POTENTIAL REMEDIATION OF ^{137}Cs AND ^{90}Sr CONTAMINATED SOIL BY ACCUMULATION IN ALAMO SWITCHGRASS*

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Abstract. Cesium-137 (^{137}Cs) and Strontium-90 (^{90}Sr) are radionuclides characteristic of nuclear fallout from nuclear weapons testing and nuclear reactor accidents. Alamo switchgrass (*Panicum virginatum* L.) is a perennial C^4 species native to central North America that produces exceptionally high biomass yields in short periods of time. In three separate experiments, Alamo switchgrass plants were tested for their ability to accumulate ^{137} Cs and ^{90}Sr from a contaminated growth medium. Plants in experiment 1 were grown in 33 × 20 × 7 cm plastic pans containing 2.5 kg sand. Plants in experiments 2 and 3 were grown in 30 × 3 cm diameter test tubes containing 0.3 kg growth medium. After 3 months of plant growth, either 102 Bq ^{137}Cs or 73 Bq ^{90}Sr g^{-1} soil were added to the growth medium. Plants in all three experiments were grown within a greenhouse that was maintained at 22 ± 2 °C with a photosynthetic active radiation of 400–700 μmol m^{-2} s^{-1} and a 14–16 h photoperiod. Above-ground plant biomass did not differ between plants that were not exposed to these radionuclides (controls) and those that were exposed to growth medium containing ^{137}Cs or ^{90}Sr over the course of the experiment. Plants accumulated 44 and 36% of the total amount of ^{90}Sr and ^{137}Cs added to growth medium after the first 5 harvests. After the first two harvests, the concentration of ^{137}Cs and ^{90}Sr in plant tissue and the amount of ^{137}Cs or ^{90}Sr removed from growth medium declined with each successive harvest. Duration of exposure correlated curvilinearly with accumulation of both ^{90}Sr and ^{137}Cs by plants (r^2 = 0.95 and 0.78, respectively). As concentration of both ^{137}Cs and ^{90}Sr in growth medium increased, plant accumulation of both radionuclides increased and correlated curvilinearly in seedlings (r^2 = 0.83 and 0.89 respectively).

Key words: phytoremediation, radionuclides, switchgrass, ^{137}Cs, ^{90}Sr

1. Introduction

Radionuclide contamination of ecosystems throughout the world has resulted from aboveground nuclear testing (Maraha, 1993), nuclear reactor accidents (Clark and Smith, 1988; Konshin, 1992) and weapons production (Whicker *et al.*, 1990; Sanzharova and Aleksakhin, 1982). Upon release into the environment, ^{137}Cs and ^{90}Sr can become more concentrated as they move up the food chain and may exceed human health standards (Breshears *et al.*, 1992; Robinson *et al.*, 1988; Clark and Smith, 1988). Even under prolonged high rainfall, appreciable quantities of ^{137}Cs

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and ^{90}Sr are unlikely to be leached from most soils (Kirk and Staunton, 1989; Friend and Grakovskiy, 1988).

Several studies have shown that plants can accumulate ^{137}Cs and ^{90}Sr from soil and accumulate these radioisotopes in their tissue (Entry *et al.*, 1993; 1994; Salt *et al.*, 1992, Whicker *et al.*, 1990; Nifontova *et al.*, 1989). Certain plant species may be good choices for removing ^{137}Cs and ^{90}Sr from contaminated soil because of their rapid growth rates and the ability to accumulate large amounts of radionuclides from soil (Entry *et al.*, 1995). Switchgrass (*Panicum virgatum* L.), is a perennial, fast growing species native to North America that has produced the highest biomass yields of any grass tested (Sladden *et al.*, 1991). Previous research has identified the Alamo variety of switchgrass as a primary species for biomass production because of its unusually fast growth rate, ability to grow in soils with low nitrogen concentrations, and its low production costs (Sladden *et al.*, 1991; McLaughlin, 1992).

We tested the ability of Alamo switchgrass to remove ^{137}Cs and ^{90}Sr from a growth medium to determine the possibility of using this plant to remediate contaminated soil. Once planted in the field, Alamo switchgrass would remove radioisotopes from a soil and immobilize them in plant tissue. Once the grass is established, harvesting operations could periodically remove above-ground portions and radioisotopes could be recovered and concentrated by burning plant tissue at temperatures of 300–500 °C or by decomposition. Radionuclides would be concentrated in ash and could be disposed of properly. The objective of this study was to: (1) determine the efficacy of Alamo switchgrass to accumulate ^{137}Cs and ^{90}Sr from contaminated growth medium, and (2) compare accumulation ratios of each radioisotope at various periods of exposure and over a range of radioisotope concentrations in the soil.

2. Methods

2.1. Experimental design

Three experiments were conducted. Experiment 1 was arranged in a randomized complete block design (Kirk, 1982). There were 24 pans planted with Alamo switchgrass; 12 received ^{137}Cs and 12 received ^{90}Sr. There were 4 pans in each block with 3 replications. For the three replicates, a total of 12 pans received ^{137}Cs; the same number of pans planted with Alamo switchgrass received ^{90}Sr. Experiments 2 and 3 were arranged with completely randomized designs. In experiments 2 and 3, 25 Alamo switchgrass plants received ^{137}Cs and 25 plants received ^{90}Sr.

2.2. Plant growing conditions

Alamo switchgrass seeds were immersed in 30% H_2O_2 for 30 min to ensure the absence of pathogenic or mycorrhizal fungi. For experiment one, 2.5 kg of sand

was washed three times with distilled deionized water. The sand was then mixed with spaghum peat moss to a 4:1 (v:v) sand:peat mixture and placed in 33 × 20 × 7 cm plastic pans. One gram of seeds was placed on the surface and approximately 100 ml of distilled water added. Plants received 1.5 mg N, 0.5 mg P and 0.6 mg K in 100 ml H_2O each week. In experiments 2 and 3, 300 g of the growth medium was treated as above was placed in 30 cm long × 3-cm-diameter test tubes. Plants in each test tube received 0.075 mg N, 0.025 mg P and 0.030 mg K in the 5 ml of H_2O at the beginning of the experiments. Ten seeds, washed as described above, were placed in each test tube. Plants were grown in the tubes for three months within a greenhouse that was maintained at 22 ± 3 °C. Plants in test tubes were watered weekly with 5 ml of distilled deionized water over the course of the experiment. During that time, the seedlings were exposed to sunlight which was a photosynthetic active radiation of 400–700 μmol m^{-2} S^{-1} and a 14–16 hr photoperiod.

2.3. RADIOISOTOPE TREATMENTS

After three months, ^{137}Cs was added as $^{137}CsCl$ or ^{90}Sr was added as $^{90}SrCl_2$ to the growth medium in all experiments. In experiment 1, either 258,086 Bq ^{137}Cs or 177,417 Bq ^{90}Sr in 50 ml distilled deionized H_2O was added to each pan and dispersed throughout the growth medium with an additional 100 ml distilled deionized H_2O. In experiment 1, ten 1.0 g samples of growth medium were randomly taken from each pan to determine the effectiveness of ^{137}Cs and ^{90}Sr dispersion. The average concentration of ^{137}Cs in the growth medium was 102 Bq g^{-1} with a standard deviation of 8 Bq g^{-1}; the average concentration of ^{90}Sr in the growth medium was 73 Bq g^{-1} with a standard deviation of 7 Bq g^{-1}. In experiment 2, all plants received either 102 Bq ^{137}Cs g^{-1} growth medium or 73 Bq ^{90}Sr g^{-1} growth medium in 5.0 ml, distilled, deionized H_2O. In experiment 2, three 1.0 g samples of growth medium were randomly taken from each test tube to determine the effectiveness of ^{137}Cs and ^{90}Sr dispersion. The average concentration of ^{137}Cs in the growth medium was 102 Bq g^{-1} with a standard deviation of 6 Bq g^{-1}; the average concentration of ^{90} Sr in the growth medium was 73 Bq g^{-1} with a standard deviation of 5 Bq g^{-1}. Plants were permitted to grow for an additional month before harvesting. In experiment 2, five plants per radioisotope treatment were harvested weekly for 5 weeks. In experiment 3, five plants per radioisotope treatment received 1.0 ml distilled deionized H_2O containing either 0.5, 1.0, 1.9, 3.7, or 11.0 Bq ^{137}Cs g^{-1} growth medium or 1.5, 3.0, 6.0, 12.0 or 24.0 Bq ^{90}Sr g^{-1} growth medium followed by an additional 5.0 mL sterile, distilled deionized H_2O. In experiment 3, three 1.0 g samples of growth medium were randomly taken from each test tube to determine the effectiveness of ^{137}Cs and ^{90}Sr dispersion. The average concentration of ^{137}Cs in the growth medium was 0.46, 0.98, 1.86, 3.70 and 11.10 Bq g^{-1} with a standard deviations of 0.03, 0.05, 0.07, 0.12, and 0.14, Bq g^{-1} respectively; the average concentration of ^{90}Sr in the growth medium was

1.5, 3.1, 6.0, 12.2 or 23.8 Bq g^{-1} with a standard deviation of 0.07, 0.14, 0.15, 0.18, and 0.21 Bq g^{-1} respectively. Plants in experiments 3 were also permitted to grow for an additional month before harvest. At the end of each experiment the growth medium was split into four, 2 cm vertical section. A 1 g sample from each section was placed in a 10 mL plastic counting vial and analyzed for ^{137}Cs using methods described below. A 1 g sample of growth medium that received ^{90}Sr treatment was extracted with 3 washes of 3 mL 2 M $CaCl_2$. Three washes with 2 M $CaCl_2$ removes all detectable ^{90}Sr from this type of growth medium (Entry *et al.*, 1993, 1994). The extract was pooled, shaken for 3 min and a 1 mL subsample was counted for ^{90}Sr for 10 min at 0.45.0 meV on a Beckman LS 7000 autoscintillation counter.

2.4. HARVEST PROCEDURES

In experiment 1, the above-ground portion of plants in each pan were cut using hand shears to 2.5 cm in height on the first day of each month from June through October 1994. In experiment 2, five plants were harvested from five test tubes each week for five weeks. In experiments 3, all plants growing in test tubes were harvested five weeks after radionuclide treatment. In experiment 1 at the October harvest and in experiments 2 and 3, at designated harvest times, plants were removed from the test tubes and separated into root and shoots. To remove any radioisotope from root surfaces, roots of ^{137}Cs-treated seedlings were washed in distilled deionized water and then in a 1.0 M KCl solution; ^{90}Sr-treated roots were washed in distilled deionized water and then in a 1.0 M $CaCl_2$ solution (Doll and Lucas, 1973). All roots were then rewashed twice in distilled deionized water. All root and shoot tissue was dried at 80 °C for 48 hr and then weighed. After removal of plants, the growth medium was also analyzed for ^{137}Cs or ^{90}Sr.

2.5. RADIOIOTOPE COUNTS

All roots and shoots were analyzed separately. Mean values for replicate counts for both radioisotopes were compared with known activity of standard sources to determine the efficiency of the counting system. Tissues containing ^{137}Cs were placed in a 10 mL plastic counting vial and counted in a 7.62 × 7.62 cm NaI (Tl) well detector coupled with a single channel analyzer adjusted to record counts in a 50 keV of interest surrounding the at the 661.65 kaV total absorption peak. In experiment 1 at final harvest, plants were removed and five samples of the growth medium were analyzed for radionuclide concentration. In experiment 2 and 3 at each harvest, plants were removed and three samples of growth medium were analyzed for radionuclide concentration. Five g of the growth medium was placed in 10 mL plastic counting vials described above and analyzed for ^{137}Cs. Background ^{137}Cs was determined by averaging the results of six 100-min counts of blank vials and this background value was subtracted from the sample values.

The lower limit of detection was calculated at the 30 disintegrations per minute from the sytem background described above.

Tissues containing ^{90}Sr were placed in 20 mL glass scintillation vials and ashed for 6 hr at 525 °C ± 5þC. Residue was resuspended in 1 mL 3 M HCl and 17 mL of Biosafe II scintillation cocktail (Research Products International Corp., Mt Prospect, IL) was added. The amount of ^{90}Sr in growth medium was analyzed by placing 5 g of growth medium in a 20 mL scintillation vial and adding 10 mL of 2 M $CaCl_2$. The mixture was shaken on an Eberbach (Ann Arbor, MI) shaker at 80 rpm for 30 min, then filtered through a Whatman # 1 filter. One mL of the filtrate was mixed with 17 mL of Biosafe II scintillation cocktail. Filtrate containing ^{90}Sr was counted for 10 min at 1.0 MeV on a Beckman LS 7000 autoscintillation counter. The amount of ^{137}Cs or ^{90}Sr counts from six blank samples was not significantly different from background counts. All ^{137}Cs and ^{90}Sr values are reported as values above background values.

2.6. Calculations

The amount of radionuclide removed was calculated by multiplying the Bq of radionuclide g^{-1} tissue by the total dry (g) of harvested tissue. Percentage uptake of radioisotope from the growth medium was determined by dividing the amount of radioisotope measured in seedling tissue by the amount of radioisotope placed in each container or test tube, multiplied by 100. The bioconcentration ratio was calculated as Bq radioisotope g^{-1} in dry Alamo switchgrass tissue/Bq radioisotope g^{-1} dry growth medium. Mass balances for each experiment were calculated with the formula:

$$MB = R_a - (R_{ps} + R_{pr} + R_s)/100$$

where MB = mass balance or the percentage of ^{137}Cs or ^{90}Sr accounted for, R_a = the amount of ^{137}Cs or ^{90}Sr added to the growth medium, R_{ps} = the amount of ^{137}Cs or ^{90}Sr in plants shoots, R_{pr} = the amount of ^{137}Cs or ^{90}Sr measured in plant roots and R_s = the amount of ^{137}Cs or ^{90}Sr in the growth medium.

2.7. Statistical analysis

All data were found to be normally distributed; data were then subjected to a one-way analysis of variance (ANOVA) (Kirk, 1982). Residuals were normally distributed with constant variance. Differences among treatment means were considered to be significant at $þ \leq 0.05$ using the Least Square Means test.

Table I

Results from experiment 1: Biomass ^{137}Cs concentration, amount of ^{137}Sr removed, percent of ^{137}Cs removed and bioconcentration ratio of *Panicum virginatum* after grown for 5 months in 102 Bq ^{137}Cs g^{-1} growth medium

Harvest	Biomass (g)[a]	Concentration (Bq)[ab]	^{137}Cs removed (Bq)[a]	^{137}Cs removed (%)[a]	Bio-concentration ratio [ac]
June	9.63 B	3502 A	32,971 A	12.78 A	33.93 A
July	9.70 B	3648 A	35,521 A	13.76 A	35.33 A
August	9.50 B	1852 B	17,196 B	6.67 B	17.94 B
September	9.28 B	516 C	4,769 C	1.84 C	5.00 C
October	8.97 B	328 D	2,996 C	1.16 C	3.17 C
Roots (Otober)	16.01 A	50 E	800 D	0.31 D	0.48 D
Total Above Ground Parameters	47.08		93,453	36.21	

[a] Within each column, values followed by the same letter are not significantly different as determined by Least Squared Means test ($p \leq 0.05$) n = 12 for all values.
[b] Concentration g^{-1} = grams tissue/Bq radioisotope.
[c] Bioconcentration ratio = Bq ^{137}Cs g^{-1} in plant tissue/Bq ^{137}Cs in growth medium (sand).

Table II

Results from experiment 1: Biomass, ^{90}Sr concentration, amount of ^{90}Sr removed, percent of ^{90}Sr removed and bioconcentration ratio of *Panicum virginatum* after grown for 5 months in 73 Bq ^{90}Sr g^{-1} growth medium

Harvest	Biomass (g)[a]	Concentration (Bq)[ab]	^{90}Sr removed (Bq)[a]	^{90}Sr removed (%)[a]	Bio-concentration ratio [ac]
June	9.97 B	1965 A	19,573 A	10.77 A	27.04 A
July	10.04 B	1778 A	17,660 A	9.69 A	24.46 A
August	9.46 B	1560 AB	14,759 B	8.12 AB	21.46 A
September	9.01 B	1447 B	12,946 B	7.21 B	19.91 A
October	8.59 B	1623 B	14,119 B	7.77 B	22.33 A
Roots (Otober)	16.34 A	719 C	11,851 C	6.52 C	9.90 B
Total Above Ground Parameters	47.07		79,057	43.56	

[a] Within each column, values followed by the same letter are not significantly different as determined by Least Squared Means test ($p \leq 0.05$) n = 12 for all values.
[b] Concentration g^{-1} = grams tissue/Bq radioisotope.
[c] Bioconcentration ratio = Bq ^{90}Sr g^{-1} in plant tissue/Bq ^{90}Sr in growth medium (sand).

3. Results

3.1. Experiment 1

3.1.1. *Monthly Harvest of Aboveground Biomass*

The above ground biomass of Alamo switchgrass plants accumulated 36 and 44% of the total amount of the ^{137} Cs and ^{90}Sr added to the growth medium after five harvests (Tables I and II). Above-ground plant biomass did not differ between exposure to ^{137}Cs or ^{90}Sr over the course of the experiment. After the first two harvests the concentration of ^{137}Cs and ^{90}Sr in plant tissue, amount and percent of ^{137}Cs and ^{90}Sr removed from the growth medium declined with each successive harvest. Each month, plants removed from 0.3 to 12.8% of the ^{137}Cs and from 6.5 to 10.8% of the ^{90}Sr added to the growth medium each month. Biocencentration ratios of ^{137}Cs averaged from 35.3 in July to 3.2 in October; ^{90}Sr bioconcentration ratios averaged from 27.0 in June to 19.9 in September. After 5 months, root biomass was almost twice as much as the above-ground biomass in plants receiving both ^{137}Cs or ^{90}Sr treatments. After five harvests, 92,653 Bq ^{137}Cs and 67,206 Bq ^{90}Sr were harvested in shoot tissues while only 800 Bq ^{137}Cs and 11,851 Bq ^{90} Sr were harvested in root tissues of Alamo Switchgrass plants. We accounted for 97% of the ^{137}Cs and 96% of the ^{90}Sr added to the growth medium using mass balance calculations.

3.2. Experiment 2

3.2.1. *Weekly Harvest of Entire Tissue*

Duration of exposure correlated curvilinearly with accumulation of both ^{137}Cs and ^{90}Sr by plants ($r^2 = 0.78$ $p < 0.01$ and $r^2 = 0.95$; $p < 0.01$, respectively) (Figures 1 and 2). The largest amount of ^{137}Cs was accumulated from week 1 through 3; in contrast to ^{90}Sr where the largest amounts were accumulated from week 3 to 5. The concentration of ^{137}Cs and ^{90}Sr in plant tissue correlated curvilinarly with ^{137}Cs and linearly with ^{90}Sr with time of exposure. ($r^2 = 0.75$ $p < 0.01$ and 0.86 $p < 0.01$, respectively) (Figures 1 and 2). When plants were exposed to ^{137}Cs the concentration of the radionuclide in plant tissue decreased rapidly during the first week and then more linearly from week 2 through 5; when plants were exposed to ^{90}Sr the concentration of the radionuclide in plant tissue decreased at a steady rate from week 1 to 5. We accounted for 99% of the ^{137}Cs and 97% of the ^{90}Sr added to the growth medium using mass balance calculations.

3.3. Experiment 3

3.3.1. *Uptake as a function of Radionuclide Concentration*

As concentration of ^{137}Cs and ^{90}Sr in the growth medium increased, total seedling accumulation by plants and concentration of radioisotopes in plant tissue increased curvilinearly (Figures 3 and 4). Correlation coefficients (r^2) for ^{137}Cs were 0.83

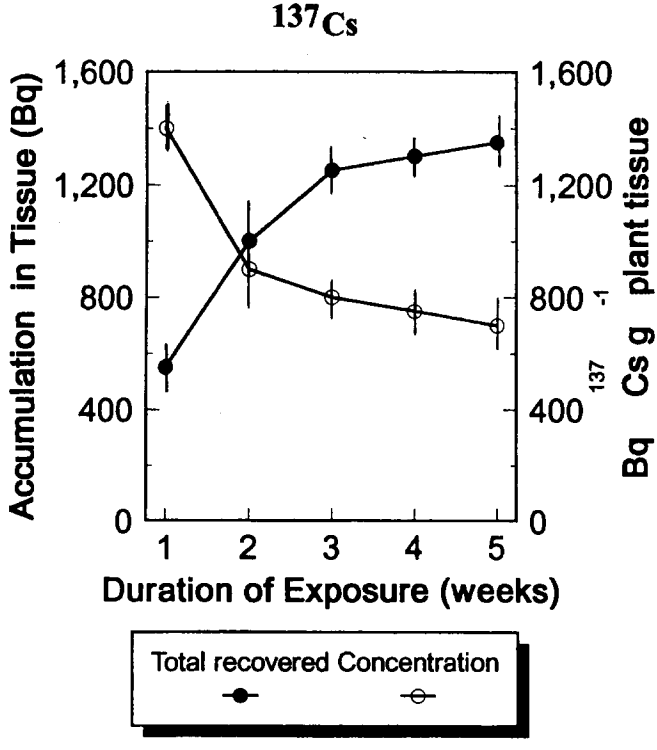

Figure 1. Accumulation (left scale) and concentration (right scale) of ^{137}Cs in *Panicum virginatum* tissue over time. ^{137}Cs accumulation in whole plant tissue was explained by the following polynomial regression. $^{137}Cs = -2.80 + 10.97$ (week no) $- 2.74$ (week no)$^2 + 0.26$ (week no)^3. $r^2 = 0.78$; ($p > 0.0001$). ^{137}Cs concentration in tissue $= 0.25 - 0.16$ (week no) $+ 0.04$ (week no)$^2 - 0.004$ (week no)^3. $r^2 = 0.75$; ($p < 0.0001$).

for plant accumulation and 0.85 for concentration of ^{137}Cs in tissue (Figure 3). Correlation coefficients (r^2) for ^{90}Sr were 0.88 $p < 0.01$) for plant accumulation and 0.90 ($p < 0.01$) for concentration in tissue. We accounted for 94% of the ^{137}Cs and 93% of the ^{90}Sr added to the growth medium using mass balance calculations.

4. Discussion

The relationships between time and uptake of ^{137}Cs indicate that most of this radionuclide is accumulated by the plant during the first three weeks of growth. When using this grass to remove ^{137}Cs from soil one might with shorter periods between harvests. Relationships between accumulation and time ^{90}Sr concentration in plant tissue indicates that most of this radionuclide is accumulated by the plant during the last two weeks of growth. If we are to use this grass to remove ^{90}Sr from contaminated soils one might experiment with longer periods between harvests.

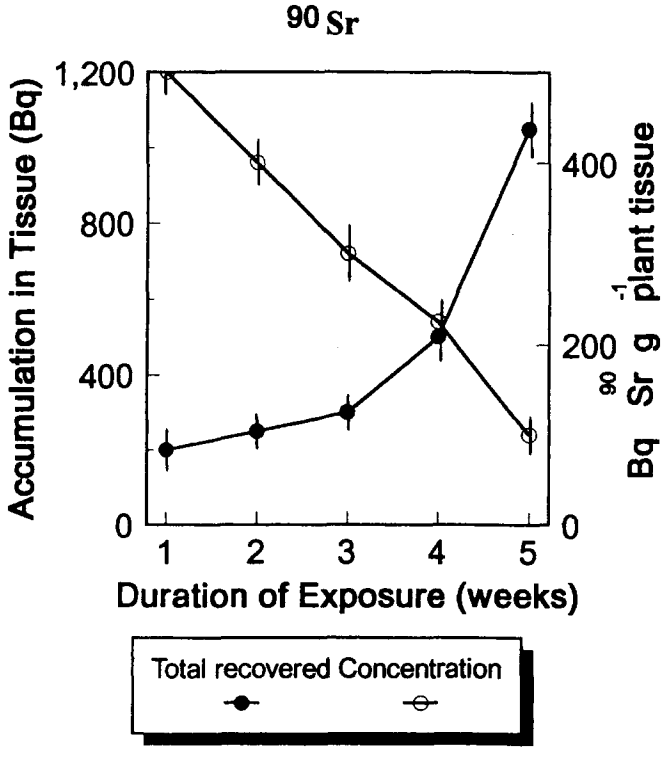

Figure 2. Accumulation (left scale) and concentration (right scale) of ^{90}Sr in *Panicum virginatum* tissue over time. ^{90}Sr accumulation in whole plant tissue was explained by the following polynomial regression. $^{90}Sr = -6.97 + 34.73$ (week no) $- 15.11$ (week no)$^2 + 2.57$ (week no)^3. $r^2 = 0.95$; ($p < 0.001$). ^{90}Sr concentration in tissue $= 0.053 - 0.008$ (week no) $+ 0.0008$ (week no)$^2 - 0.00017$ (week no)^3. $r^2 = 0.86$; ($p < 0.0001$).

The large amount of ^{90}Sr and ^{137}Cs removal from this growth medium is likely due to the fast growth rates and the extensive root system of Alamo switchgrass. In the early stages of phytoremediation, the plants grow increasing photosynthetic surface area; root production will follow an exponential growth rate from weight and volume with respect to time (Van den Driesshe, 1987). Our data suggest that as roots explore new volumes of soil during growth this grass will likely continue to accumulate these radionuclides at high rates in the early stages of phytoremediation.

The fact that the amount of ^{137}Cs and ^{90}Sr declined with later harvests indicates that if Alamo switchgrass is planted on a contaminated site it may not be able to remove all of these radionuclides from soils. As radionuclide concentration in a contaminated soil decreases due to plant uptake, root contact with those radionuclides will become increasingly less frequent. The rate and amount of radionuclide accumulation by plants will decline.

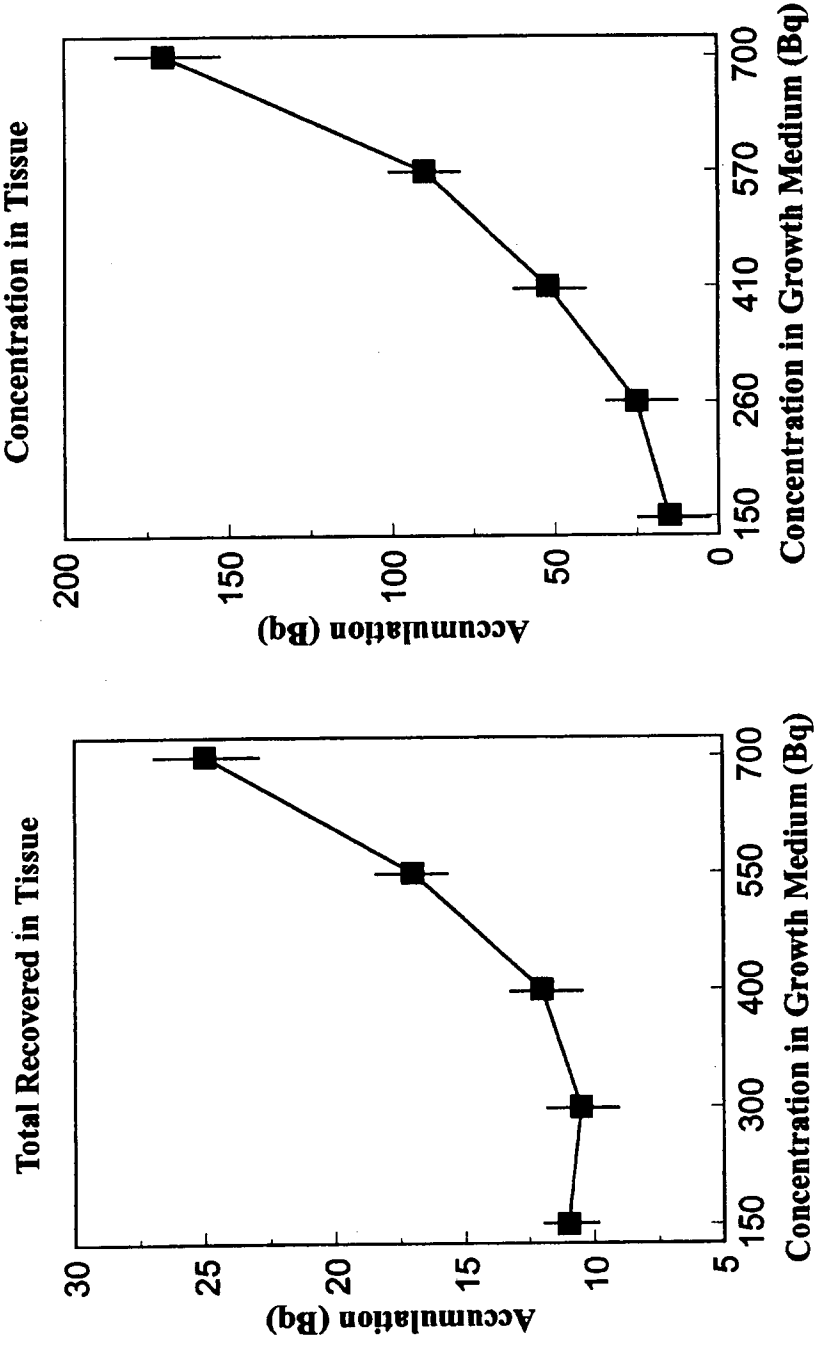

Figure 3. Accumulation (left graph) and concentration (right graph) of ^{137}Cs by *Panicum virginatum* tissue from the growth medium containing different concentrations of the radionuclide. Total ^{137}Cs accumulated in whole plant tissue was explained by the following polynomial regression. $^{137}Cs = -6.68 + 0.21\ (^{137}Cs\ \text{concentration}) - 0.0004\ (^{137}Cs\ \text{concentration})^2 + 0.0000007\ (^{137}Cs\ \text{concentration})^3$. $r^2 = 0.85$; ($p < 0.0001$). ^{137}Cs concentration in whole plant tissue was explained by the following polynomial regression. $^{137}Cs = -5.44 + 0.26\ (^{137}Cs\ \text{concentration}) - 0.0007\ (^{137}Cs\ \text{concentration})^2 + 0.0000007\ (^{137}Cs\ \text{concentration})^3$. $r^2 = 0.83$; ($p < 0.0001$).

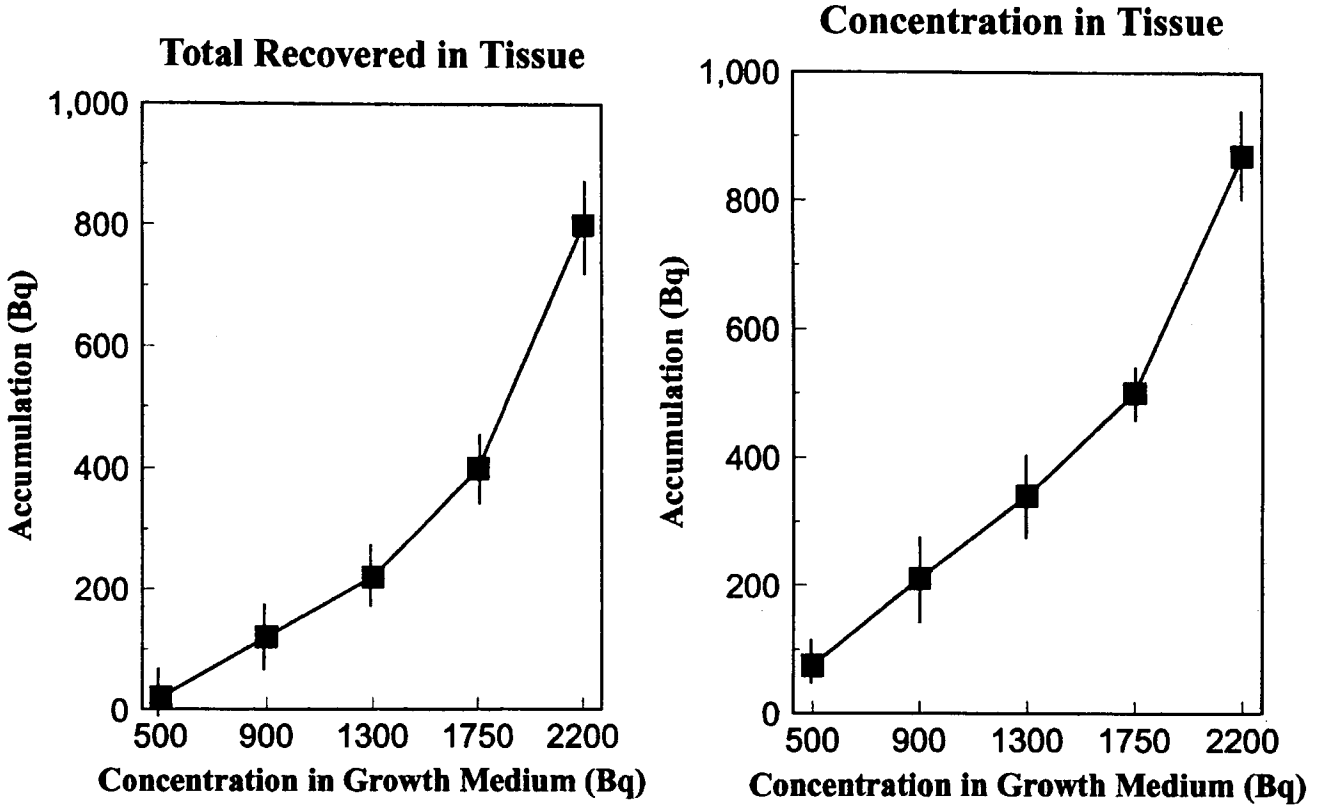

Figure 4. Accumulation (left graph) and concentration (right graph) of ^{90}Sr by *Panicum virginatum* tissue from the growth medium containing different concentrations of the radionuclide. Total ^{90}Sr accumulated in whole plant tissue was explained by the following polynomial regression. $^{90}Sr = -227.22 + 0.88$ (^{137}Cs concentration) $- 0.0007$ (^{137}Cs concentration)$^2 + 0.0000002$ (^{137}Cs concentration)^3. $r^2 = 0.90$; ($p < 0.0001$). ^{90}Sr concentration in whole plant tissue was explained by the following polynomial regression. $^{90}Sr = -359.26 + 1.33$ (^{137}Cs concentration) $- 0.001$ (^{137}Cs concentration $- 0.001$ (^{137}Cs concentration)$^2 + 0.0000001$ (^{137}Cs concentration)^3. $r^2 = 0.90$; ($p < 0.001$).

Due to their individual physiological characteristics, some plant species, such as grasses, may be more adapted to accumulating ^{90}Sr while other plants may be more adapted to accumulating ^{137}Cs (Entry *et al.*, 1995). Substantial quantities of ^{90}Sr and ^{137}Cs have been accumulated by other grasses. Salt *et al.* (1992) reported that *Lolium perenne, Festuca rubra, Trifolium repens* and *Cerastium fontanum* accumulated from 28 to 1040 Bq ^{137}Cs g^{-1} of plant tissue in a re-seeded pasture in Scotland. Coughtrey *et al.* (1989) found that a *Festuca/Agrostis* plant community in the United Kingdom accumulated 4–19% of the ^{137}Cs deposited by Chernobyl fallout. Accumulation of ^{137}Cs was higher in *Carex* spp than 9 other species of grasses in an upland area in Great Britain (Coughtrey *et al.*, 1989).

Effectiveness of any plant species to remove radioisotopes from contaminated soil will undoubtedly depend on the specific type of soil that has been contaminated, (e.g. soils containing high clay contents should retain a larger amount of radionuclides than soils with high sand contents). Appreciable quantities of ^{137}Cs and ^{90}Sr are not likely to be leached from contaminated soils or taken up by plants, due to the ability of clay minerals to fix cations, especially ^{137}Cs in clay lattices (Coughtrey *et al.*, 1989; Kirk and Staunton, 1989; Fried and Grakovskiy, 1988). Radionuclide availability to plants, especially ^{137}Cs will also be influenced by organic matter content, cation saturation and pH of the soil as well as rooting density of plants (Kirk and Staunton, 1989).

Soil organic amendments and fertilization practices could increase the rate of ^{137}Cs and ^{90}Sr accumulation by plants (Entry *et al.*, 1995). Nitrogen fertilization in nitrogen-limited soils should have indirect effects on ^{137}Cs and ^{90}Sr uptake by increasing plant growth which will increase root growth and the density of roots in the soil and ultimately increase the accumulation of radionuclides from the soil. Kirk and Staunton (1989) found that the higher the density of roots in the soil the more ^{137}Cs and was accumulated by plants. Plant uptake of ^{137}Cs may be substantially reduced by fertilization with large amounts of K or P (Robison and Stone, 1992). Water availability also has a major effect on plant uptake of radionuclides. Sanzharova and Aleksakhin (1982) and Tensho *et al.* (1961) found that *Hordeum vulgare, Medicago sativa, Oryza sativa* and *Zea mays* accumulated substantially more fission products when they were irregated. *Lolium multiflorium* accumulated more ^{137}Cs and ^{90}Sr when grown on sphagnum peat than compost or *Carex* spp peat. Cation exchange capacity, base saturation and pH influence the behavior of ^{137}Cs and ^{90}Sr in the soil.

Plants inoculated with a specific mycorrhizal fungus may increase the ability of the plant to acquire necessary nutrients while removing large quantities of ^{137}Cs and ^{90}Sr from contaminated soils (Rogers and Williams, 1986; Clint and Dighton, 1992; Entry *et al.*, 1994). Entry *et al.* (1994) found that the species of fungus forming the mycorrhizae with a specific tree species can have significant effects on the amount of ^{90}Sr accumulated by that tree. Physiological status of the plant will also regulate requirements for soil nutrients and thus can be expected to influence the rate of ^{90}Sr and ^{137}Cs uptake. The amount of radioisotopes accumulated in

the plant will likely fluctuate with the amount and availability of the isotope in soil, plant water status, and phostosynthetically active radiation received by plants. Actual rates of radioisotope accumulation and removal in the field may be increased through soil amendments and manipulation of plant growing conditions.

The substantial amounts and percentage of ^{90}Sr and ^{137}Cs removed from this growth medium by Alamo switchgrass indicates that this grass may be a good candidate species to remediate soils contaminated with these radioisotopes. Alamo switchgrass can grow in a wide geographical range that includes extremely variable edaphic conditions in the central United States. Since Alamo switchgrass removed 36% of the ^{137}Cs and 44% of the ^{90}Sr added to the growth medium in 5 months, we think further investigation of the ability of the species to accumulate radionuclides from contaminated soils is warranted.

References

Alexakin, R. M.: 1993, *Sci. Total. Environ.* **137**, 9.

Beshears, D. D., Kirchner, T. B. and Whicker, F. W.: 1992, *Ecol. Appl.* **2**, 285.

Clark, M. J. and Smith, F. B.: 1988, *Nature* **33**, 245.

Coughtrey, P. J., Kirton, J. A. and Mitchell, N. G.: 1989, *Environ. Pollut.* **62**, 281.

Clint, G. M. and Dighton, J.: 1992, *New Phytol.* **121**, 555.

Doll, E. C. and Lucas, R. E.: 1973, 'Testing soils for potassium, calcium and magnesium', in L. M. Walsh and J. D. Beaton (eds.), *Soil Testing and Plant Analysis*, third ed. SSSA Book Ser. 3 SSSA Madison, WI.

Entry, J. A., Rygiewicz, P. T. and Emmingham, W. H.: 1993, *J. Environ. Qual.* **22**, 742.

Entry, J. A., Rygiewicz, P. T. and Emmingham, W. H.: 1994, *Environ. Pollut.* **86**, 201.

Entry, J. A., Vance, N. C. Hamilton, M. A., Zabowski, D. Watrud, L. S. and Adriano. D. C.: 1995, *Water. Air, and Soil Pollut.* **88**, 176.

Freid, A. S. and Grakovskiy, V. S.: 1988, *Pochvovedeniye.* **2**, 78.

Kirk, G. J. D. and Staunton, S.: 1989, *J. Soil Sci.* **40**, 71.

Kirk, R. E.: 1982, *Experimental Design*, Brooks/Cole Publishing, Monterey, CA 911 pp.

Kirk, T. K. and Farrell, R. L.: 1987, *Ann. Rev. Microbiol.* **41**, 465.

Konshin, D. V.: 1992, *Health Phys.* **63**, 307.

McClaughin, S. B.: 1992, 'New switchgrass biofuels research program for the southeast', *Proceedings of the Annual Automotive Technology Development Center*, in D. F. Bezecicek (ed.), Dearborn, MI 342 pp.

Nifontova, M. G. Kulikov, G. I., Tarshis, G. I. and D'yachenko, A. P.: 1989, *Ekologiya* **3**.

Paasikallio, A.: 1984, *Ann. Agric. Fenn.* **23**, 109.

Prister, B., Loschchilov, L., Perepelyatnikova, G., Perepelyatnikova, L. and Bondar, P.: 1992, *Sci. Total Environ.* **112**, 79.

Robinson, W. L., Conrado, C. A. and Stuart, M. L.: 1988, 'Radiological Condtions at Bikini Atoll: Radionuclide Concentrations in vegetation, Animals, Cistern Water and Ground Water', UCRL-53840, *Lawerence National Laboratory*, Livermore, CA.

Robinson, W. L. and Stone, E. L.: 1992, *Health Phys.* **62**, 496.

Rogers, R. D. and Williams, S. E.: 1986, *Soil Biol. Biochem.* **18**, 371.

Salbu, B., Oughton, E. H., Ratnikov, A. V., Zhigareva, T. L., Kuglov, S. V. Petrov, K. V. Grebenshakikova, N. V., Firsakova, S. K., Astasheva, N. P., Loshchilov, N. A. Hove, K. and Strand, P.: 1994, *Health Physics.* **67**, 518.

Salt, C. A., Mayes, R. W. and Elston, D. A.: 1992, *J. Appl. Ecol.* **29**, 378.

Sanzharova, K. I., Fesenko, S. V., Alexakin, V. S., Anisimov, V. K., Kuznetsov, V. K. and Cheryayeva, L. G.: 1994, *Sci. Total Environ.* **154**, 9.

Sanzharova, K. I. and Aleksakhin, R. M.: 1982, *Pochvovedeniye.* **9**, 59.

Schimmack, W., Bunzl, K. and Zelles, L.: 1989, *Geoderma* **44**, 211.
Sladden, S. E., Bransby, D. I. and Aiken, G. E.: 1991, *Biomass and Bioenergy* **1**, 119.
Tensho, K., Yeh., K. L. and Mitsui, S.: 1961, *Soil and Plant Food* **6**, 4.
Van den Driesshe, R.: 1987, *Can. J. For. Res.* **17**, 776.
Velasko, R. H., Belli, M., Sanasone, U. and Menegon, S.: 1993, *Health Physics.* **64**, 37.
Whicker, W. F., Pinder, J. E. III, Bowling, J. W., Alberts, J. J. and Brisbin, I. K. Jr.: 1990, *Ecol. Monogr.* **60**, 471.