). The soils were chosen to represent widely different properties of pH, texture, organic matter content, carbonate content and original drainage. The crops were chosen to represent edible plants typical of natural, field crop and horticultural crop settings and each crop was grown on the two most appropriate soils. Radishes were planted in all the containers, except those with wild rice, to allow some direct comparisons across all of the soils. The soil-plant combinations were repeated for each of the radionuclides and for three replicates. Two lysimeter sizes were chosen based on the growth habits of the crops (Table 1).

A secondary experiment (B) was a partially replicated concentration-series experiment with eight concentrations of each of the radionuclides including controls and another treatment involving nitrogen (N) fertilization (Table 2). The silt-loam soil from Experiment A was used and radishes were the test crop. Mini-lysimeters of 1-L volume were used.

### 2. Collection and Preparation of the Soils

All of the soils were collected within 20 km of Pinawa, Manitoba in the fall of 1986. The soils were air dried to a workable moisture content (Table 3), sieved to pass a 1.3-cm mesh and stored in sealed containers. Subsamples of the soils were analysed for the chemical and physical properties shown in Table 3. Weighed aliquots of the soils representing sufficient volume to fill a 20-cm depth of the lysimeters in Experiment A or all of the lysimeters in Experiment B were placed in plastic bags. Farm grade fertilizers were added to the mineral soils to supply the equivalent of 60-120-40-16 μg N-P-K-S /g for corn, 40-120-40-16 μg N-P-K-S /g for barley, spinach, and potatoes and none for blueberries and wild rice. The same amount of fertilizer on a volumetric basis was added to the organic soil as was added to the mineral soils. These amounts were based on soil fertility tests and general fertilizer recommendations.

The concentration series of Experiment B resulted in a range of N applications because nitric acid was part of the radionuclide stock solutions. The supply of N to the plants was equalized to that of treatment #7 by the addition of $NH_4NO_3$. An exception was treatment #4-N that had no additional N and thus was fertilized at 40 μg N/g as in Experiment A.

The soils used for the blueberry plants were handled differently beyond this stage to accommodate the transplanting of the plants. The plants were obtained as two-year-old nursery stock (sweet lowbush cv Northblue). The original organic soil was washed off the blueberry roots and the plants were replanted in the study soils. This was done on May 6 before the plant leaves were fully expanded.

Table 1 Selection of soils, crops and soil·crop combinations with the associated rationale

| | lysimeter size ($cm^2$) | rationale |
|---|---|---|
| Crop: | | |
| spinach | 130 | -leafy vegetables usually have the highest CR values |
| potato | 590 | -root crop, especially important for low-solubility U/Th decay series nuclides |
| corn | 590 | -very fast growing, with C-4 metabolism |
| barley | 130 | -in contrast to corn, a cereal with C-3 metabolism |
| blueberry | 130 | -grows on very acid soils, is very slow growing, and is an edible, native species |
| wild rice | 590 | -grows on water-saturated and anaerobic soils, and also is an edible native species |
| Soil: | | |
| luvisolic clay-loam (c) | | -neutral pH soil typical of agricultural soils in Southern Ontario |
| calcareous, gleyed loam (l) | | -a typical agricultural soil but also one that might reasonably be flooded (for wild rice) |
| podzolic sand (s) | | -low pH soil typical of northern areas |
| humified organic (o) | | -medium to low pH, highly organic soil typical of northern areas, bog-land vegetable production and flooding for wild rice production |
| Combinations: | | |
| spinach / c | | -typical upland agricultural practice |
| / o | | -typical bog-land agricultural practice |
| potato / l | | -reasonable upland agricultural practice |
| / s | | -acidic and loose texture, typical of potato growing areas |
| corn / c | | -typical upland agricultural practice |
| / l | | -typical upland agricultural practice |
| barley / c | | -typical upland agricultural practice |
| / l | | -typical upland agricultural practice |
| blueberry / s | | -must be acidic, typical upland setting |
| / o | | -must be acidic, similar to organic litter layers and rock-fissure infill materials |
| wild rice / l | | -soil that could be flooded |
| / o | | -soil that could be flooded |

Table 2 Design of Experiment B

| Treatment Number[1] | Number of Replicates | Radionuclide Concentration | | |
|---|---|---|---|---|
| | | U (µg/g) | $^{230}$Th (Bq/g) | $^{210}$Pb (Bq/g) |
| 0 | 4 | 0 | 0 | 0 |
| 1 | 4 | 10 | 0.8 | 2 |
| 2 | 1 | 20 | 1.6 | 4 |
| 3 | 1 | 50 | 4 | 10 |
| 4 | 4 | 100 | 8 | 20 |
| 4-N | 4 | 100 | 8 | 20 |
| 5 | 1 | 200 | 16 | 40 |
| 6 | 1 | 500 | 40 | 100 |
| 7 | 4 | 1000 | 80 | 200 |

[1] Treatment number 4-N has the same amount of N as in Experiment A, whereas all the other treatments in Experiment B have the amount of N that accompanied the radionuclide in treatment number 7. Treatments numbered 4 and 4-N used the same radionuclide concentrations as used in Experiment A.

Table 3 Properties of the Soils Used in the Experiments

| Property | Soil | | | |
|---|---|---|---|---|
| | clay-loam | loam | sand | organic |
| pH | 7.0 | 7.3 | 4.9 | 5.5 |
| organic matter content (%) | 3.3 | 5.1 | 0.8 | 64 |
| texture of mineral phase | silty clay loam | loam | medium sand | very fine sandy loam |
| clay content(%): | 36 | 15 | 2 | 12 |
| silt content(%): | 47 | 43 | 3 | 16 |
| sand content(%): | 17 | 42 | 95 | 72 |
| carbonate/bicarbonate content (meq/L) | 1.9 | 4.6 | 0.7 | 1.1 |
| cation exchange capacity (meq/100g) | 27.5 | 17.4 | 5.8 | 115.8 |
| nitrate N (µg/g) | 20.6 | 10.4 | 0.4 | 150 |
| available P (µg/g) | 19.0 | 15.4 | 8.4 | 9.4 |
| exchangeable K (µg/g) | 285 | 58 | 20 | 95 |
| sulphate S (µg/g) | 4.4 | >20 | 0.8 | 4.6 |
| exchangeable Ca (µg/g) | 3450 | 5880 | 155 | 7920 |
| exchangeable Mg (µg/g) | 585 | 600 | 36 | 825 |
| exchangeable Na (µg/g) | 22 | 41 | 16 | 235 |
| extractable Cu (µg/g) | 1.0 | 0.8 | 0.4 | 4.5 |
| extractable Fe (µg/g) | 31 | 49 | 65 | 415 |
| extractable Mn (µg/g) | 15 | 5.8 | 0.6 | 3.0 |
| extractable Zn (µg/g) | 2.5 | 2.2 | 0.7 | 18 |
| working moisture content (% g/g) | 6.18 | 2.88 | 0.11 | 233 |
| working bulk density (g/cm$^3$) | 1.10 | 1.13 | 1.50 | 0.203 |

## 3. Outdoor Lysimeter Facility

Experiment A used lysimeters with surface areas of 130 and 590 $cm^2$ and depths of 60 and 40 cm, respectively. The lower or subsoil horizons of the lysimeters were filled with fine sand leaving a 20-cm depth for the surface, treatment soils. The exceptions were the lysimeters for the wild rice where there was no subsoil material, the treatment soil filled the lower 20 cm of the lysimeter and the upper 20 cm was filled with water. Experiment B used mini-lysimeters with surface areas of 100 $cm^2$ and were completely filled with treatment soil to their depth of 13 cm. All of the lysimeters were placed outdoors and were buried so that their soil surfaces were level with the surrounding soil. In this way, the lysimeters were exposed to natural sunlight, rainfall and soil temperatures.

## 4. Contamination of the Soils

The U was supplied by Eldorado Nuclear, Port Hope, Ontario in 1974 as $UO_2$ powder and was 0.771% $^{235}U$ by weight. This was dissolved in $HNO_3$ and diluted to a final stock solution of 0.1651 g U/mL and 29.1 mg N/mL. The $^{230}Th$ was supplied by Isotope Products Laboratory, Burbank, California and the $^{210}Pb$ was supplied by the Chemistry Division, UKAEA Harwell, Oxfordshire. Both isotopes were carrier free and were supplied in $HNO_3$ solutions. They were further diluted to final stock solutions of 11.84 GBq $^{230}Th$/mL and 26.64 GBq $^{210}Pb$/mL, respectively, also containing 29.1 mg N/mL.

The amount of radionuclide added to each soil was calculated to provide the desired concentrations on a dry weight basis. Because the soil dry bulk densities varied, the amount of radionuclide per lysimeter varied from soil to soil. The radionuclide concentrations for Experiment A were 100 µg U/g, 8 Bq $^{230}Th$/g and 20 Bq $^{210}Pb$/g. To apply the radionuclides to the soils, the required aliquots of the stock solutions were further diluted to 50 or 250 mL for the small and large lysimeters, respectively. The pre-weighed amount of soil was spread to a 2-cm-thick layer and one fifth of the working solution was applied in droplets evenly over the soil surface. The soil was then thoroughly mixed and the procedure repeated until all the solution was applied. The soils were then transferred to the lysimeters. The soils were analysed after the experiment to confirm the radionuclide concentrations. One lysimeter for each soil·crop combination, excluding the saturated wild rice lysimeters, was selected for sampling. Two to four soil cores of the 0-20 cm layer were collected from each of these lysimeters and the cores were homogenized. The resulting 10 samples for each radionuclide were analysed. There was 88±30 µg U/g, 7.3±3.0 Bq $^{230}Th$/g and 16.7±3.3 Bq $^{210}Pb$/g in the respective samples. Thus, all soils were within one standard deviation of the target concentrations. The measured values tended to be lower than the targets, perhaps because of leaching from the soil into the underlying sand.

The procedure was similar for Experiment B except that varied amounts of the stock solutions were used to achieve the desired soil concentrations. The volume of the solution applied was 25 mL in five aliquots.

A different procedure was used for the blueberry plants that had already been planted. For these treatments, the working solution was 100 mL and this was injected in ten equal aliquots. A 15-cm long syringe needle was used and the aliquots were discharged as the needle was withdrawn from the soil to spread the radionuclide throughout the soil depth. This was done on June 8 for all three radionuclides.

## 5. Planting and Maintenance of the Crops

Transplanting of the blueberries was described above. Twelve seeds of hybrid sweet corn (cv Golden Beauty), five seeds of barley (cv Harrington), eight seeds of spinach (cv Long Standing Bloomsdale) and three seed-pieces of potato (cv unknown) were planted in their respective lysimeters. Six to twelve seeds of radish (cv Cherry Bell) were planted in all lysimeters except those with wild rice. Wild rice seeds, obtained from natural stands, were manually scarified and germinated in distilled water. Twelve seedlings were planted in each lysimeter and held in place by a 2-cm deep layer of sand. The water level was set initially at 10 cm deep and was gradually raised to 20 cm deep over two weeks. Snails were added to the wild rice lysimeters to control algae. Experiment B was planted with six seeds of radish per lysimeter.

The planting date for the seed and potato crops was June 15 for the treatments with U and Th. This was 10 to 12 days after the soils were contaminated. The corresponding planting date for the Pb treatments was delayed due to retarded shipment of the $^{210}$Pb. Contamination and planting of the Pb treatments was done on July 1 and 2. The radish in Experiment B grew rapidly, allowing the planting of a second crop. The first planting of spinach grew poorly because of the hot weather and spinach was replanted on August 3.

Deionized water was used to irrigate the lysimeters. The soils were watered to their field capacity after planting and additional water was added to keep the surface moist during the first week. After this, water was only added when the soils became especially dry. This was required because, although there was 24.0 cm of natural rainfall during the growth period, some of this rainfall was directed away from the lysimeters by the leaf canopy.

The delay in planting meant some of the plants would not be ready to harvest before there was a relatively high risk of frost. To reduce this risk, a 30 x 30 x 3 m framework was erected over the lysimeter facility and it was covered with 6-mil polyethylene film on August 18. This cover was vented to prevent overheating. The lysimeters were then watered as required using deionized water.

Occasional, temporary foliar symptoms occurred during the growth period on the corn and potatoes. These were likely micronutrient disorders, specifically zinc and boron. As is typical of these elements, the symptoms were alleviated by changes in the weather and the plant growth rates.

## 6. Sample Collection and Preparation

The barley and corn plants were thinned to 4 and 3 plants per lysimeter 20 days after planting. Radish were thinned at the same time to remove any that were judged to be crowding other plants. The thinning samples were dried at 85°C for 24 hours.

Plant samples were collected as the plants reached the stage normally harvested as a food crop. Sample fresh weights were recorded. The spinach, potato and radish samples were washed in a 50 g/L Calgon solution (a commercial preparation of $NaPO_3$ and $Na_2CO_3$ yielding at this concentration a solution of pH 8.3 and 0.5 mol Na/L) to disperse all adhering soil particles. All samples were dried at 85°C for 24 hours and sample dry weights were recorded.

Radishes were harvested when the roots were at least 1-cm diameter. The roots and leaves were separated and the lateral and lower roots were discarded. Blueberry fruits were harvested as they ripened and composited into one sample per plant. The leaves and stems were collected at the end of the season. The spinach was harvested 53 days after planting before it began to bolt to the flowering stage. The barley was harvested 98 days after planting when the grains were mature. The plants were cut 2 cm above the soil surface and the grain was thrashed from the chafe and straw by hand.

The wild rice grain was harvested daily as the grains matured from 40 to 61 days after transplanting. The emergent and submergent parts of the plants were harvested separately after all the grain was matured. The potatoes were harvested 78 days after planting. The tubers were peeled and the skins and flesh retained as separate samples. The corn was harvested 78 days after planting as the grains approached a soft dough stage. The kernels were cut off the cobs and the remaining leaves and stalks, called stover, were retained as a separate sample.

The plant samples were ashed at 525°C and the weight of ash was recorded.

## 7. Sample Analysis

### 7.1 Neutron Activation

Ashed samples of the U treatments were analysed directly by neutron activation/delayed neutron counting (NA/DNC). The sample weights ranged from 0.005 to 1.0 g resulting in detection limits of 0.1 to 1 µg U/g plant ash.

### 7.2 Liquid Scintillation Counting

Ashed samples of the other treatments were dissolved in 1 mol HCl/L at a ratio of 2 mL/0.1 g ash, up to 1 g of ash. Treatment with peroxide and heating removed some colouring from the solutions and facilitated dissolution of the ash. Five- to eight-mL aliquots of the dissolved ash were placed in 20 mL glass liquid scintillation counting (LSC) vials and 10 mL of Instagel LSC cocktail was added. The vials were counted in a Packard 2000 LSC counter programmed to automatically adjust windows to maximize counting efficiency for the level of quench in each sample. Activity from $^{210}$Pb was differentiated from that of its daughters, $^{210}$Bi and $^{210}$Pb, by treating them as independent radioisotopes and using the dual-label, peak resolution program of the Packard 2000. Quench correction was determined using quench standards prepared in the same matrix with additions of uncontaminated plant ash and acids to obtain the same levels of quench as in the samples.

## 7.3 Radiochemical Analysis

These radiochemical techniques were substantially more expensive than LSC and were used 1) to analyse the soils, where the LSC methods were inappropriate, 2) to analyse samples that were undetectable by LSC, and 3) to provide interlaboratory/intermethod comparisons. These methods were provided by the Saskatchewan Research Council (SRC).

For $^{230}$Th, the ashed plant and dry soil samples were solubilized by fusion with potassium pyrosulphate. Thorium was separated from the prepared sample solutions by coprecipitation with barium sulphate. The barium sulphate was dissolved in a strongly alkaline solution of ethylenediaminetetraacetic acid (EDTA) and the thorium was precipitated as hydroxide with 50 µ mol/L cerium carrier. The precipitate was mounted on a 25 mm 0.2 micron membrane filter for alpha spectrometry. Alpha spectrometry was performed using a vacuum chamber mounted, surface barrier detector. The detection limit was about 0.01 Bq/g ash.

For $^{210}$Pb, the ashed plant and dry soil samples were digested with aqua-regia and $HClO_4$. The amount of $^{210}$Bi was measured and the corresponding amount of $^{210}$Pb calculated by assuming secular equilibrium. The $^{210}$Bi was extracted with diethylammonium diethyldithiocarbamate (DDTC) from the prepared sample solution. After evaporation, the organic extract was dissolved in nitric acid, diluted and bismuth oxychloride precipitated. The quantity of $^{210}$Bi present was determined by beta counting with a low background counting system. The detection limit was 0.02 Bq/g.

The LSC method was found to be unreliable for $^{230}$Th because of interference with the $^{40}$K that was highly concentrated in the plant ash. All $^{230}$Th samples were reanalysed by the radiochemical method. The LSC cocktail was removed from the samples by slowly heating them over several weeks from 30°C to 200°C and then reashing them at 525°C.

The LSC method could not quantify the $^{210}$Pb in about one third of the samples because of colour and turbidity quenching. These samples were also reanalysed by the radiochemical method. The LSC cocktail was removed by freezing the aqueous phase at -15°C and decanting the organic phase. The organic phase was analysed by LSC to measure the $^{210}$Pb remaining, and the aqueous phase was analysed by the radiochemical methods. The two results were added to compute the total $^{210}$Pb in the samples.

## 8. Statistical Analysis

Concentration ratios (CR) were computed as:

$$CR = \frac{\text{radionuclide/unit plant}}{\text{radionuclide/unit soil}}$$

CR values tend to conform to a log-normal distribution, as expected for ratios based on the central limit theorem, and were log-transformed prior to analysis. All means of CR data are therefore geometric means. The effects of the treatment variables in Experiment A were interpreted by way of analysis of variance using the General Linear Models procedure of the Statistical Analysis System (SAS, 1985). The relationship of CR to soil radionuclide concentrations in Experiment B was analysed as a regression model using the same computer procedure. The impact of uncontrolled experimental variables such as plant yield on the CR data was calculated using simple correlations.

## C. RESULTS AND DISCUSSIONS

### 1. Plant Characteristics

This study involved a broad range of plant types, especially in terms of the plant parts used by humans. We document here (Tables 4 and 5) several of the intensive characteristics of the plants, such as weight ratios between plant parts, moisture contents, ash/dry weight ratios and ash/fresh weight ratios. The plants were generally healthy and there were no serious disease or pest infestations. Yields per plant were lower than ideal for commercial production, and we attribute this to the delay in planting and the fairly dense planting used to ensure sufficient biomass per lysimeter.

Moisture contents varied from 0.4 to 26 g water/g dry plant, representing cereal grains and fruits at the extremes. Ash contents expressed either as a fraction of dry weight or of fresh weight also ranged eight to ten fold. Stem and leaf tissues tended to have high ash contents and storage and reproductive tissues tended to have low ash contents, in keeping with their respective physiological roles. The variation in these data clearly illustrate the importance of defining the basis for presentation of concentration ratios (CR). We present CR values on a dry weight basis, followed by ash and fresh weight bases.

### 2. CR Data for Uranium, Experiment A

The CR data for U, expressed on a dry plant/dry soil basis (Table 6), varied from 0.00036 to 0.15. Analysis of the variance (Table 7) showed significant differences among the soils and among the plant species and parts. Furthermore, the effects of the soils varied among the plant species. Much of this interaction was probably attributable to the markedly higher CR values for blueberries grown on sand compared to those grown on organic soil. Some generalizations are possible:

- potato peels contained markedly more U than the flesh, by 8 to 33 fold
- grains contained much less U than the corresponding stems, by about 30 fold
- the organic soil yielded lower CR values than the mineral soils when compared for the same crops, by 4 to 40 fold.

These generalizations were valid only for the dry plant/dry soil data and the fresh plant/dry soil data (Table 9), the plant ash/dry soil CR data (Table 8) responded differently. This difference was especially true for the grains where, because of their relatively low ash content, they had correspondingly high plant ash/dry soil CR values.

The use of radish as a companion crop allowed more direct comparison of the effect of soil type. This was limited to some extent because the growth of the radish was affected by the presence of the main crop. The result was that the CR data for the radish varied significantly in response to the main crop. In the affected treatments, the radish grew very slowly, had relatively small roots, and these roots appeared especially tough and dense. These effects could be accounted for in the analysis of variance by

Table 4 Weight ratios between plant parts (n=6)

| plant part | | dry | ash | fresh |
|---|---|---|---|---|
| potato | peel/flesh | 0.12 | 0.22 | 0.17 |
| corn | grain/stover | 0.31 | 0.15 | 0.37 |
| blueberry | leaf/stem | 0.77 | 2.0 | 0.77 |
| wild rice | grain/aerial stem | 0.52 | 0.14 | 0.35 |
| barley | grain/stem | 0.57 | 0.19 | 0.58 |

Table 5 Moisture content (g water/g dry plant), ash weight/dry weight ratios and ash weight/fresh weight ratios for the plant species and parts studied[1]

| | | moisture content | ash weight to dry weight | ash weight to fresh weight |
|---|---|---|---|---|
| | | | | |
| spinach | leaf | 5.2 | 0.22 | 0.037 |
| potato | peel | 7.2 | 0.079 | 0.0097 |
| | flesh | 4.5 | 0.042 | 0.0075 |
| corn | grain | 3.4 | 0.034 | 0.0080 |
| | stover | 2.2 | 0.071 | 0.023 |
| blueberry | berry | 26 | 0.16 | 0.0062 |
| | leaf | 1.0 | 0.080 | 0.039 |
| | stem | 1.0 | 0.030 | 0.015 |
| wild rice | grain | 0.49 | 0.026 | 0.017 |
| | aerial stem | 1.3 | 0.091 | 0.041 |
| | submerged | 11 | 0.11 | 0.0090 |
| barley | grain | 0.44 | 0.029 | 0.020 |
| | straw | 0.43 | 0.089 | 0.062 |
| radish | root | 9.3 | 0.13 | 0.013 |
| | | | | |
| mean | | 3.8 | 0.079 | 0.024 |

Table 6 Uranium dry plant/dry soil Concentration Ratios (CR), n=3 except where indicated

| | | clay | silt | sand | organic | mean |
|---|---|---|---|---|---|---|
| spinach | | 0.033 | | | 0.0079 | 0.018 |
| potato | peel | | 0.15 | 0.066 | | 0.10 |
| | flesh | | 0.019 | 0.0020 | | 0.0061 |
| corn | grain | <0.04 | 0.00036 | | | 0.00036 |
| | stover | 0.0019 | 0.012 | | | 0.0048 |
| blueberry | leaf | | | 0.11 | 0.0028 | 0.018 |
| | stem | | | 0.038 | 0.0039 | 0.0063 |
| wild rice | grain | | n=1<br>0.00051 | | <0.09 | 0.00051 |
| | stem | | 0.017 | | n=1<br>0.0018 | 0.0097 |
| barley | grain | <0.05 | 0.0021 | | | 0.0021 |
| | straw | 0.012 | 0.066 | | | 0.028 |
| mean | | 0.0090 | 0.016 | 0.027 | 0.0036 | 0.013 |

- submerged stems of wild rice had CR values for silt and organic soils of 0.34 and 0.011, respectively
- whole potatoes had CR values for silt and sand soils of 0.033 and 0.0090, respectively
- overall mean ± pooled standard deviation of $\log_{10}$-transformed CR data was $-1.9 \pm 0.26$

Table 7 Summary of probabilities resulting from analyses of variance of Experiment A

| source[1] | df[2] | dry plant / dry soil | plant ash / dry soil | fresh plant / dry soil |
|---|---|---|---|---|
| | | Uranium | | |
| soil | 3 | ***[3] | *** | *** |
| crop | 5 | *** | *** | *** |
| soil x crop | 3 | ** | * | ** |
| part(crop) | 6 | *** | *** | *** |
| error | 57 | | | |
| | | Thorium | | |
| soil | 3 | NS | NS | NS |
| crop | 5 | NS | * | ** |
| soil x crop | 2 | NS | NS | NS |
| part(crop) | 4 | *** | *** | *** |
| error | 31 | | | |
| | | Lead | | |
| soil | 3 | ** | ** | ** |
| crop | 5 | * | ** | *** |
| soil x crop | 1 | NS | NS | NS |
| part(crop) | 5 | ** | ** | ** |
| error | 30 | | | |

[1] source of variance: soil x crop are the soil by crop interaction effects, part(crop) are the effects of plant part nested within crop, error is the variance resulting from replication and the interaction of replication with the other effects.

[2] df refers to degrees of freedom

[3] probability levels: NS - not significant, * - $P < 0.05$, ** $P < 0.01$ *** $P < 0.001$.

Table 8 Uranium plant ash/dry soil Concentration Ratios (CR), n=3 except where indicated

| | | clay | silt | sand | organic | mean |
|---|---|---|---|---|---|---|
| spinach | | 0.15 | | | 0.036 | 0.082 |
| potato | peel | | 2.0 | 0.80 | | 1.3 |
| | flesh | | 0.47 | 0.047 | | 0.14 |
| corn | grain | <1 | 0.010 | | | 0.010 |
| | stover | 0.023 | 0.20 | | | 0.068 |
| blueberry | leaf | | | 1.3 | 0.042 | 0.23 |
| | stem | | | 1.2 | 0.037 | 0.21 |
| wild rice | grain | | n=1<br>0.020 | | <4 | 0.020 |
| | stem | | 0.21 | | n=1<br>0.018 | 0.11 |
| barley | grain | <1.8 | 0.075 | | | 0.075 |
| | straw | 0.12 | 0.82 | | | 0.31 |
| mean | | 0.074 | 0.27 | 0.49 | 0.047 | 0.17 |

- submerged stems of wild rice had CR values for silt and organic soils of 2.9 and 0.11, respectively
- whole potatoes had CR values for silt and sand soils for 0.75 and 0.19, respectively
- overall mean ± pooled standard deviation of $\log_{10}$-transformed CR data was $-0.75 \pm 0.27$

Table 9 Uranium fresh plant/dry soil Concentration Ratios (CR), n=3 except where indicated

| | | clay | silt | sand | organic | mean |
|---|---|---|---|---|---|---|
| spinach | | 0.0063 | | | n=1<br>0.0010 | 0.0031 |
| potato | peel | | 0.020 | 0.0077 | | 0.012 |
| | flesh | | 0.0035 | 0.00035 | | 0.0011 |
| corn | grain | <0.01 | 0.000077 | | | 0.000077 |
| | stover | 0.00064 | 0.0035 | | | 0.0015 |
| blueberry | leaf | | | 0.056 | 0.0014 | 0.0089 |
| | stem | | | 0.018 | 0.00053 | 0.0031 |
| wild rice | grain | | n=1<br>0.00035 | | <0.06 | 0.00035 |
| | stem | | 0.0073 | | n=1<br>0.00073 | 0.0041 |
| barley | grain | <0.03 | 0.0015 | | | 0.0015 |
| | straw | 0.0083 | 0.046 | | | 0.019 |
| mean | | 0.0032 | 0.0042 | 0.0073 | 0.00091 | 0.0033 |

- submerged stems of wild rice had CR values for silt and organic soils of 0.026 and 0.0010, respectively
- whole potatoes had CR values for silt and sand soils of 0.0058 and 0.0015, respectively
- overall mean ± pooled standard deviation of $\log_{10}$-transformed CR data was $-2.5 \pm 0.25$

using the yield per plant, the ash weight/dry weight ratio and the moisture content as covariates. This effectively adjusted the data to represent radish plants of average characteristics and the effect of the main crop on the CR values became insignificant. The results before and after this statistical adjustment (Table 10) differed mostly for the sand soil. Overall, the organic soil gave very low CR values and the sand soil gave relatively high CR values. The CR values for the organic and sand soils differed by 100 fold. These differences were expected based on the expected mobility of U in these soils. The organic soil would be most effective at immobilizing U, whereas the sand soil would be least effective. Clearly, plants can absorb U more easily when it is present in the soil in a relatively mobile form.

### 3. CR Data for Thorium, Experiment A

The CR data for Th, expressed on a dry plant/dry soil basis (Table 11), varied from 0.0001 to 0.07. Analysis of the variance (Table 7) showed significant differences among the plant species and parts, but not among the soil types. In contrast to U, the corn grain on the silt soil contained a 45-fold higher concentration of Th than the stover, an unexpected and unexplained result. Unfortunately, Th was below detection limits on the other grain samples, and it is not possible to compare with these corn data. Some generalizations are possible:

- potato peels contained substantially more Th than the flesh, by 26, to 45 fold
- the organic soil yielded only slightly lower CR values than the sand soil on average

The data for plant ash/dry soil CR and fresh plant/dry soil CR are shown in Tables 12 and 13.

The Th data for the radish companion crop was similar to that for U in that CR values varied depending upon the main crop. As with U, statistical adjustment to represent radish plants of average characteristics eliminated this effect. This adjustment had most effect on the sand soil (Table 14). Overall, the organic soil tended to give low CR values and the sand soil tended to give high CR values. This difference was less than for U, the organic and sand soils differed by about 50.

### 4. CR Data for Lead, Experiment A

The CR data for Pb, expressed on a dry plant/dry soil basis (Table 15), varied from 0.00021 to 0.11. The $^{210}$Pb in about two thirds of the samples could not be quantified by LSC methods. Half of these had very low activities. The other half had considerable activity, but were heavily quenched making it impossible to differentiate the activity of the daughters from that of $^{210}$Pb. The radiochemical method was applied to these samples, providing data in most cases. A statistical test showed that results from the two methods were comparable, and thus Tables 15-17 represent data obtained with two methods.

Table 10 Uranium Concentration Ratios (CR) for radish grown as a companion crop to the main crops of Experiment A

| | clay | silt | sand | organic | P[1] |
|---|---|---|---|---|---|
| | unadjusted means | | | | |
| dry plant/dry soil | 0.092 | 0.096 | 0.031 | 0.0024 | *** |
| plant ash/dry soil | 0.61 | 0.84 | 0.23 | 0.026 | *** |
| fresh plant/dry soil | 0.010 | 0.0094 | 0.0026 | 0.00017 | *** |
| | adjusted means[2] | | | | |
| dry plant/dry soil | 0.092 | 0.095 | 0.23 | 0.0023 | ** |
| plant ash/dry soil | 0.61 | 0.84 | 1.4 | 0.025 | ** |
| fresh plant/dry soil | 0.010 | 0.0094 | 0.024 | 0.00014 | *** |

[1] probability levels for an effect of soil: ** - $P < 0.01$, *** $P < 0.001$

[2] adjusted by analysis of covariance to represent average yield per plant, ash content and moisture content

Table 11 Thorium dry plant/dry soil Concentration Ratios (CR), n=3 except where indicated

| | | clay | silt | sand | organic | mean |
|---|---|---|---|---|---|---|
| spinach | | 0.0041 | | | n=1<br>0.013 | 0.0054 |
| potato | peel | | 0.0082 | 0.020 | | 0.013 |
| | flesh | | 0.00018 | 0.00078 | | 0.00037 |
| corn | grain | no grain | 0.011 | | | 0.011 |
| | stover | 0.0011 | n=2<br>0.00042 | | | 0.00075 |
| blueberry | leaf | | | 0.070 | 0.0024 | 0.013 |
| | stem | | | n=2<br>0.00010 | 0.0013 | 0.00048 |
| wild rice | grain | | <0.004 | | <0.03 | <0.01 |
| | stem | | n=2<br>0.00029 | | <0.002 | 0.00029 |
| barley | grain | <0.001 | <0.009 | | | <0.003 |
| | straw | 0.0026 | 0.0033 | | | 0.0029 |
| mean | | 0.0023 | 0.0014 | 0.0044 | 0.0024 | 0.0022 |

- submerged stems of wild rice had CR values for silt and organic soils of 0.00058 and <0.005, respectively
- whole potatoes had CR values for silt and sand soils of 0.0012 and 0.0040, respectively
- overall mean ± pooled standard deviation of $\log_{10}$-transformed CR data was $-2.49 \pm 0.53$

Table 12 Thorium plant ash/dry soil Concentration Ratios (CR), n=3 except where indicated

| | | clay | silt | sand | organic | mean |
|---|---|---|---|---|---|---|
| spinach | | 0.028 | | | n=1<br>0.063 | 0.034 |
| potato | peel | | 0.13 | 0.27 | | 0.19 |
| | flesh | | 0.0045 | 0.016 | | 0.0087 |
| corn | grain | no grain | 0.48 | | | 0.48 |
| | stover | 0.0012 | n=2<br>0.0079 | | | 0.010 |
| blueberry | leaf | | | 0.97 | 0.044 | 0.21 |
| | stem | | | n=2<br>0.0031 | 0.058 | 0.018 |
| wild rice | grain | | <0.1 | | <1 | <0.4 |
| | stem | | n=2<br>0.0038 | | <0.03 | 0.0038 |
| barley | grain | <0.04 | <0.3 | | | <0.1 |
| | straw | 0.029 | 0.026 | | | 0.027 |
| mean | | 0.021 | 0.022 | 0.079 | 0.052 | 0.034 |

- submerged stems of wild rice had CR values for silt and organic soils of 0.0047 and <0.06 respectively
- whole potatoes had CR values for silt and sand soils of 0.028 and 0.078, respectively
- overall mean ± pooled standard deviation of $\log_{10}$-transformed CR data was $-1.47 \pm 0.52$

Table 13 Thorium fresh plant/dry soil Concentration Ratios (CR), n=3 except where indicated

| | | clay | silt | sand | organic | mean |
|---|---|---|---|---|---|---|
| spinach | | 0.00098 | | | n=1<br>0.0019 | 0.0012 |
| potato | peel | | 0.0011 | 0.0024 | | 0.0016 |
| | flesh | | 0.00003 | 0.00013 | | 0.00007 |
| corn | grain | no grain | 0.0031 | | | 0.0031 |
| | stover | 0.00040 | 0.00015 | | | 0.00027 |
| blueberry | leaf | | | 0.033 | 0.0012 | 0.0062 |
| | stem | | | n=2<br>0.00005 | 0.00065 | 0.00023 |
| wild rice | grain | | <0.002 | | <0.02 | <0.007 |
| | stem | | 0.00011 | | <0.0009 | 0.00011 |
| barley | grain | <0.0009 | <0.006 | | | <0.002 |
| | straw | 0.0020 | 0.0022 | | | 0.0021 |
| mean | | 0.00092 | 0.00032 | 0.0011 | 0.00096 | 0.00063 |

- submerged stems of wild rice had CR values for silt and organic soils of 0.00005 and <0.0004, respectively
- whole potatoes had CR values for silt and sand soils of 0.00021 and 0.00063 respectively
- overall mean ± pooled standard deviation of $\log_{10}$-transformed CR data was -3.20±0.0.54

Table 14 Thorium Concentration Ratios (CR) for radish grown as companion crop to the main crops in Experiment A

| | clay | silt | sand | organic | P[1] |
|---|---|---|---|---|---|
| | unadjusted means | | | | |
| dry plant/dry soil | 0.23 | 0.012 | 0.021 | 0.0025 | * |
| plant ash/dry soil | 0.14 | 0.11 | 0.20 | 0.031 | * |
| fresh plant/dry soil | 0.0016 | 0.00098 | 0.0020 | 0.00016 | * |
| | adjusted means[2] | | | | |
| dry plant/dry soil | 0.023 | 0.012 | 0.095 | 0.0018 | NS |
| plant ash/dry soil | 0.14 | 0.11 | 0.73 | 0.023 | NS |
| fresh plant/dry soil | 0.0016 | 0.00098 | 0.095 | 0.00012 | NS |

[1] probability levels for an effect of soil: * - $P < 0.05$, ** - $P < 0.01$,

[2] adjusted by analysis of covariance to represent average yield per plant, ash content and moisture content

Analysis of variance (Table 7) showed significant differences among the soils and among plant species and parts. There were few data to test the interaction, although it appeared not to be significant. Similar generalizations to those with U and Th can be made, but with less confidence because of the few data. The major point is:

- potato peels contain much more Pb than the flesh, by 20 to 60 fold

The plant ash/dry soil and fresh plant/dry soil CR ratios are shown in Tables 16 and 17.

The CR data for the radish companion crop (Table 18) were independent of the main crop. We present adjusted means in Table 18 only for uniformity with Tables 10 and 14. The effect of soil type was similar to that shown by U and Th. The CR values for the organic soil were about 30-fold lower than those for the sand soil.

## 5. Correlation of CR Data to Plant Characteristics

We examined correlations between the CR data and the plant characteristics. For the radish grown as a companion crop, the CR values were positively correlated to the ash content and negatively correlated to the yield per plant and the moisture content at harvest (Table 19). The correlations were most distinct for U, but were of similar sign for all three elements. We interpreted these correlations to indicate a relationship with growth performance and used this relationship to adjust the CR data for radish. In general, the highest dry weight yields were from plants that had relatively low ash contents and were relatively succulent, that is, were relatively moist at harvest. The implication in terms of CR values appears to be that CR values are lower when the plant grows more quickly and productively. This makes sense from the viewpoint that radionuclide flux to plant roots is a time-dependent process. When a plant grows faster, it allows less time for radionuclide uptake and it biologically dilutes the absorbed radionuclides by its rapid dry matter accumulation. When correlations were examined across all the plant species (Table 20), similar trends were apparent.

## 6. Relationship of CR to Soil Concentration, Experiment B

The use of CR values implies that there is a linear relationship between plant concentrations and soil concentrations. This seldom exists in non-experimental settings, probably because many other variables can effect CR values. Experiment B was designed to re-evaluate this linearity assumption. The addition of a range of radionuclide concentrations resulted in elevated nitrogen (N) levels (because the radionuclides were dissolved in nitric acid), and this also afforded a test of the effect of N on CR values.

Table 15 Lead dry plant/dry soil Concentration Ratios (CR), n=3 except where indicated

| | | clay | silt | sand | organic | mean |
|---|---|---|---|---|---|---|
| spinach | | 0.0041 | | | NQ[1] | 0.0041 |
| potato | peel | | 0.015 | 0.049 | | 0.027 |
| | flesh | | 0.00021 | 0.0025 | | 0.00072 |
| corn | grain | n=2<br>0.0022 | NQ | | | 0.0022 |
| | stover | 0.0016 | 0.00064 | | | 0.0010 |
| blueberry | leaf | | | n=1<br>0.090 | n=1<br>0.016 | 0.038 |
| | stem | | | 0.11 | 0.0068 | 0.027 |
| wild rice | grain | | NQ | | NQ | NQ |
| | stem | | NQ | | n=1<br>0.0016 | 0.0016 |
| barley | grain | n=2<br>0.025 | n=2<br>0.0019 | | | 0.0068 |
| | straw | 0.0051 | 0.014 | | | 0.0085 |
| mean | | 0.0042 | 0.0022 | 0.027 | 0.0038 | 0.0050 |

[1] NQ - not quantifiable

- submerged stems of wild rice had CR values for silt and organic soils of NQ and 0.017, respectively
- whole potatoes had CR values for silt and sand soils of 0.0012 and 0.0066, respectively
- overall mean ± pooled standard deviation of $\log_{10}$-transformed CR data was $-2.29 \pm 0.57$

Table 16 Lead plant ash/dry soil Concentration Ratios (CR),
n=3 except where indicated

| | | clay | silt | sand | organic | mean |
|---|---|---|---|---|---|---|
| spinach | | 0.026 | | | NQ[1] | NQ |
| potato | peel | | 0.25 | 0.76 | | 0.026 |
| | flesh | | 0.0056 | 0.070 | | 0.020 |
| corn | grain | n=2<br>0.064 | NQ | | | 0.064 |
| | stover | 0.025 | 0.012 | | | 0.017 |
| blueberry | leaf | | | n=1<br>3.2 | n=1<br>0.33 | 1.02 |
| | stem | | | 3.9 | 0.29 | 1.06 |
| wild rice | grain | | NQ | | NQ | NQ |
| | stem | | NQ | | n=1<br>0.026 | 0.026 |
| barley | grain | n=2<br>0.74 | n=2<br>0.062 | | | 0.21 |
| | straw | 0.050 | 0.13 | | | 0.081 |
| mean | | 0.057 | 0.041 | 0.70 | 0.081 | 0.096 |

[1] NQ - not quantifiable
- submerged stems of wild rice had CR values for silt and organic soils of NQ and 0.021, respectively
- whole potatoes had CR values for silt and sand soils of 0.031 and 0.18, respectively
- overall mean ± pooled standard deviation of $\log_{10}$-transformed CR data was $-1.02 \pm 0.55$

Table 17 Lead fresh plant/dry soil Concentration Ratios (CR), n=3 except where indicated

| | | clay | silt | sand | organic | mean |
|---|---|---|---|---|---|---|
| spinach | | 0.00054 | | | NQ[1] | 0.00054 |
| potato | peel | | 0.0020 | 0.0064 | | 0.0036 |
| | flesh | | 0.00004 | 0.00049 | | 0.00014 |
| corn | grain | n=2<br>0.00029 | NQ | | | 0.00029 |
| | stover | 0.00040 | 0.00013 | | | 0.00023 |
| blueberry | leaf | | | n=1<br>0.045 | n=1<br>0.0081 | 0.019 |
| | stem | | | 0.050 | 0.0033 | 0.013 |
| wild rice | grain | | NQ | | NQ | NQ |
| | stem | | NQ | | n=1<br>0.00099 | 0.00099 |
| barley | grain | n=2<br>0.015 | n=2<br>0.0014 | | | 0.0046 |
| | straw | 0.0034 | 0.010 | | | 0.0058 |
| mean | | 0.0012 | 0.00065 | 0.0067 | 0.00097 | 0.0014 |

[1] NQ - not quantifiable

- submerged stems of wild rice had CR values for silt and organic soils of NQ and 0.00014, respectively
- whole potatoes had CR values for silt and sand soils of 0.00022 and 0.0013, respectively
- overall mean ± pooled standard deviation of $\log_{10}$-transformed CR data was -2.9±0.56

Table 18 Lead Concentration Ratios (CR) for radish grown as a companion crop to the main crops of Experiment A

| | clay | silt | sand | organic | P |
|---|---|---|---|---|---|
| | unadjusted means | | | | |
| dry plant/dry soil | 0.0079 | 0.017 | 0.090 | 0.0028 | *** |
| plant ash/dry soil | 0.072 | 0.15 | 0.93 | 0.030 | *** |
| fresh plant/dry soil | 0.00042 | 0.0014 | 0.011 | 0.00019 | *** |
| | adjusted means[2] | | | | |
| dry plant/dry soil | 0.0079 | 0.017 | 0.12 | 0.0017 | NS |
| plant ash/dry soil | 0.059 | 0.15 | 0.89 | 0.020 | NS |
| fresh plant/dry soil | 0.00042 | 0.0014 | 0.013 | 0.00008 | NS |

[1] probability levels for an effect of soil: NS - not significant, *** $P < 0.001$

[2] adjusted by analysis of covariance to represent average yield per plant, ash content and moisture content

Table 19 Significant correlations ($P < 0.05$) between Concentration Ratios for radish and the plant characteristics

| concentration ratio | dry yield per plant | moisture content | $\frac{\text{ash weight}}{\text{dry weight}}$ |
|---|---|---|---|
| | | Uranium (n=27) | |
| dry plant/dry soil | -0.63 | -0.50 | 0.56 |
| plant ash/dry soil | -0.63 | -0.54 | 0.40 |
| fresh plant/dry soil | -0.64 | -0.64 | 0.52 |
| | | Thorium (n=24) | |
| dry plant/dry soil | -0.44 | -0.55 | 0.53 |
| plant ash/dry soil | -- | -0.57 | -- |
| fresh plant/dry soil | -0.49 | -0.46 | 0.51 |
| | | Lead (n=23) | |
| dry plant/dry soil | -- | -0.61 | -- |
| plant ash/dry soil | -- | -0.63 | -- |
| fresh plant/dry soil | -- | -0.78 | -- |

Table 20 Significant correlations ($P < 0.05$) between Concentration Ratios and plant characteristics

| concentration ratio | fresh weight | dry weight | ash weight | moisture content | $\frac{\text{ash weight}}{\text{dry weight}}$ |
|---|---|---|---|---|---|
| Uranium (n=58) | | | | | |
| dry plant/dry soil | -- | -0.28 | -- | 0.40 | 0.35 |
| plant ash/dry soil | -- | -- | -- | 0.30 | -- |
| fresh plant/dry soil | -0.32 | -0.32 | -- | -- | -- |
| Thorium (n=46) | | | | | |
| dry plant/dry soil | -0.39 | -0.33 | -- | -- | -- |
| plant ash/dry soil | -0.31 | -- | -- | -- | -- |
| fresh plant/dry soil | -0.42 | -0.30 | -- | -0.32 | -- |
| Lead (n=45) | | | | | |
| dry plant/dry soil | -0.57 | -0.55 | -0.44 | -- | -- |
| plant ash/dry soil | -0.52 | -0.50 | -0.44 | -- | -- |
| fresh plant/dry soil | -0.58 | -0.53 | -0.42 | -0.45 | -- |

Experiment B used a log-scale concentration series and thus, the soil concentration should be log-transformed for regression analysis. The linearity assumption for CR is expressed as:

$$\text{plant conc.} = \text{CR} \cdot \text{soil conc.} \qquad (1)$$

taking logs:

$$\log(\text{plant conc.}) = \log(\text{CR}) + \log(\text{soil conc.}) \qquad (2)$$

restating as a linear regression model:

$$\log(\text{plant conc.}) = \log(\text{CR}) + b \cdot \log(\text{soil conc.}) \qquad (3)$$

where b is the regression coefficient.

For the equations 2 and 3 to be equal, the coefficient b must be unity. Thus, the appropriate statistical test is to compare least square estimates of b to unity. An alternative test is to compute individual CR values and test for an effect of soil concentration in an analysis of variance. We present both tests (Table 21).

Uranium concentrations in leaves were not linearly related to soil concentrations. As soil concentration increased, plant concentrations increased to a greater extent than expected (Figure 1). This is probably attributable to a concentration-dependent retention of the U in the soil. At high concentrations, relatively less of the U is retained on the soil solids. Nitrogen had no significant effect on CR values for U, although with less N the CR values tended to be about two-fold lower.

The mean CR value (dry plant/dry soil) for radish on the silt soil in Experiment A was 0.095. This coincides with the low N treatment of Experiment B, where the mean was 0.76. This 8-fold difference was significant and is quite close to the 6-fold difference reported by Sheppard and Evenden (1987) for small pot studies. A major contributor to this difference may be the tendency of the mini-lysimeters to dry out very rapidly. This hypothesis fits with our previous observation with U that impeded growth resulted in higher CR values. The difference may also be related to the fact that U will migrate in lysimeters and will accumulate at the soil surface. This may have been accentuated in the mini-lysimeters.

Thorium concentrations in leaves were linearly related to the soil concentrations (Figure 2), the slopes were not significantly less than unity. There were significant differences among the CR values across the treatments, but these did not represent a consistent trend. Thus, an assumption of linearity as implied by the use of CR is not inappropriate. The CR values were significantly higher when less N was applied. This was not related to different growth characteristics or yield of the radish. The CR values from Experiment A used the lower, and more typical levels of N. Thus, the CR values of Experiment A would be higher than in situations where excess N was applied, but this is conservative in terms of food chain model dose estimates. The mean CR values (dry plant/dry soil) for radish on the silt soil in Experiment A was 0.012. This coincides with the low N treatment of Experiment B, where the mean was 0.20. This difference between Experiments A and B was significant and confirms the result with U that CR values from small-pot experiments tend to be high.

Figure 1. Uranium concentrations in radish roots (dry weight basis) versus concentrations in soil

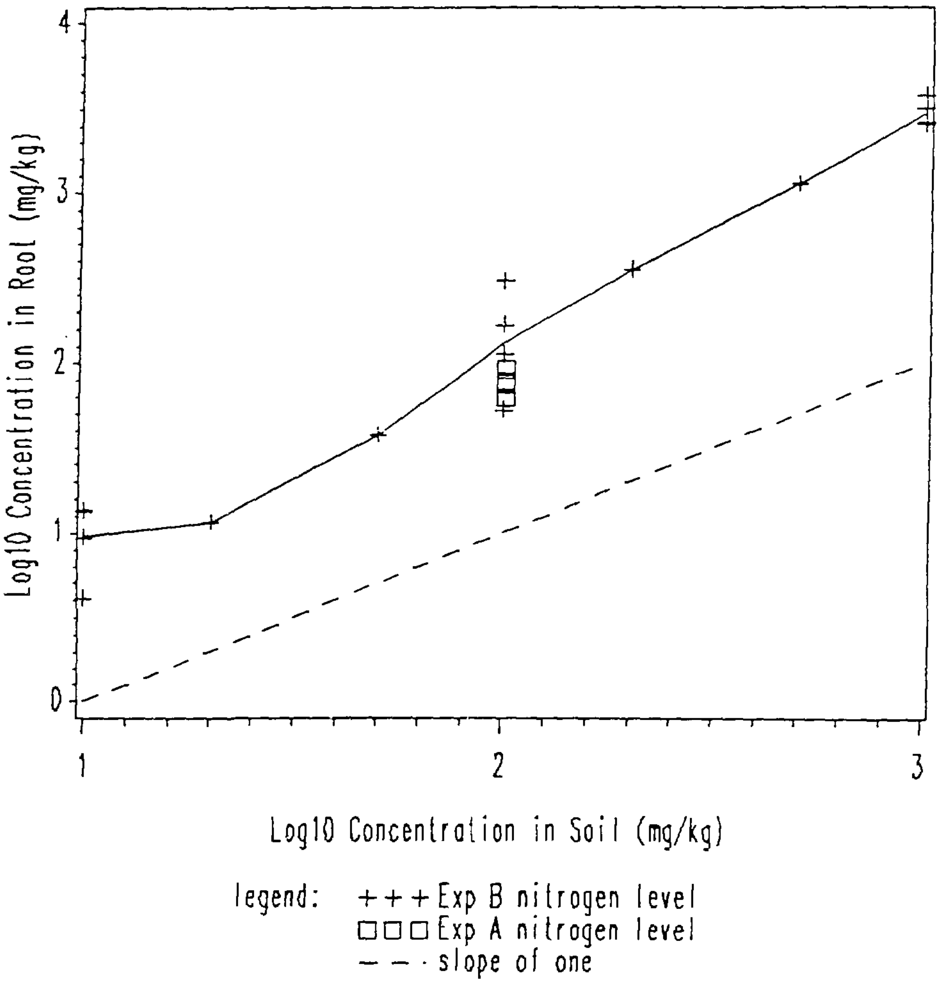

Figure 2 Thorium-230 concentrations in radish root (dry weight basis) versus concentrations in soil

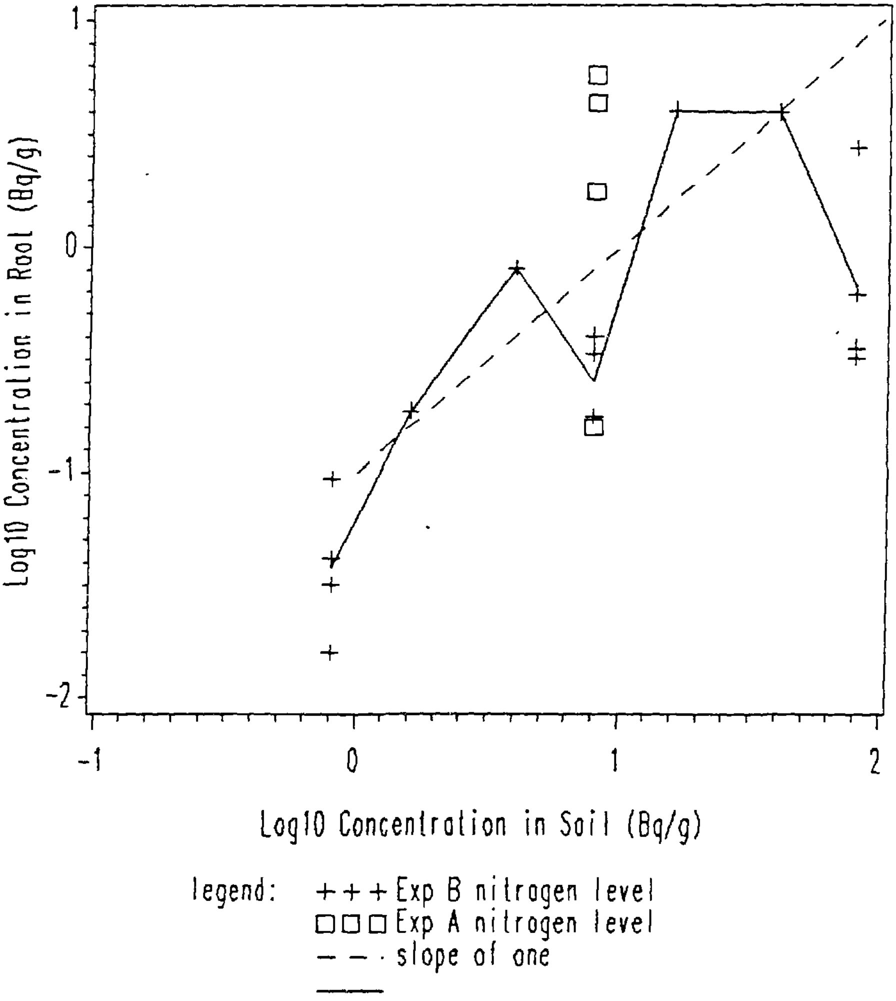

Figure 3 Lead-210 concentrations in radish root (dry weight basis) versus concentrations in soil

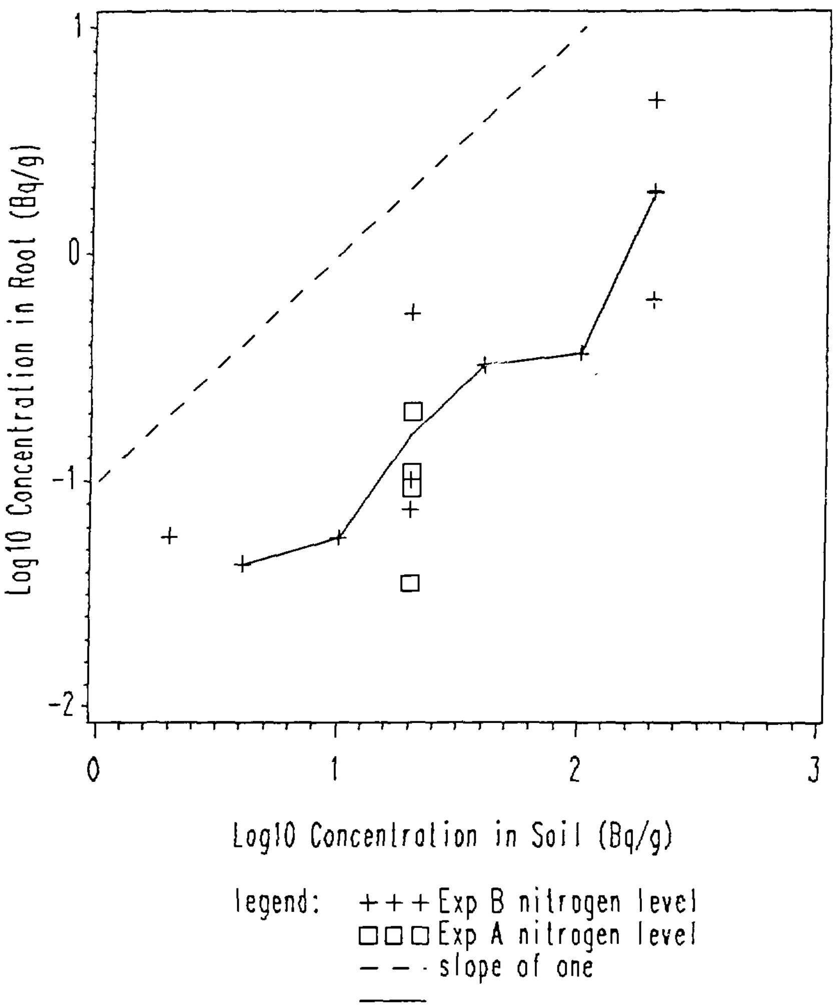

Table 21 Relationship of CR for radish root to soil concentration, Experiment B

| statistical consideration[1] | $\frac{\text{dry plant}}{\text{dry soil}}$ | $\frac{\text{plant ash}}{\text{dry soil}}$ | $\frac{\text{fresh plant}}{\text{dry soil}}$ |
|---|---|---|---|
| | | Uranium | |
| slope of log-log line | 1.28* | 1.13* | 1.26* |
| range of CR | 0.41-3.8 | 5-32 | 0.035-0.34 |
| effect of soil concentration | * | NS | * |
| effect of nitrogen | NS | NS | NS |
| | | Thorium | |
| slope of log-log line | 0.67 NS | 0.68 NS | 0.64 NS |
| range of CR | 0.0039-0.71 | 0.056-9.5 | 0.00046-0.1 |
| effect of soil concentration | * | * | * |
| effect of nitrogen | * | * | * |
| | | Lead | |
| slope of log-log line | 0.91 NS | 0.90 NS | 0.93 NS |
| range of CR | 0.0017-0.029 | 0.031-0.27 | 0.00025-0.0041 |
| effect of soil concentration | NS | NS | NS |
| effect of nitrogen | NS | NS | NS |

[1] the statistical considerations are 1) the slope of the log tissue concentration versus log soil concentration line and the probability level by t-test of whether it is significantly different from unity, 2) range of CR values, 3) probability level following an F-test of whether soil concentration affects $\log_{10}$ CR, and 4) probability level following a t-test of whether nitrogen had an effect on the CR values.

Concentrations of Pb in leaves were linearly related to the concentrations in soil (Figure 3). The CR values were not significantly affected when less N was applied. The mean CR values (dry plant/dry soil) for radish on the silt soil in Experiment A was not significantly different from corresponding low N treatment of Experiment B.

The conclusions of Experiment B are:

- plant concentrations were linearly related to soil concentrations for Th and Pb, but not linearly related for U
- levels of applied N did not modify the CR data for U and Pb
- even for shallow-rooted small plants like radish, there is an effect of container size and/or companion crop on CR data.

## 7. Summary of Effect of Soil on CR

The effect of soil type on CR has been discussed for each radionuclide in several preceeding sections. The overall trends are summarized here. The working hypothesis was that plant uptake, and hence CR, would be inversely related to the sorption or retention strength of the soil. Plants would absorb more U, Th and Pb from soils less able to retain these elements. The sand soil was expected to have the lowest retention because it has the lowest particle surface area, the lowest organic matter content and probably the lowest charged surface density. The organic soil was expected to have the highest retention capacity for having the opposite characteristics. It was not clear a priori how the clay and silt would behave as their pH, texture and carbonate contents were expected to counter-balance in creating the net effect.

The main crop plants in Experiment A showed the highest uptake from the sand for each radionuclide, in agreement with the hypothesis. There was no consistent trend among the other soils. The radish from Experiment A, especially after statistical adjustment for growth characteristics, consistently showed highest uptake from the sand and lowest uptake from the organic soil. These results confirm our hypothesis, and show no basis to distinguish plant uptake of U, Th and Pb between the clay and silt soils. The effect of soil type was up to 100-fold for U in radish.

## 8. Comparison to Literature Review

Ranges of dry weight CR from this study were compared to the literature survey of Sheppard and Evenden (1987), using the same categories as they reported (Table 22). There is a difficultly in doing such comparisons because the methods and especially the definitions of the categories vary throughout the literature. This study provided data for a number of the categories missing in the literature. The values are in the same ranges as most of the literature values. It must be remembered that CR values are quite variable and differences of at least an order of magnitude are to be expected. In contrast to the literature review, this study provides a basis to compare CR values measured in a uniform experimental protocol.

Table 22 Range of CR values (dry plant/dry soil) summarized in same categories as used by Sheppard and Evenden (1987), with the corresponding literature values where available in parentheses

| plant type[1] | clay to loam | sand | organic | not specified |
|---|---|---|---|---|
| | | Uranium | | |
| cereals | 0.00013-0.0026<br>(0.001-0.0083) | ---<br>(0.001) | --- | ---<br>(0.001-0.003) |
| vegetables | 0.02-0.05<br>(0.0002) | --- | 0.008 | ---<br>(0.003-0.01) |
| root crops | 0.012-0.36 | 0.0014-0.35 | 0.002-0.003 | ---<br>(0.002-0.007) |
| | | Thorium | | |
| cereals | <0.001-0.03<br>(0.0007-0.042) | ---<br>(0.0005-0.02) | --- | ---<br>(0.0002-0.003) |
| vegetables | 0.0023-0.01<br>(0.0002-0.04) | --- | 0.013 | ---<br>(0.0006) |
| root crops | 0.0002-0.039 | 0.0004-0.18<br>(0.003) | | --- |
| | | Lead | | |
| cereals | 0.0019-0.025 | --- | --- | --- |
| vegetables | 0.0041 | --- | | ---<br>(0.0003) |
| root crops | 0.00021-0.049 | 0.0025-0.12 | 0.0012-0.0071 | ---<br>(0.0002) |

---

[1] we included grain of corn, barley and wild rice as cereals, spinach as vegetable and potatoes and radish as root crops.

## D. CONCLUSIONS

Plant/soil concentration ratios (CR) are used to predict dose to humans from contaminated soil. A literature review revealed there were very few CR data for U, Th and Pb. This study measured CR values for these elements using four distinctly different soils and seven crop species. The measured CR data are presented as dry plant/dry soil ratios, the preferred mode of expression, as well as plant ash/dry soil and fresh plant/dry soil ratios. The interrelationships among the CR values were much as expected. Specifically:

- CR values were lower in soils expected to have the highest sorption capacity.
- CR values were lower in grains than in stems for U and Pb
- CR values were higher in the skin of root crops than in the flesh.

## E. RECOMMENDATIONS AND FUTURE WORK

- The CR values given in this study are appropriate and probably preferrable to literature values for use in modelling the transfer of U, Th and Pb in Canadian environments.

- This study did not address the effects of inhomogeneous distribution of U, Th and Pb in the soil, or of subsoil sources of U, Th and Pb. Inhomogeneous distribution can result when contaminated materials are covered with soil or when contaminants are carried to the site by groundwater. Further experimental work may show that uptake from buried sources can be predicted by modifying the results of this study to reflect a different root contact with the contaminants.

- The CR values reported here average about 0.01 on a dry weight basis. Soil contamination on plants of 1% on a dry weight basis would give the same apparent CR value. This is about 2 g dry soil per kilogram fresh plant, an amount easily left on vegetables that are not scrupulously cleaned. The contribution of soil load on vegetables to radionuclide consumption should be carefully assessed for relatively immobile elements such as U, Th and Pb.

- CR values are closely dependent upon the mobility of the elements in the soil. This mobility, typically characterized by partition coefficient ($K_d$) measurements, can be assessed in the laboratory without the need to grow plants. We recommend that a survey of $K_d$ values be done to extend the information on the effect of soil on radionuclide uptake. The $K_d$ information can be used directly to estimate radionuclide migration in soil, and indirectly to either deterministically or stochastically select appropriate CR values for a given soil.

## F. REFERENCES

Sheppard S.C. and W.G. Evenden, 1987. Review of effect of soil on radionuclide uptake by plants. Atomic Energy Control Board, INFO-0230.

SAS, 1985. SAS User's Guide: Statistics. Statistical Analysis System, SAS Institute Inc., Cary, N.C.

## APPENDIX A

### Interlaboratory/Intermethod Comparisons

The LSC method we used for $^{210}$Pb is not commonly used, principally because this isotope would be mixed with many other natural isotopes in most applications. The LSC system has only limited capability to discriminate isotopes. With $^{210}$Pb, both the $^{210}$Bi and $^{210}$Po daughters are detectable, emitting a beta and an alpha, respectively and having half-lives of 5 days and 138 days, respectively. Dual isotope LSC techniques can be used because the detection peaks of $^{210}$Bi and $^{210}$Po overlap, but are distinct from those of $^{210}$Pb.

In order to assure our LSC methods, we undertook an interlaboratory/intermethod comparison. This was limited to the few samples where there was sufficient material to allow for two analytical methods and where the LSC method found detectable amounts. The alternate lab (the Saskatchewan Research Council) used the radiochemical methods described in the text.

The results (Table A1) showed very good agreement for $^{210}$Pb. All of the SRC results were within 1.5-fold of the LSC results. This is equivalent to the experimental error found after analysis of variance.

The extension of the $^{210}$Pb analysis using the SRC methods in cases where LSC was limited by severe quench allowed another comparison of laboratories and methods. Although none of these samples were analysed by both methods, there was overlap in the types of samples. We used an artificial covariate to characterize the effect of the analytical method in our analysis of variance and found it to have no significant effect. Thus, results from the two methods were indistinguishable.

Table A1 Interlaboratory/intermethod comparison of the LSC method with results from the Saskatchewan Research Council (SRC) for $^{210}$Pb

| vegetation sample |  |  | experimental replicate number | LSC (Bq/g ash) | SRC (Bq/g ash) |
|---|---|---|---|---|---|
| (soil, | crop, | crop part) |  |  |  |
| clay | corn | stover | 1 | 0.40 | 0.58/0.30 |
| clay | barley | grain | 1 | 6.2 | 3.2 |
| silt | potato | flesh | 3 | 0.05 | <0.04 |
| silt | barley | straw | 2 | 4.7 | 4.5/8.5 |
| sand | potato | flesh | 1 | 1.8 | 1.4 |
| sand | potato | flesh | 2 | 1.2 | 1.5 |
| sand | potato | flesh | 3 | 1.4 | 1.4 |