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FIELD AND GREENHOUSE EXPERIMENTS ON THE FATE OF TECHNETIUM IN PLANTS AND SOIL†

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Abstract—The behavior of ^{95m}Tc in plants and in a Captina silt loam soil following a single application of the pertechnetate form of the radionuclide to bare soil was compared between field and greenhouse conditions. Over a period of approx. six months, the net uptake of ^{95m}Tc by plants from undisturbed, intact soil in the greenhouse was about a factor of 10 greater than that in the field. Sieving the soil through a 2-mm mesh screen before potting and then planting new grass further increased plant uptake of ^{95m}Tc by approx. a factor of 20 relative to the field. Uptake by new grass was increased even more by decreasing the pot size. Most of the ^{95m}Tc applied to soil in the field or the greenhouse remained in the top 4 cm of the profile. Soon following application to soil, pertechnetate was transformed, or otherwise immobilized, such that extractions with 0.01 M $CaCl_2$ recovered only a portion of the ^{95m}Tc present in soil. The extractability of ^{95m}Tc from soil using $CaCl_2$ decreased over time as did ^{95m}Tc concentrations in vegetation. The pertechnetate applied to soil appeared to be converted over time to a less soluble and therefore less bioavailable form.

INTRODUCTION

TECHNETIUM-99 is a long-lived radionuclide (half-life 210,000 yr) of recent interest because of its high production in nuclear reactor fuel, its release to the atmosphere during the recycling of spent nuclear fuel, and its potential high degree of mobility in terrestrial food chains (Wi79). The uptake of technetium by plants from soil in laboratory and greenhouse studies is among the highest of any radionuclide. Plant/soil concentration ratios (CR = Tc/g dry wt vegetation ÷ Tc/g dry wt soil) for wheat, soybeans, cheatgrass and tumbleweed range between approx. 50 and 1000 (La77; Wi77; Ro78).

Under field conditions, we observed substantially lower concentration ratios for Tc than those observed in the laboratory and greenhouse experiments cited above. In areas adjacent to operating uranium-enrichment facilities, CR values for ^{99}Tc ranged from 1.4 to 44 with a geometric mean [geometric mean = exp (arithmetic mean of ln transformed data)] of 9.5 (Ho80). In field experiments, after a single application of a solution of $^{95m}TcO_4^-$ to bare soil, the initial CR value (decay-corrected) for regrowth herbaceous vegetation was approx. 30 but declined over a period of approx. seven months to about 2.0 (Ho82a). The behavior of Tc in soil and vegetation over time indicated weathering removal of Tc from plant tissue, decreasing availability of Tc in soil for plant uptake, and dilution of the Tc in vegetation due to growth. We hypothesized that the reduced availability of technetium in soil for uptake into plants was due to the chemical reduction of soluble pertechnetate (Tc VII) to lower insoluble valence states (Tc IV) (Ho82a; Ho82b).

This report describes a combined field and greenhouse study that follows up on our previous work (Ho82a; Ho82b). Our first objective was to directly compare the relative behavior of Tc in forage plants and soil subsequent to a single application of a solution of $^{95m}TcO_4^-$ to

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bare soil in the field and greenhouse. In addition, the effect of pot size, soil disturbance, and new growth on technetium uptake into vegetation was examined in the greenhouse experiment, because these factors have been postulated as potentially accounting for differences between results obtained in the greenhouse and field (Ho80). The second objective was to determine whether differences in the bioavailability to vegetation of Tc in soil can be indicated by the relative extractability of Tc from soil using 0.01 M calcium chloride solution as an extractant. This extractant is commonly used to measure soil pH and has been used previously to measure nonsorbed ^{99}Tc in soil (La77) because for many soils it approximates the total electrolyte concentration in the soil solution (Wh79).

METHOD AND MATERIALS

Radionuclide

For these experiments we used ^{95m}Tc (radiochemical purity >98% with the principal contaminant being ^{96}Tc having a 4.3-day half-life). Technetium-95m was used as an analog for the long-lived ^{99}Tc isotope for three reasons. First, ^{95m}Tc does not persist as radioactive contamination in the environment (half-life = 61 days). Second, ^{95m}Tc is a gamma-ray emitter and is more easily detected at low levels in environmental samples than the low-energy beta emission from ^{99}Tc (max. .292 MeV). Third, because of its high specific activity, ^{95m}Tc can be applied to soil at lower mass concentrations than ^{99}Tc which is toxic to plants at soil concentrations greater than 0.1 μg/g (Wi79). Technetium-95m was obtained as sodium pertechnetate ($^{95m}TcO_4^-$) in water from New England Nuclear. After decay of the ^{96}Tc impurity, the ^{95m}Tc was added to distilled water to make solutions for application to soil. Gamma spectrometry using standards made in our laboratory was used for analysis of ^{95m}Tc in plants, soils, and soil extracts. All data were subsequently corrected for the radioactive decay of ^{95m}Tc to simulate the persistence of the longer-lived ^{99}Tc.

Field studies

For several years we observed the same pattern of seasonal change in forage vegetation at an open field located on the Department of Energy Oak Ridge Reservation, TN. In spring (February–May), after mowing the standing vegetation, fescue grass (*Festuca* sp.) is prevalent. During summer (June–September) *Lespedeza* sp. becomes more common until it dominates the vegetation biomass. The soil at our field site is a Captina silt loam with an average pH ($\pm$S.D.) of 4.6 ($\pm$0.38) in 0.01 M $CaCl_2$ and an organic matter content of 6.2 ($\pm$2.5)% (both for 12 samples taken to a depth of 4 cm).

In the field, three plots (each 1 m^2) were cleared of all vegetation to bare soil in late February 1981. Each plot was sprayed uniformly with 112 μCi (2.5×10^8 dpm or 5 ng) of ^{95m}Tc in 1 l. of distilled water (Table 1). The droplet size was large enough and wind conditions were such that no drift of the spray occurred.

The sampling periods, rainfall data and soil moisture data for the field site are shown in Table 2. At a soil moisture level of 45% (45 ml./100 g dry soil) the silt laom soil was essentially at field capacity. Within 3 hr after the applications of the ^{95m}Tc to soil and at each subsequent sampling period, three soil cores (20 cm deep) were taken at random from each plot. Cores were cut into 2-cm sections, weighed, dried at 100°C, reweighed, and analyzed for ^{95m}Tc. Two additional cores (4 cm deep) were taken at random from each plot for soil extractions (described later).

Soil and regrowth vegetation were sampled from each plot over a period of 27 weeks (Table 2). The major plant species present in each plot were randomly sampled (usually three samples of each per plot). Samples were dried at 70°C, weighed and analyzed for ^{95m}Tc. At 13, 20 and 27 weeks after beginning the experiment, one plot (not previously harvested) was cleared of all standing vegetation after sampling to measure total plant biomass and total ^{95m}Tc content of the biomass. The standing biomass was dried, chopped, mixed, subsampled and analyzed for ^{95m}Tc.

Greenhouse studies

Five intact soil columns (25-cm diam) with an undisturbed soil profile to a depth of approx. 20 cm were excavated from near the field plots and fitted into large polyethylene pots (25 cm diam and 23 cm deep). (These pots are called

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Table 1. Comparison of experimental conditions for field and greenhouse studies to determine uptake of ^{95m}Tc by plants from contaminated Captina silt loam soil collected at Oak Ridge, TN

Condition	Field plots[a]	Greenhouse: Large pots, undisturbed soil[b]	Greenhouse: Large pots, sieved soil[b,c]	Greenhouse: Small pots, sieved soil[b,c]
Surface area (m^2)	1	0.05	0.05	0.02
Moist soil vol. (cm^3)	-	9200	6900[d]	1900
Soil bulk density (dry g/cm^3)	1.3	1.1	1.0	0.9
^{95m}Tc applied (dpm)	2.5×10^8	5×10^6	5×10^6	5×10^6
Calculated (dpm/m^2)	2.5×10^8	1×10^8	1×10^8	2.5×10^8
Observed (dpm/g dry wt soil) (0-4 cm)	2900[e]	1900[e]	1800[e]	4500[e]

[a]N = 3 plots.

[b]N = 5 pots.

[c]Sieved using 2-mm screen.

[d]Sieved soil settled approximately 25% by the end of the experiment.

[e]Concentration at last sampling period.

"large pots, undisturbed soil" in the tables.) Each pot contained an average 10.9 kg moist soil (range 9.9–11.7 kg/pot). Five more pots (same size) were filled to a depth of approx. 20 cm with moist field soil that had been sieved through a 2-mm screen to remove stones and organic debris. (The latter pots are called "large pots, sieved soil".) In addition, five smaller polyethylene pots (16 cm diam and 14 cm deep) were filled to a depth of approx. 10 cm with the sieved soil. (These pots are called "small pots, sieved soil" in the tables.) All 15 pots were set in a greenhouse. A small hole in the bottom of each pot allowed the collection of leachate in 1-l. polyethylene bottles beneath the pots.

The vegetation was removed from the pots containing undisturbed soil, and the soil was uniformly sprayed with 2.3 μCi (5×10^6 dpm) of $^{95m}TcO_4^-$ in 50 ml. of distilled water. Both sets of large and small pots containing sieved soil received the same single application of $^{95m}TcO_4^-$ (Table 1).

The natural vegetation on the undisturbed soil was allowed to recover. The sieved soil in the large and small pots was seeded with tall fescue (*Festuca* sp. var Kentucky 31). On each sampling date (Table 2), two pots from each set of soils (Table 1) were completely harvested of all standing vegetation by slipping to near the surface of the potted soil. Samples of grass and/or *Lespedeza* were collected from the remaining three pots in each set without removing much vegegation biomass. A soil core (4 cm deep) was collected from pots containing undisturbed and sieved soil to determine the extractability of ^{95m}Tc from potted soil at each sampling period. Soil was only sampled at the end of the experiment from the remaining pots to avoid destroying the pattern of water percolation through the soil. At the end of the experiment, soil cores were taken from all pots to determine the ^{95m}Tc concentration in the 0- to 4-cm and below 4-cm zone of the soil profile. Pots received sprinklings of distilled water two

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Table 2. Sampling period, sampling date, elapsed time in weeks (ET) following ^{95m}Tc application to surface soil, cumulative amount of rainfall (field) or watering (greenhouse), and percent soil moisture for field and greenhouse experiment

Conditions	Sampling period	Date	ET	Cumulative rainfall (L)[a]	Percent soil moisture: Undisturbed soil	Percent soil moisture: Sieved soil
Field	0	Feb. 25	0	-	50 ± 8	
	1	March 26	4	58	50 ± 6	
	2	April 28	9	206	46 ± 7	
	3	May 29	13	262	40 ± 5	
	4	July 14	20	422	38 ± 4	
	5	Sept. 4	27	572	35 ± 3	
Greenhouse large pots	0	March 2	0	-	43	39
	1	March 31	4	63	18	18
	2	May 5	9	192	22	12
	3	June 2	13	292	30	27
	4	July 22	20	432	24	12
	5	Sept. 4	26	562	23 ± 6	25 ± 2
Small pots	0	March 2	0	-		22
	1	March 31	4	100		22
	2	May 5	9	241		32
	3	June 2	13	300		17
	4	July 22	20	402		35
	5	Sept. 4	26	462		20 ± 1

[a]1.0 cm rain over 1 m^2 is 10 L water in the field; in the greenhouse, the volume of water applied to 0.02 or 0.05 m^2 of potted soil was scaled to 1 m^2 by multiplying by a factor of 50 or 20, respectively.

[b]Percent soil moisture = [(wt of moist soil - wt of dry soil)/wt of dry soil] x 100; average values (±SD) are based on 6 to 10 soil cores (0-4 cm deep), while values with no SD are based on a single soil core.

to three times a week to maintain sufficient soil moisture to sustain plant growth (Table 2). Watering was kept to a minimum to prevent leaching losses of ^{95m}Tc from the potted soil.

Soil extractions

We know from prior experiments that most of the ^{95m}Tc applied to field soil is retained in the upper few centimeters of the soil profile (Ho82b). Because of this retention in the surface soil and because of greater ease in handling and sample preparation, soil extractions were based on a 0- to 4-cm-deep soil core. Each core was chopped and mixed in a dish with a spatula. One-half of the sample (approx. 10 g) of moist soil was put into a 40-ml. centrifuge tube with

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0.01 M $CaCl_2$ (pH 6.9) in the proportion 23 ml. $CaCl_2$: 10 g soil. Soils and solution were shaken on a wrist-action shaker for 30 min, then centrifuged. Ten ml. of the $CaCl_2$ supernatant were removed and analyzed for ^{95m}Tc. The unextracted half of the sample was analyzed to determine ^{95m}Tc concentration in soil. Based on the analysis of both portions of the soil sample, the percent extractable ^{95m}Tc from soil was calculated.

To test the efficiency of the extraction procedure, 7- to 8-g samples of washed beach sand and uncontaminated soil from the field site were put into centrifuge tubes, spiked with 1 ml. of ^{95m}Tc (pertechnetate) in water (approx. 2.5×10^5 dpm/tube), and extracted after remaining at room temperature overnight. Two sand and two soil samples were extracted three times with 0.01 M $CaCl_2$, followed by three successive extractions with cold 5% NaOCl.

RESULTS AND DISCUSSION

Soil extractions

Analysis of variance showed the extractability of ^{95m}Tc from field plot soils using $CaCl_2$ decreased significantly ($P < 0.05$) over time (Table 3). In the field, the extractability was not 100% immediately after application indicating a rapid immobilization of soluble pertechnetate by some reaction with soil. Extractability was unchanged (25–29%) for the first four weeks of the experiment but then declined sharply sometime between four and nine weeks post-contamination to about one-third the initial amount. After 27 weeks, only 6.7% of the ^{95m}Tc in soil could be extracted with $CaCl_2$. In potted soil kept in the greenhouse, the extractability was 16–24% immediately after application of the ^{95m}Tc to the soil. Extractability in the potted soil decreased by more than one-half within four weeks following contamination. The extractability of ^{95m}Tc from potted soil fluctuated around a mean value of 6 to 9% after one month in the greenhouse.

The extraction of ^{95m}Tc-contaminated soil with 0.01 M $CaCl_2$ appeared to remove soluble pertechnetate, the chemical form available for uptake into plant roots, from soil. When samples of beach sand were spiked with $^{95m}TcO_4^-$ and left undisturbed overnight, the first extraction with 0.01 M $CaCl_2$ removed an average ($\pm$S.D.) 91($\pm$)% of the total ^{95m}Tc. The amount removed from Captina silt loam soil samples (spiked in the laboratory) by a single extraction with $CaCl_2$ under the same conditions as the sand was 39 ($\pm$7)%. Hence, as observed in the

Table 3. Changes in the percent extractable ^{95m}Tc from soil (0–4 cm deep) with a single treatment using 0.01 M $CaCl_2$ over time for both field and greenhouse conditions

Sampling period	Elapsed time (weeks)	Percent $CaCl_2$ extractable: Field soil[a]	Large pot, undisturbed soil[b]	Large pot, sieved soil[b]	Small pot, sieved soil[b]
0	0	29* ± 11	24	16	21
1	4	25* ± 6	11	6.3	8.0
2	9	8.7+ ± 5.3	5.5	3.2	10
3	13	8.1+ ± 1.7	9.0	9.5	9.0
4	20	7.8+ ± 2.7	10.7	7.8	2.9
5	27	6.7+ ± 2.5	9.4 ± 3.0	5.5 ± 1.9	3.6 ± 0.3

[a]Mean (±SD) values (N=2) in the same column not sharing the same symbol are significantly different as determined by ANOVA and Duncan's Multiple Range Test.

[b]N = 1 or 2 sample cores.

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field and the greenhouse, there was a dramatic retention of soluble pertechnetate by soil soon following application. Successive extractions using 0.01 M $CaCl_2$ showed a progressive reduction in the amount of ^{95m}Tc removed from Captina silt loam soil for the first three extractions: (1) $38 \pm 6\%$, (2) $15 \pm 1\%$, (3) $8 \pm 0.1\%$.

An extraction of the soil with cold 5% NaOCl was used to further characterize the fraction of ^{95m}Tc retained following successive extractions with $CaCl_2$. The NaOCl extraction removed ^{95m}Tc present in a reduced valence state and/or $^{95m}TcO_4^-$ reacted with an oxidizable matrix, like soil organic matter. Using cold 5% NaOCl as an extractant following the three treatments with $CaCl_2$ resulted in a significant increase ($32 \pm 6\%$) in the remaining amount of ^{95m}Tc extracted from soil. Two additional treatments with cold 5% NaOCl removed 9% of the ^{95m}Tc in soil. The sharp increase in the amount extracted using cold 5% NaOCl, an oxidant, following extractions with 0.01 M $CaCl_2$, indicated the oxidation of reduced insoluble Tc(IV) to soluble Tc(VII) or destruction of interactions between ^{95m}Tc and surfaces of soil organic matter. There is also the possibility that the pertechnetate ion in soil reacted with sulfide or sulfhydryl groups resulting in insoluble complexes (Sa82) which were destroyed by treatment with NaOCl. In any case, the use of these two extractants demonstrated the existence of an available (TcO_4^-) and unavailable pool of ^{95m}Tc in soil.

Uptake by vegetation

The net uptake of ^{95m}Tc from contaminated soil into vegetation was calculated as the product of the vegetation yield above a unit area of soil (kg/m^2) and the concentration in vegetation (dpm/kg). The net uptake divided by the amount of ^{95m}Tc applied to soil ($\times 100$) gave the net percent uptake of ^{95m}Tc by vegetation relative to the initial deposit. To permit comparisons among the various experimental conditions, the percent uptake was normalized by dividing by vegetation yield, thereby adjusting percent uptake values for any differences due to vegetation biomass. Comparison of the normalized percent uptake (Table 4) shows approximately a factor of 10 greater uptake of ^{95m}Tc by greenhouse plants from undisturbed soil (large pots) than by plants in the field. Considering only the large pots, sieving the soil and planting new grass increased uptake by approximately a factor of two. Furthermore, considering only sieved soil, decreasing the pot size enhanced the uptake of ^{95m}Tc from soil into new grass by a factor of approx. 1.8. In these comparisons, all of the field plots and greenhouse pots contained fescue or fescue in combination with other species (e.g. fescue and *Lespedeza*). Therefore, the observed differences were due primarily to differences in plant age, environmental conditions and soil treatment, not to differences in species composition.

It is apparent from Tables 3 and 4 that ^{95m}Tc extractability from the Captina silt loam soil did not vary as much under different conditions (field vs greenhouse) or treatments (sieved vs nonsieved) as did normalized percent uptake by the vegetation. For example, the highest uptake from sieved soil in the small pots was not associated with greater availabililty of ^{95m}Tc from soil as measured by $CaCl_2$ extractability. Also, the lower net uptake by vegetation under field as compared to greenhouse conditions is not explainable by differences in ^{95m}Tc extractability from soil under these conditions. Other reasons for differences in uptake among the various soil treatments appear to be more important than availabililty of ^{95m}Tc for uptake from soil. Plausible reasons include: new grass on the sieved soil had greater uptake due to rapid root development and high nutrient requirements of the new growth; small pots forced a greater root mass per unit soil volume and allowed for greater root contact with the ^{95m}Tc; and the absence of dew and rain, and forced airflow within the greenhouse by exhaust fans, caused higher transpiration rates for potted plants resulting a greater plant uptake of ^{95m}Tc from undisturbed soil in the greenhouse as compared to the field.

Retention in soil

Comparison of ^{95m}Tc concentrations at the first and last sampling period indicated little change in the distribution of ^{95m}Tc throughout the soil profile over the 27 weeks of the field study. This was consistent with other evidence that the pertechnetate applied to field soil was reduced to a less soluble chemical form or otherwise immobilized by interactions with or-

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Table 4. Mean (±S.D.) ^{95m}Tc uptake into vegetation expressed as a percentage of the total amount initially applied to bare soil and normalized for the total vegetation yield over a period of approx. six months

Experimental conditions	Vegetation type	Vegetation yield (kg/m^2)	Total net % uptake[a]	Normalized % uptake (m^2/kg)
Field plots	Mixed (fescue and *Lespedeza*)	0.74 ± 0.23	0.75 ± 0.26	1.0 ± 0.11
Greenhouse				
Large pots, undisturbed soil[b]	Mixed (fescue and *Lespedeza*)	0.39 ± 0.07	4.3 ± 1.7	11 ± 2.4
Large pots, undisturbed soil[c]	Mixed (fescue and *Lespedeza*)	0.24 ± 0.06	1.7 ± 0.5	7.2 ± 1.7
Large pots, sieved soil[b]	Fescue	0.25 ± 0.02	6.7 ± 1.0	27 ± 2.1
Large pots, sieved soil[c]	Fescue	0.13 ± 0.03	2.7 ± 0.9	21 ± 6.9
Small pots, sieved soil[b]	Fescue	0.31 ± 0.03	14 ± 2.0	46 ± 2.7
Small pots, sieved soil[c]	Fescue	0.12 ± 0.01	4.3 ± 0.4	38 ± 6.3

[a]Total net amount of decay-corrected ^{95m}Tc in harvested vegetation divided by the amount initially applied to soil.

[b]Vegetation in these pots (N = 2) was completely harvested at each sampling period.

[c]Vegetation in the pots (N = 3) was harvested only at last sampling date.

ganic matter. Regression analysis showed that concentrations in the surface field soil (0–4 cm) did decrease significantly with time (Table 5). However, concentrations at soil depths below 4 cm were generally less than 10% of those found in the top 4 cm of field soil at each sampling period.

In the greenhouse, the total dpm of ^{95m}Tc collected in leachate from the potted soils over the entire experiment was less than 5% of the total amount of radioactivity applied to the soil surface. This was partly because the watering schedule minimized leaching losses. The final distribution of ^{95m}Tc in the soil profile from both sieved and unsieved potted soil was not unlike that found in the field plots. In all potted soils the concentration of ^{95m}Tc in the subsurface zones (>4 cm deep) was, on the average, less than 15% (N = 20) of the concentration in the surface soil (0–4 cm) at the last sampling period. Soil extraction data (Table 3) indicated that $^{95m}TcO_4^-$ applied to potted soil was quickly converted to a less soluble and, therefore, less mobile chemical form which also minimized downward movement.

Retention in vegetation

In the field, ^{95m}Tc concentrations in fescue grass decreased with time over the course of the experiment with a half-time of 27 days (Table 5). This pattern was in contrast to ^{95m}Tc concentrations in *Lespedeza* which did not decrease with time. This may be explained by the emergence of *Lespedeza* in the field plots after the availabililty of ^{95m}Tc in soil had declined to a relatively constant, low value (Table 3).

In the greenhouse, concentrations of ^{95m}Tc in fescue grown on undisturbed soil and sieved soil

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Table 5. Geometric mean concentration (dpm/g dry wt) *of* ^{95m}Tc *in field soil* (0–4 cm), *field vegetation and vegetation grown on undisturbed and sieved soil under greenhouse conditions at various sampling times*

Sampling period	Field plots[a]			Greenhouse			
				Large pots, undisturbed soil[b]		Large pots, sieved soil[b]	Small pots, sieved soil[b]
	Soil	Fescue	Lespedeza	Fescue	Mixed sp.[c]	Fescue	Fescue
0	7100						
1	5000	185000		19000	32000	63000	211000
2	3500	9700	2200	12000	15000	31000	115000
3	2500	5100	2100	7000	8900	27000	114000
4	2800	2300	1700	-	7700	15000	107000
5	2900	1700	2000	4800	3600	20000	82000
N[d]	54	45	30	10	10	25	25
T_w[e]	150	27	f	82	53	90	140
r[g]	-0.51**	-0.82**	-0.04	-0.71*	-0.90**	-0.60**	-0.58**

[a]N = 3 per sampling period per plot.

[b]N = 5 pots.

[c]At each sampling period the concentration of ^{95m}Tc was measured in vegetation (fescue and *Lespedeza*) completely harvested from 2 pots.

[d]Total number of samples.

[e]T_w = weathering half-time = 0.693/b, where b is the slope of the exponential decay curve, conc. = ae^{-bt}, and where t = time in days (see Ho82a, Ho82b).

[f]Weathering half-time not calculated since ^{95m}Tc concentration was not significantly correlated with time.

[g]Correlation coefficient.

*P = <0.05, **P = <0.01.

decreased over the course of the study (Table 5) but with decay-corrected half-times longer than those observed for fescue in the field. The longer half-times in the greenhouse were probably due to the absence of meterological processes that can accelerate weathering under field conditions (e.g. rain, wind, dew and fog). Samples of mixed species of vegetation from the undisturbed pots harvested at each sampling period had a shorter half-time (53 days) due to the continuous removal of vegetation and the decreasing availability of ^{95m}Tc to regrow vegetation between sampling periods.

Correlation between uptake by fescue and extractability over time

The concentration ratio as an index to soil-plant uptake of ^{95m}Tc was calculated as:

$$CR = (\text{dpm per g dry wt plant})/(\text{dpm per g dry wt soil}),$$

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where the soil concentration was determined over a 0- to 4-cm soil depth. In each set of conditions under which plant uptake of ^{95m}Tc was examined over time, there was a tendency for greater plant uptake of ^{95m}Tc to be associated with greater extractability from soil using 0.01 M $CaCl_2$ (Fig. 1). However, the correlation between uptake and extractability was statistically significant only in the case of fescue grown on sieved soil in small pots ($r = 0.93$; $P \leq 0.05$). The trends between fescue CR value and percent $CaCl_2$ extractable ^{95m}Tc from Captina soil were, in part, a consequence of both variables decreasing with time under greenhouse and field conditions. The CR value for fescue in the field and in the greenhouse usually decreased abruptly with the time of decreased extractability of ^{95m}Tc from soil. For example, between the first and second sampling periods in the field, the CR value decreased from 37 to 2.8 (Table 5), while the extractability from soil declined from 25 to 8.7% (Table 3).

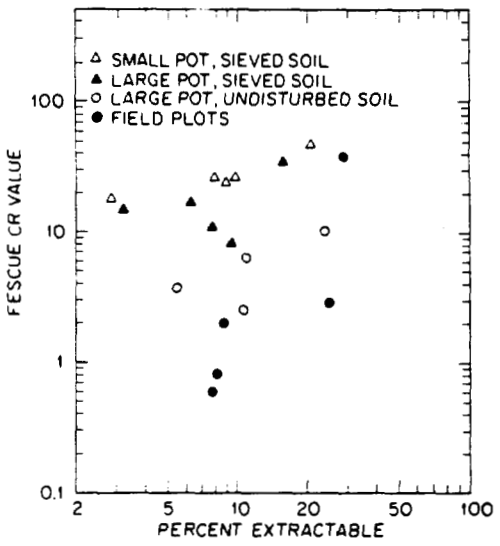

FIG. 1. Plot of fescue concentration ratios (CR) measured under four different experimental treatments vs the percent extractable ^{95m}Tc from Captina silt loam soil using 0.01 M $CaCl_2$. The CR value as an index to soil-plant uptake was calculated as: CR = (dpm per g dry wt plant)/(dpm per g dry wt soil), where the soil was 0–4 cm deep.

CONCLUSION

In field and laboratory experiments, pertechnetate ^{95m}Tc was transformed, or otherwise immobilized, such that, soon after application, extractions with 0.01 M $CaCl_2$ recovered only a portion of the ^{95m}Tc present in a Captina silt loam soil. Based on extractions of contaminated soil with 0.01 M $CaCl_2$ over a period of about six months and the history of ^{95m}Tc concentrations in vegetation, pertechnetate appeared to be converted to a chemical form less soluble and less available for root uptake by plants.

There were differences in the uptake of ^{95m}Tc by vegetation from contaminated Captina silt loam soil which were attributable to experimental conditions: field vs greenhouse, soil treatment, new vs old growth, and pot size. The difference in uptake by old plants was approximately a factor of ten greater in the greenhouse as compared to the field, probably due to higher evapotranspiration under greenhouse conditions. In the greenhouse, sieving the soil and planting new grass or decreasing the pot size increased the uptake of Tc by potted vegetation. The differences in uptake between experimental treatments did not correlate with differences in the extractability of ^{95m}Tc from soil using 0.01 M $CaCl_2$, but were more likely related to physiological differences between young and old grass roots and the greater root mass per unit soil volume in smaller pots.

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