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"Identification and Validation of Heavy Metal and radionuclide Hyperaccumulating Terrestrial Plant Species"

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Enclosed is a copy of a manuscript we are submitting to the Journal of Environmental Quality on our research on the development of phytoremediation technologies for radiocesium contaminated soils. The acknowledgment of DOE support is on page 2 of the manuscript.

Title: Potential for phytoextraction of ^{137}Cs from a contaminated soil

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Abstract

Potential for phytoremediation of an aged radiocesium-contaminated soil from Brookhaven National Laboratory was investigated in three phases: 1) hydroponic screening for plant species capable of accumulating elevated levels of cesium in shoots, 2) amending contaminated soil to enhance ^{137}Cs bioavailabilty, and 3) phytoextracting radiocesium with plant roots and its removal in harvested shoots.

The bioaccumulation ratio of Cs in shoots of hydroponically grown plants ranged between 38 and 165. From solution, dicot species accumulated 2- to 4-fold more cesium in shoots than grasses. The effect of several chemical compounds on ^{137}Cs desorption from the contaminated soil was investigated. Ammonium salts were the most effective at desorbing Cs from contaminated soil, but only 25% of radiocesium could be desorbed. Although release of radiocesium from the soil was concentration-dependent, this effect appeared to level off above 0.2 M ammonium in solution. In a pot study, from the soil contaminated with 400 pCi g^{-1} soil, the greatest amount of ^{137}Cs, 140 pCi, was removed in shoots of cabbage *(Brassica oleracea* var. *capitata*). ^{137}Cs accumulation in shoots was significantly increased by the addition of 40 NH_4NO_3 kg^{-1} soil. Increasing NH_4NO_3 application from 40 to 80 mmoles kg^{-1} soil did not further increase radiocesium phytoextraction. The ability to accumulate radiocesium from soil in shoots was significantly different among species tested. This ability increased in order: reed Canary grass (*Phalaris arundinacea*) < Indian mustard (*Brassica juncea*) < tepary bean *(Phaseolus acutifolius)* < cabbage.

Introduction

Soils have become contaminated with radionuclides as a result of above ground nuclear testing, accidental release or nuclear energy generation. ^{137}Cs is a long-lived ($t_{1/2}$ 30.2 years) by-product of nuclear fission. Although recently contamination of the environment with ^{137}Cs from the testing of nuclear weapons has been drastically reduced, large areas are still polluted with radiocesium. For example, in the Republic of Belarus about 1 million hectares of arable land were contaminated with ^{137}Cs and ^{90}Sr by Chernobyl nuclear accident (Kavkhuta et al., 1994). Decontamination of these polluted-soils remains an intractable problem, in part because of the high cost. Recently, the U.S. Department of Energy Assistant Secretary for Environment Restoration and Waste Management was quoted as saying that the $200 to $300 billion cost for the cleanup of radionuclide-contaminated soils may be drastically underestimated (Watson et al., 1993).

Phytoremediation is emerging as an attractive alternative to energy-intensive, high-cost traditional cleaning methods. This new technology employs the use of higher plants capable of accumulating high levels of contaminants in shoots. Contaminants are removed by harvesting the above-ground plant tissues. In addition of being cost effective (Salt et al., 1995), phytoremediation decontaminates the soil in situ thus preserving both the environment and the ecosystems. Because of these advantages, phytoremediation has been cited as the method of choice for the clean up of large areas polluted with low to moderate levels of contaminants (Baker et al., 1994).

Numerous studies have reported on the potential of higher plants to accumulate

^{137}Cs in shoots (Dahlman et al., 1975; Salt et al., 1992; Entry et al., 1993; Demirel et al., 1994). These studies were conducted with soils of different physicochemical properties and contamination characteristics which both affect cesium uptake into plants. Therefore the available information is of limited use when planning to phytoremediate sites with different soil chracteristics.

Ealier work indicated that upon entry into internal plant tissues radiocesium is fairly mobile (Resnik et al., 1969). However, phytoremediation of radiocesium-contaminated sites is impeded by the marked capacity of soils to tightly adsorb Cs (Nishita et al., 1968) . In part, this results from the trapping of Cs in layer silicate minerals (Cremers et al., 1988). Desorption from soil particles is an important step toward increasing cesium bioavailability and consequently its uptake into roots. Although earlier reports indicate that radiocesium desorption can be chemically induced (Field et al., 1993; Gombert, 1993) the extent of this release was shown to be highly dependent on soil properties (Francis and Brinkley, 1976; Kirk and Staunton, 1989).

In this study, we analyzed the potential for phytoremediation of a ^{137}Cs-contaminated soil from Brookhaven National Laboratory (BNL). The work was conducted in three phases: 1) hydroponic screening for high-biomass-producing plants capable of accumulating elevated levels of cesium in shoots, 2) identification of chemical treatments capable of desorbing ^{137}Cs from the soil, and 3) evaluation of ^{137}Cs extraction in shoots of selected species grown in pots with contaminated soil.

Material sand Methods

Hydroponic screening was conducted in a greenhouse at ambient temperature (12°-20°C) with natural illumination supplemented daily with 10 h of artificial light. Two to three seeds of Indian mustard [*Brassica juncea* (L.) Czern] , Arcadia, a commercial variety of broccoli (*B. oleracea* var *botrytis* L.), Storage #4, a commercial variety of cabbage (*B. oleracea* var *capitata* L.), Snow crown, a commercial variety of cauliflower (*B. oleracea* var *botrytis* L.), kochia [*Kochia scoparia* (L.) Schrad], tepary bean (*Phaseolus acutifolius* A. Gray), hairy vetch (*Vicia villosa* Roth.), colonial bent grass *(Agrostis capillaris* Sibth), red fescue (*Festuca rubra* L.*)*, and reed Canary grass (*Phalaris arundinacea* L.) were germinated on discs cut of 1 mm nylon mesh. Discs were placed at the open bottom of polyethylene cups mounted in holes drilled in lids of 2-L containers (four cups/lid). The composition of the culture solution was; 1.2 mM KNO_3; 0.4 mM $Ca(NO_3)_2$; 0.1 mM $NH_4H_2PO_4$; 0.2 mM $MgSO_4$; 50 µM KCl; 12.5 µM H_3BO_3; 0.1 µM $NiSO_4$; 1.0 µM $ZnSO_4$; 0.5 µM $CuSO_4$; 1.0 µM $MnSO_4$; 0.1 µM H_2MoO_4; 10 µM Fe^{3+}-EDDHA (for dicot) or Fe^{3+}-HEDTA (for grasses); 1.0 mM Mes-Tris (pH 6.0) and 1.0 µM CsCl. After seed germination, discs were covered with a layer of polyethylene black beads to reduce illumination of the nutrient solution and provide support to emerging seedlings. Nutrient solution was replaced every week. Shoots of four-week-old plants were harvested and dried for 3 days at 65°C. Dry shoots were ground, weighed, and a 0.05-g aliquot was digested overnight in 1 mL of doubled-distilled HNO_3 in a heat block at 120°C. Subsequently, samples were dissolved in 0.75 mL of HNO_3:$HClO_4$ (1:1, v/v) and incubated at 220°C until dry. Samples were then redissolved in 10 mL of 5% HNO_3 and analyzed for cesium content with an Elan-Sciex-250 Analyzer via inductively-coupled argon plasma mass spectroscopy.

Study of the ^{137}Cs desorption from contaminated BNL soil

The loamy sand soil obtained from Brookahven National Laboratory (BNL) was cleaned of gravel and organic debris before being passed through a 2-mm sieve. The < 2 mm soil fraction was air-dried and stored for further analyses. Desorption of the ^{137}Cs from the soil was investigated using 0.05 and 0.5 M solutions of the following extractants: 1) weak organic acids: acetic, citric, formic, malic, or oxalic, 2) strong acid: hydrochloric and nitric acid, 3) reducing agents: Na-dithionite or hydroxylamine/hydrochloric acid, 4) neutral ammonium salts: chloride, sulfate, or nitrate, 5) buffered ammonium salts: modified Morgan's solution [0.7 M acetic acid plus 1.35 M ammonium acetate (Morgan, 1941)], or a modified Morgan's extractant containing 0.02 M Na_2-EDTA (sodium salt of ethylene diamine tetracetic acid) (Lakanen and Erviö, 1971), and 6) neutral potassium salts: chloride, nitrate, or sulfate. A 15-g aliquot of the <2 mm soil fraction and 45 mL of the chemical extractant were mixed in a 125-mL Erlenmeyer flask and agitated at room temperature in a rotary shaker at 150 rotations min^{-1}. After 2 h, the slurry was filtered through a Whatman No. 42 filter paper. The resulting filtrate was vacuum-passed through a 0.45 μm Millipore membrane. The final filtrate was collected in a 20-mL counting vial and radioactivity was measured using a gamma counter (model 5530, Packard, Downers Grove, Il).

Evaluation of ^{137}Cs phytoextraction from contaminated soil

Before starting the pot study, the pH of the strongly acidic BNL soil was raised by adding 3 g of $Ca(OH)_2$ to 20 kg of soil. Ten days later, soil pH had increased from 3.8 to 5.4. This pH was more suitable for plant growth, and because soil pH in the 3.9-8.4 range was reported to have little effect on cesium accumulation in plants (Fredericksson et al., 1966) we felt confident that pH correction would not be detrimental to ^{137}Cs transfer from soil to shoots. Twelve pots containing 1 kg of soil were each seeded with two pregerminated seeds of cabbage, Indian mustard, reed Canary grass, and tepary bean and placed in a greenhouse at ambient temperature (18°- 27°C) and illuminated with natural light. Pots were watered with a nutrient solution with composition similar to that described above but containing only 300 µM KNO_3. We minimized the K^+ concentration because it is known that K^+ competes with Cs for uptake into roots (Shaw and Bell, 1991) and because the differences in ^{137}Cs uptake rates between plant species were shown to be greater at low potassium concentrations (Buysse et al., 1996). The twelve pots were divided into four sets of three pots. After 4 weeks of growth, one pot in each set received 13 mmoles of NH_4NO_3 as 100 mL of a 130 mM NH_4NO_3 solution. The second received 27 mmoles of NH_4NO_3 as 100 mL of a 270 mM NH_4NO_3 solution. The third pot from each set received only 100 mL of tap water. These treatments were repeated 3 and 6 days later. Thus, each of the four sets contained one pot which received: water (control), 40 mmoles of NH_4NO_3, and 80 mmoles of NH_4NO_3. Six days after the last treatment the shoots were harvested and plant material dried at 65°C for 3 days. Dry shoots were weighed, ground and ^{137}Cs activity was measured via gamma activity detection.

Statistical analysis

The design of the pot experiment was a two-factorial (four plant species x three soil treatments) replicated in four completely randomized blocks. Data were subjected to ANOVA with soil NH_4^+ applications and plant species as the two experimental factors. The differences among treatments were compared with Fisher's least significant difference ($p < 0.01$).

Results and Discussion

Hydroponic screening

Hydroponic screening allowed us to test a large number of plant species for their ability to accumulate cesium in shoots from a nutrient solution containing 1 μM CsCl. The greatest amount of cesium accumulated in shoots of cabbage followed by tepary bean (Table 1). Among grasses, reed Canary grass accumulated the most cesium. Bioaccumulation ratios ($[Cs]_{shoot}/[Cs]_{solution}$) of the species tested ranged between 38 and 165. Compared to grasses, the values of bioaccumulation ratio were 3- to 4-fold greater in shoots of dicot species. Comparable values were reported for ^{137}Cs accumulation in shoots of wheat (*Triticum aestivum* L.) (Smolders and Shaw, 1995). Values of bioaccumulation ratio significantly greater than 1 suggest that when available cesium is readily taken up plants.

Based on the results of hydroponic screening we selected cabbage, Indian mustard, reed Canary grass, and tepary bean to be tested in pots.

Study of ¹³⁷Cs desorption from BNL soil

The major factor limiting ^{137}Cs absorption by plants is likely to be its low bioavailability in soil. Cesium ions are selectively absorbed at the frayed edges or trapped into interlayer voids of micaceous minerals. Vermiculite (Sawhney, 1965) and illite (Tamura, 1964) are two common micaceous silicates found in soil that exhibit high affinity for cesium. Fixation of ^{137}Cs by micaceous clays and by soils containing these clays has been demonstrated in desorption studies. For example, only 18% of the radiocesium could be displaced by 1 M sodium acetate from an illitic soil 11 days after the treatment (Dahlman et al., 1975). However, 87% of the ^{137}Cs was desorbed from a soil containing predominantly non-expanding kaolinitic clays. The poor desorption from the illitic soil was interpreted as being caused by strong cesium fixation at selective binding sites.

In this study we investigated the effect of several chemical compounds on ^{137}Cs desorption from the BNL soil. We used ammonium and potassium salts to desorb the exchangeable radiocesium soil fraction. Because Entry et al. (1996) sugested that synthetic chelates could enhance the release of ^{137}Cs making it more accesible for plant uptake we also extracted the BNL soil with a Na_2-EDTA solution. Organic acids were tested because previous work indicated some success with these compounds (Field et al., 1993). Strong mineral acids hydrochloric and nitric acids were used to investigate the direct effect of H^+ on ^{137}Cs desorption. Reducing agents such as Na-dithionite and hydroxylamine/hydrochloric acid were employed to release a ^{137}Cs fraction potentially associated with iron or manganese oxides.

Finston and Kinsley (1961) noted that the ions NH_4^+, K^+, and Cs^+ form a homologous series with a great degree of physicochemical similarities. Therefore ^{137}Cs displacement from the soil is expected to increase following addition of monovalent cations. Jackson et al., (1965) reported that ^{137}Cs mobility in soil increased with the addition of the monovalent cations in the following order: Rb^+>NH_4^+>K^+. Similar findings were reported by Tensho et al. (1961). However, Livens and Loveland (1988) reported greater radiocesium mobility under low K^+ or high NH_4^+ in soil. Although it is generally agreed that NH_4^+, and K^+ are important for ^{137}Cs mobility in soil, the effect of these ions on radiocesium uptake into roots is less obvious . For example, as a result of enhanced bioavailability, greater cesium uptake into plants was reported following ammonium and potassium addition (Schultz et al., 1965). Shaw and Bell, (1991), however, described a competitive inhibition of Cs uptake into roots by any ion of the homologous series.. Clearly, there is some confusion as to the effect of NH_4^+ and K^+ ions on radiocesium mobility in soil and its uptake into roots. Furthermore, because some of these earlier studies were conducted with experimentally contaminated soils (binding to soil particles not completed), it is difficult to apply their findings to a soil contaminated with aged radiocesium (binding to soil particles completed) such as BNL soil.

Desorption of ^{137}Cs from the soil following chemical treatments is shown in Table 2. Ammonium salts of strong acids at 0.5 M desorbed about 25% of the soil ^{137}Cs. Somewhat less ^{137}Cs (17%) was desorbed from the soil with 1 M ammonium acetate with or without EDTA. These results indicate that EDTA had little effect on radiocesium desorption from soil.. Compared to NH_4^+, approximately 40% less radiocesium was desorbed with K^+ salts (Table 2, Fig. 1). Despite successes reported in the literature (Field et al. 1993), extraction of ^{137}Cs with organic acids was totally ineffective. Only small reductions in soil ^{137}Cs activity were obtained with strong mineral acids (2-3%) or reducing agents (1-7%). Our results show that most of the ^{137}Cs was desorbed from the BNL soil by exchange (25% of total radiocesium in the soil).

Desorption of ^{137}Cs by monovalent cations was concentration-dependent (Fig. 1); it increased with cation concentration up to 0.2 M. Further increases in concentration did not significantly increase ^{137}Cs desorption. It is possible that after a 2-h incubation in a 0.2 M solution, equilibrium was reached between monovalent cations and a rapidly exchanging ^{137}Cs soil fraction.

Phytoextraction of ^{137}Cs from contaminated soil

We investigated the potential for radiocesium removal in shoots of four plant species grown in pots with untreated (control) or NH_4^+-treated BNL soil. The effect of soil treatment on ^{137}Cs shoot concentration and shoot biomass is shown in Fig. 2. Concentration of ^{137}Cs was greater in shoots of the plants grown in ammonium nitrate-treated soil. Compared to control (no NH_4NO_3), addition of 80 mmoles increased ^{137}Cs concentartion in shoots from 135% (Indian mustard) to 1200% (reed Canary grass).

Although ammonium addition increases radiocesium desorption from soil particles, other mechanisms have also been proposed to account for the ammonium-induced increase in ^{137}Cs mobility and subsequently its uptake in roots. Thus, Kavkhuta et al. (1994), proposed that ^{137}Cs is retained in soil via two distinct processes: 1) specific sorption to soil minerals and 2) radionuclide incorporation in insoluble particles of fuel origin where ^{137}Cs is trapped by a cover of uranium dioxide. These authors proposed that NH_4NO_3 addition stimulates the activity of soil microorganisms involved in the breakdown of the uranium cover increasing bioavailability of this radiocesium fraction. However because of the short period of time which elapsed between ammonium application and shoot harvesting, it is unlikely that the latter mechanism may have played a significant effect on ^{137}Cs uptake into roots.

Regardless of the soil treatment, the greatest level of radiocesium was concentrated in shoots of cabbage. From the soil treated with 80 mmoles NH_4NO_3, cabbage concentrated approximately 1100 pCi g^{-1} dry shoot (Fig. 2A). This represents a 3.2-fold increase compared to shoots of cabbage grown in soil withot added NH_4NO_3.

In all treatments, including control, the greatest amount of biomass was produced by tepary bean followed by cabbage. Addition of ammonium nitrate at either 40 or 80 mmoles kg^{-1} soil depressed biomass production in all four species (Fig. 2B); undoubtedly as a result of ammonium toxicity. High ammonium generally inhibits cation uptake, which in turn suppresses growth primarily by inducing deficiencies of magnesium (Manolakis and Lüdders, 1977) and calcium (Pill et al., 1978). The species most susceptible to ammonium toxicity was reed Canary grass; 80 mmoles ammonium nitrate caused a 70% reduction in shoot biomass.

The amounts of ^{137}Cs removed from the soil in shoots of the tested species are shown in Table 3. The greatest amount of radiocesium, 140 pCi, was accumulated in shoots of cabbage grown in pots treated with 80 mmoles NH_4^+. This represents approximately 0.04% of the ^{137}Cs in the pot. It should be remembered, however, that this amount was removed in shoots of 6-week-old seedlings which produced only 0.14 g of dry mass. Ammonium application was most efficient in reed Canary grass increasing ^{137}Cs accumulation in shoots by more than 20-fold. It is possible that roots of Canary grass might have a very low ability of solubilizing radiocesium from soil particles. This would explain the very low ^{137}Cs shoot concentration in plants grown in soil without NH_4NO3 added. However, total radiocesium accumulated in shoots of this grass was the least among species tested.

Bioaccumulation of radiocesium in shoots was statistically analyzed using ANOVA for a completely randomized two factorial design. Interactions between species and soil treatment were not statistically significant ($p>0.05\%$). The amount of ^{137}Cs accumulated in shoots, however, was significantly affected ($p< 0.01$) by both, plant species and soil treatment. The abilities of tested species to accumulate ^{137}Cs in shoots were significantly different ($p< 0.01$). This ability increased in order: reed Canary grass < Indian mustard < tepary bean < cabbage. Soil treatments were also compared using Fisher's least significant difference ($p<0.01$). Compared to control, NH_4NO_3 addition significantly increased radiocesium accumulation in shoots. However, the two ammonium applications were not significantly different from each other.

Addition of 40 mmoles of ammonium nitrate increased the bioaccumulation ratio ($[^{137}Cs]_{dry\ shoot}/[^{137}Cs]_{dry\ soil}$) in all four species. With the exception of cabbage, however, doubling the amount of ammonium nitrate (from 40 to 80 mmoles kg^{-1} soil) had little effect on the value of bioaccumulation ratio. It is possible that at high concentrations NH_4^+ competes with cesium for uptake into roots. Such an effect has been previously described (Shaw and Bell, 1991). Only cabbage apparently responded to greater addition of NH_4NO_3; the greatest bioaccumulation ratio (2.8) was obtained in pots treated with 80 mmoles NH_4NO_3 (Fig. 3).

In control pots, the value of the bioaccumulation ratio for ^{137}Cs varied between 0 (reed Canary grass) and 1.0 (cabbage) (Fig. 3). Comparison of these ratios with those reported in the literature should be approached with caution. One concern is that some earlier studies have reported on the bioaccumulation of radiocesium from artificially contaminated soil in which the initial bioavailability of cesium was high. It is well known that radiocesium bioavailability decreases as it ages in these experimentally contaminated soil (Nisbet and Shaw, 1994). Such a difference in bioavailability would make the comparison of the ^{137}Cs bioaccumulation ratios between plants grown in soil with freshly applied ^{137}Cs and those grown in radiocesium-aged soil inappropriate. Comparison of ^{137}Cs bioaccumulating properties could also be confounded if plants were grown in different types of soil. Thus, it has been shown that the organic matter content of the soil has a large impact (up to a factor of 10) on cesium transfer from the soil to shoots (van Bergeijk et al., 1992). This concern has been previously addressed by Cremers et al., (1988).

Conclusions

Results obtained in this study suggest that phytoremediation of the ^{137}Cs-contaminated BNL soil may be feasible. The BNL soil is contaminated to a depth of approximately 10 cm with 400 pCi of ^{137}Cs g^{-1}. With good management practices, a fast growing high biomass producing crop such as cabbage could yield 15-20 tones dry wt ha^{-1} $year^{-1}$. Our results suggest that with high ammonium, ^{137}Cs bioaccumulation ratio in shoots of cabbage might be a shigh as 3. Taking these parameters at face values, decontamination of BNL soil to levels below 100 pCi g^{-1} soil would be attainable in less than 15 years. Unfortunately, as radiocesium is removed from the soil the bioaccumulation ratio is likely to decrease, making further removal more difficult. It is possible, however, that implementation of specific management practices could sustain ^{137}Cs phytoextraction over successive cropping. For example, small increase in ^{137}Cs transfer with time was reported in shoots of cabbage grown in peat soil (Nisbet and Shaw, 1994). This agrees with the observation that organic soils have the ability to sustain radiocesium availability for plant uptake (Barber and Mitchell, 1963).

A major problem with this assessment is that the ammonium rates used in the green house are excessively high and could be not realistically employed for large scale phytoremediation of radiocesium-polluted sites. It is possible that application of organic fertilizer at the contaminated site could be important not only for maintaining a high biomass production but also for sustaining the rate of ^{137}Cs phytoextraction from soils treated with significantly lower rates of ammonium. The effect of combined application of organic and ammonium fertilizer on radiocesium phtoextraction is not known and should be the focus of the future research.

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Table 1. Accumulation of cesium in shoots of several plant species from a nutrient solution containing 1 μM CsCl.

	Shoot mean dry wt (g)	[Cs] in shoots $\mu g\ g^{-1}$ dry wt	Bioaccumulation ratio†	Total Cs accumulated in shoots (μg)
broccoli	0.062	14	105	0.87
cabbage	0.075	22	165	1.58
cauliflower	0.065	14	105	0.91
colonial bent grass	0.043	6	45	0.26
hairy vetch	1.071	15	113	1.11
Indian mustard	0.075	16	120	1.22
kochia	0.068	8	60	0.54
reed Canary grass	0.060	6	45	0.36
red fescue	0.028	5	38	0.14
tepary bean	0.079	19	143	1.50

† $[Cs]_{shoots}/[Cs]_{solution}$

Table 2. Effect of several chemical compounds on ^{137}Cs desorption from the BNL soil.

	Ammonium salts					Potassium salts			Organic acids					Mineral acids		Reducing agents	
	NO_3^-	Cl^-	SO_4^{2-}	Acetate$^-$	Acetate-EDTA	NO_3^-	Cl^-	SO_4^{2-}	Formic	Acetic	Oxalic	Malic	Citric	HCl	HNO_3	Na-Dithionite	Hydroxylamin-HCl
	% ^{137}Cs in dry soil†																
0.05 M	15	12	15	-‡	-	7	8	6	0	0	0	0	0	1	2	1	3
0.5 M	24	25	22	-		15	14	14	0	0	0	0	0	3	2	1	7
1.0 M	-	-	-	17	18	-	-	-	-	-	-	-	-	-	-	-	-

† ^{137}Cs activity in the BNL soil was 400 pCi g dry soil^{-1}

‡ Data not available

Table 3. Effect of soil treatment on ^{137}Cs accumulation† in shoots of four plant species.

Soil treatment	Indian mustard		cabbage		tepary bean		reed Canary grass	
	pCi	%	pCi	%	pCi	%	pCi	%
Control (no NH_4NO_3)	37	100	69	100	28	100	1	100
40 mmoles NH_4NO_3	61	165	110	159	100	357	18	1800
80 mmoles NH_4NO_3	64	173	140	203	118	421	12	1200

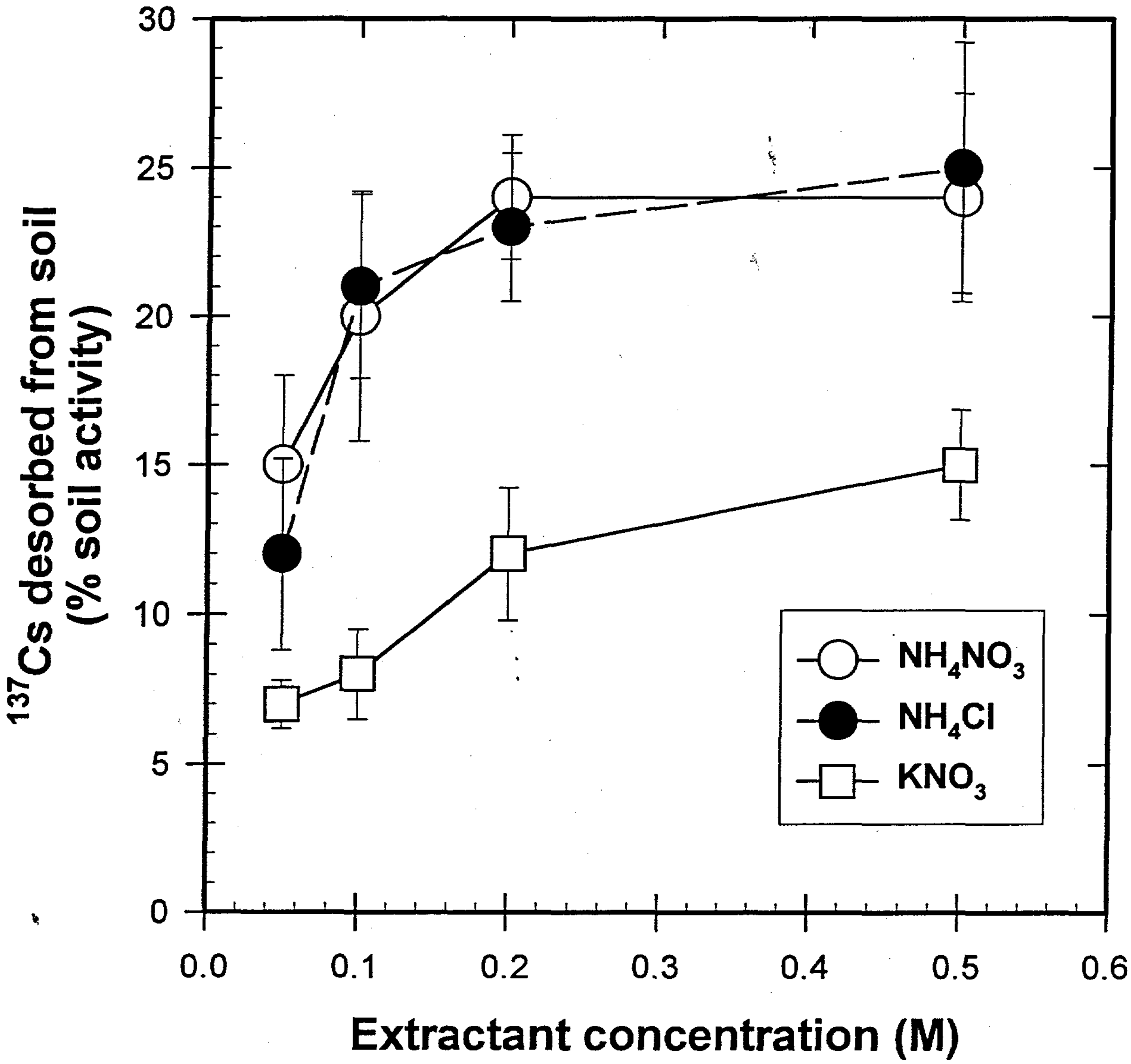
†Determined as: $[^{137}Cs]_{shoot}$ x shoot biomass

Figure legends

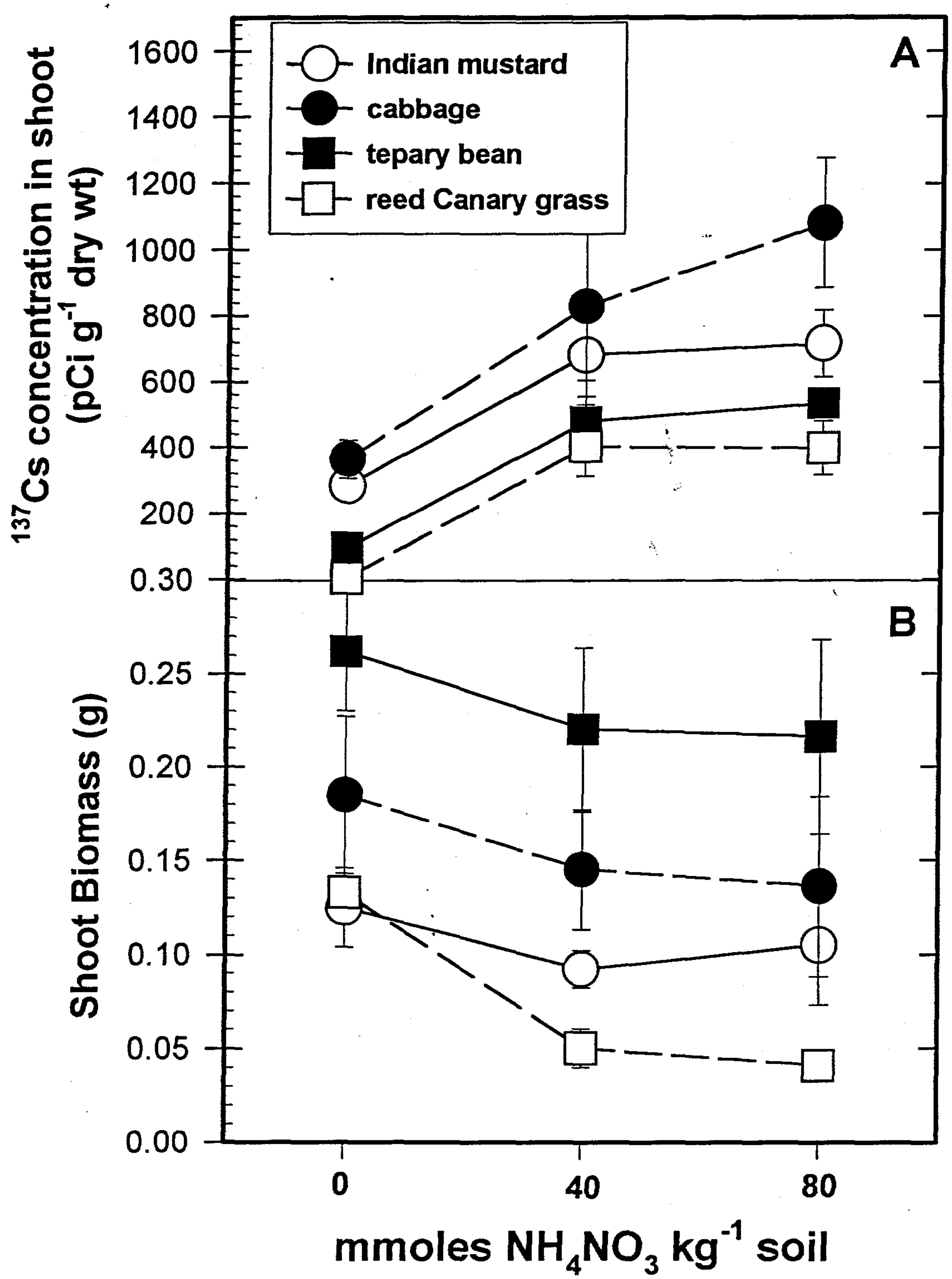
Figure 1. Concentration-dependent desorption of ^{137}Cs from the BNL contaminated soil. Soil was incubated in NH_4NO_3, NH_4Cl , or KNO_3 at concentrations shown. After 2 h, the slurry was filtered and gamma activity in solution measured.

Figure 2. Effect of soil treatment with NH_4NO_3 on: **A)** ^{137}Cs concentration in shoots, and **B)** shoot biomass of four plant species.

Figure 3. Effect of soil treatment with NH_4NO_3 on ^{137}Cs bioaccumlation ratio in shoots of 40-day-old plants.



Lasat et al. Potential for phytoextraction...Fig 1



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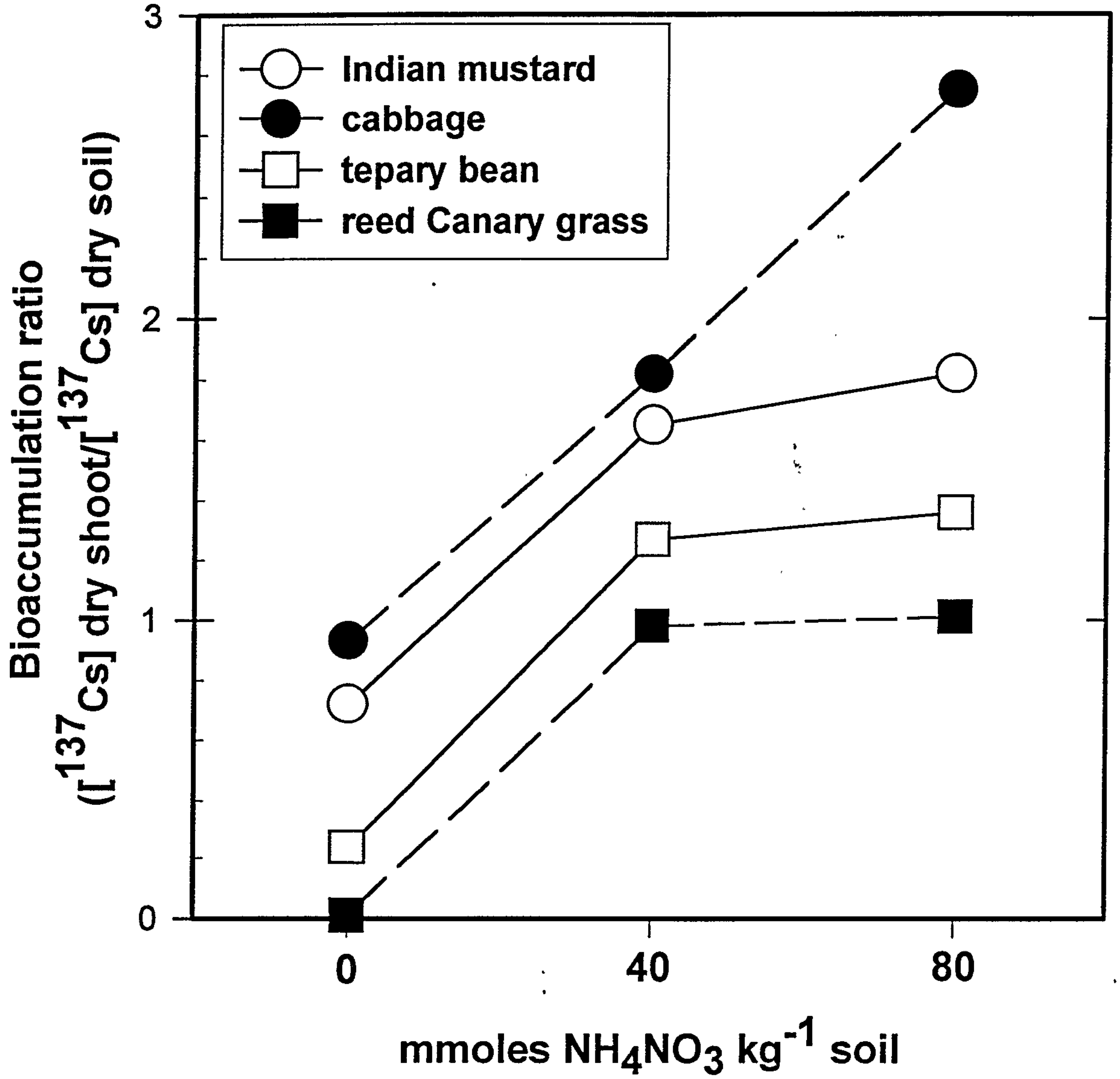

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