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Accumulation of ^{137}Cs and ^{90}Sr from contaminated soil by three grass species inoculated with mycorrhizal fungi[1]

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Abstract

The use of plants to accumulate low level radioactive waste from soil, followed by incineration of plant material to concentrate radionuclides may prove to be a viable and economical method of remediating contaminated areas. We tested the influence of arbuscular mycorrhizae on ^{137}Cs and ^{90}Sr uptake by bahia grass (*Paspalum notatum*), johnson grass (*Sorghum halpense*) and switchgrass (*Panicum virginatum*) for the effectiveness on three different contaminated soil types. Exposure to ^{137}Cs or ^{90}Sr over the course of the experiment did not affect above ground biomass of the three grasses. The above ground biomass of bahia, johnson and switchgrass plants accumulated from 26.3 to 71.7% of the total amount of the ^{137}Cs and from 23.8 to 88.7% of the total amount of the ^{90}Sr added to the soil after three harvests. In each of the three grass species tested, plants inoculated with *Glomus mosseae* or *Glomus intraradices* had greater aboveground plant biomass, higher concentrations of ^{137}Cs or ^{90}Sr in plant tissue, % accumulation of ^{137}Cs or ^{90}Sr from soil and plant bioconcentration ratios at each harvest than those that did not receive mycorrhizal inoculation. Johnson grass had greater aboveground plant biomass, greater accumulation of ^{137}Cs or ^{90}Sr from soil and plant higher bioconcentration ratios with arbuscular mycorrhizal fungi than bahia grass and switchgrass. The greatest accumulation of ^{137}Cs and ^{90}Sr was observed in johnson grass inoculated with G. mosseae. Grasses can grow in wide geographical ranges that include a broad variety of edaphic conditions. The highly efficient removal of these radionuclides by these grass species after inoculation with arbuscular mycorrhizae supports the concept that remediation of radionuclide contaminated soils using mycorrhizal plants may present a viable strategy to remediate and reclaim sites contaminated with radionuclides.

Keywords: ^{137}Cs; ^{90}Sr; Radionuclides: Contaminated

1. Introduction

Radionuclides are distributed to soil and plants in the contaminated area by physically and biologically mediated nutrient cycling processes (Breshers et al., 1992; Abbott and Rood, 1994). Radionuclides, especially ^{137}Cs and ^{90}Sr, can accumulate as they move up the food chain (Hoffman et al., 1984). Concentrations of ^{137}Cs and ^{90}Sr have been found in crops (Sanzharova and Aleksakhin, 1982; Robinson and Stone, 1992), livestock (Salt et al., 1992), fish (Whicker et al., 1990; Pennttjla et al., 1993) and wildlife (Lowe and Horrill, 1991; Rickard and Ebrhard, 1993) to warrant concerns about human and animal health. Human exposure to harmful radionuclides can occur from ingestion of food contaminated by accumulation through the food chain (Church et al., 1990) and may ultimately result in detrimental health effects, such as cancers and genetic mutations (Ansphaugh et al., 1988; Lange et al., 1988; Breshers et al., 1992).

Remediation of soil contaminated with radionuclides using present physical technologies may require that soil be transported from the contaminated site and treated with various dispersing and chelating chemicals. Transport of soil requires heavy equipment, is time consuming and expensive; it may also result in additional dispersal of pollutants through possible spills. Therefore, few attempts have been made to remediate land contaminated with radionuclides.

Several alternative approaches to remediate radionuclide contaminated soils are presently being investigated.

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Zeolites, particularly clinoptilolite and bentonite, have been investigated for efficacy to act as a in-situ permeable barrier for ground water to immobilize radionuclides in soil. (Albinsson et al., 1994; Cantrell et al., 1994; Ohnuki and Kozai, 1994; Rameback et al., 1994). Studies using fertilizer K and Ca to reduce the uptake of ^{137}Cs and ^{90}Sr respectively, to crop plants growing in contaminated soils has shown this to be a promising technology (Prister et al., 1992; Robison and Stone, 1992; Alexakhin, 1993; Vereoglou et al., 1995; Walker et al., 1997). Phytoremediation-based approaches, are attractive because those designed with planned, successive *in situ* harvests and simultaneous or sequential plantings of other species, may not only remediate a site, but may eventually reclaim it, by fostering the establishment of a plant community (Entry et al., 1996). High temperature combustion could then be used to oxidize plant material concentrating ^{137}Cs and ^{90}Sr in ash for disposal.

Mycorrhizae are a symbiotic relationship between a soil fungus and host plant root. The plant provides the fungus with carbon in the form of sugars and the fungus provides the plant with a mechanism that greatly enhances the ability of the root system to acquire soil elements and water. Plants inoculated with a specific mycorrhizal fungus have been shown to 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; Entry et al., 1994). However, Clint and Dighton (1992) found that mycorrhizal heather (*Calluna vulgaris* L.) accumulated less ^{137}Cs in liquid medium than non-mycorrhizal plants. Entry et al. (1994) found that the species of fungus forming the ectomycorrhizae with a specific tree species can have significant effects on the amount of ^{90}Sr accumulated by that tree. In this study, we tested the influence of *Glomus mosseae* and *Glomus intraradices* inoculation on roots of three grass species, bahia grass (*Paspalum notatum* var. saura Parodi.), johnson grass (*Sorghum halepense* L. Persoon.) and switchgrass (*Panicum virginatum* L.). These three grass species are perennial species native to central North America that produce exceptionally high biomass yields in short periods of time. Grasses were grown in three different soil types collected in the vicinity of the Oak Ridge Nuclear facility near Oak Ridge, Tennessee, to determine their ability to accumulate ^{137}Cs and ^{90}Sr from contaminated soils.

2. Materials and methods

2.1. Experimental design

The experiment was arranged in a 3^3 randomized factorial design. Treatments were: mycorrhizal inoculations (no mycorrhizae, inoculation with *G. mosseae* or *G. intraradices*); soil type (Crenchaw series, [thermic Typic Paleudult], a Fullerton series, [thermic Typic Paleudult], and a Lehew series, [Typic Dystochrept]) and grass species, (bahia grass [*Paspalum notatum* var. saura Parodi.], johnson grass [*Sorghum halepense* L. Persoon.] and switchgrass [*Panicum virginatum* L.]). There were 3 soil types×3 mycorrhizal inoculations×3 grass species. The entire experiment was replicated 3 times for each radionuclide.

Soils were collected from three uncontaminated sites near the Oak Ridge National Laboratory near Oak Ridge, Tennessee. Soils were sieved through a 5 mm mesh. Resident mycorrhizae in all three soils were killed by steam pasterurization at 121°C for 24 h. Steam sterilization at 121°C is known to kill resident mycorrhizal spores, but not change the soil organic structure or chemistry. Arbuscular mycorrhizal treatments were: (1) no mycorrhizae (control) in which 300 g of steam sterilized soil was placed in a 10 cm diameter×20 cm deep plastic container, (2) steam sterilized soil inoculated with *G. mosseae*, in which 295 g soil was mixed with 5 g of soil containing *G. mosseae* spores and (3) steam sterilized soil inoculated with *G. intraradices*, where 295 g soil was mixed with 5 g of soil containing *G. intraradices* spores.

2.2. Chemical analysis of soils

Soil moisture was determined gravimetrically after drying to a constant weight at 104°C for 24 h. Soil pH was determined with a 1:1 paste of soil and water (McLean, 1982). Total C was estimated by dry ashing at 525°C and assuming C equal to 50% of loss on ignition (Nelson and Sommers, 1982). Total N was determined using standard microkjeldahl procedures modified for nitrate (Bremmner and Mulvaney, 1982). C:N ratios were calculated by dividing total C by total N. Extractable P, K, Ca, Mg, Mn, Fe, Cu, B and Zn was determined by extracting a 2.00 g sample of the top 10 cm of mineral soil with four aliquots of 0.225 M NH_4OAC plus 0.0005 M diethylentriaminepentaacetic acid (DTPA). The soil was shaken for 7 min, centrifuged at 180 rpm/min and analyzed on a Jarrol Ash 9000 inductively coupled plasma spectrometer.

2.3. Mycorrhizal inoculum preparation

Mycorrhizal soils containing *G. mosseae*, and *G. intraradices* spores were obtained from the International Culture Collection of Arbuscular Mycorrhizal Fungi (INVAM) at West Virginia University. A sample of 1000 g from each soil test type was placed in each of 3,2-liter erlenmeyer flasks and autoclaved for 60 min at 140 kPa and 122°C and cooled for 24 h prior to inoculation. Arbuscular mycorrhizal fungi inoculum for each soil type was prepared by mixing 100 g of *G. mosseae* or

G. intraradices inoculum, obtained from INVAM, with 1000 g of each autoclaved test soil type. Oat (*Avena oligantha* Michx.) seeds were surface sterilized with 30% H_2O_2 as described later and then 1.0 g of seed were planted in each flask. Oats were grown in flasks for 4 weeks to provide fresh mycorrhizal inoculum. At harvest, aboveground parts of the oat plants were cut and discarded and the soil and roots in which the inoculated oat plants had grown were thoroughly mixed and used as inoculum. Bahia grass, johnson grass and switchgrass were inoculated by mixing 295 g each soil type with 5 g of soil containing spores of *G. mosseae* or *G. intraradices* in the prepared soil.

2.4. Plant growing conditions

Grass and oat seeds were immersed in 30% H_2O_2 for 30 min to ensure the absence of pathogenic or mycorrhizal fungi. Grass seed (1 g) of the desired species was placed on the surface of soil in 10 cm diameter×20 cm deep plastic containers. After 2 weeks plant shoots were thinned to three stems in each container. Plants received 1.5 mg N as NH_4NO_3 and KNO_3, 0.5 mg P as KH_2PO_4 and 0.6 mg K as KH_2PO_4 and KNO_3 in 10 ml H_2O each week. Plants were grown in the containers for 3 months in a greenhouse maintained at 22±3°C. During that time, the seedlings were exposed to sunlight which had a photosynthetically active radiation of 400–700 μmol m^{-2} S^{-1} and a 14–16 h photoperiod.

2.5. Radionuclide treatments

After 3 months of growth, either 3967 Bq ^{137}Cs as $^{137}CsCl$ or 4373 Bq ^{90}Sr as $^{90}SrCl_2$ in 10 ml distilled deionized H_2O was poured on the soil surface in each container. There was no drainage in these containers. One day after radionuclides were added, the effectiveness of ^{137}Cs and ^{90}Sr dispersion was determined by measuring the concentration of the radionuclides in a 0.5 cm diameter×7 cm deep core taken from the center of one container in each soil type×soil amendment×grass species combination. Each core soil was split into two, 3.5 cm vertical sections; a 1 g sample from each section was placed in a 10 ml plastic counting vial and analyzed for ^{137}Cs or ^{90}Sr using methods described later. The average concentration of ^{137}Cs in the soil was 100 Bq g^{-1} with a standard deviation of 8 Bq g^{-1}; the average concentration of ^{90}Sr in the soil was 112 Bq g^{-1} with a standard deviation of 7 Bq g^{-1}. At the end of the experiment the soil was split into five, 2 cm vertical sections. A 1 g sample from each section was placed in a 10 ml plastic counting vial and analyzed for ^{137}Cs using methods described later. A 1 g sample of soil 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 soil (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.

2.6. Harvesting procedures

Hand shears were used to cut the above-ground portion of plants in each container to a residual height of 2.5 cm on the first day of every 2 months from July through December 1996. At the final harvest, roots were also sampled. 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 rewashed twice in distilled deionized water. All root and shoot tissue was dried at 80°C for 48 h and then weighed.

2.7. Radionuclide counts

Roots and shoots were analyzed separately. Mean values for replicate counts for both radionuclides were compared with known activity of six standard sources for each radionuclide ranging from 10 to 1000 Bq to determine the efficiency of the counting system. Tissues containing ^{137}Cs were placed in 10 ml plastic counting vials and activity was counted for 10 min 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 region of interest surrounding the at the 661.65 keV total absorption peak. Counting errors (ϒ) for each plant and soil sample were ≥95%. At final harvest, plants were removed and five 1.0 g samples of the soil were analyzed for radionuclide concentration. Known ^{137}Cs standards were placed with each set of 20 samples to check counting efficiency. 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 system background described earlier.

At the end of the experiment the soil was split into five, 2 cm vertical sections. A 1 g sample from each section was placed in a 10 ml plastic counting vial and analyzed for ^{137}Cs using methods described earlier. A 1 g sample of soil 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 soil (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.

Tissues containing ^{90}Sr were placed in 20 ml glass scintillation vials and ashed for 6 h at 525°C±5°C.

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 soil was analyzed by placing 5 g of soil 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 No. 1 filter. A 1 ml sample 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. Counting errors (ϒ) for each plant and soil sample were ≥95%. Known ^{90}Sr standards were placed with each set of 20 samples to check counting efficiency. The ^{137}Cs and ^{90}Sr counts from six blank samples were not significantly different from background counts. All ^{137}Cs and ^{90}Sr values are reported as values above background values.

2.8. Mycorrhizal infection

Roots were removed from each test plant by sieving soil in each container to pass a 0.5 mm opening. Three roots were collected and washed three times with distilled deionized water and cut to approximately 3.0 cm lengths. Roots were cleared by placing them in a 10% (w/v) KOH solution. The solution and roots were placed in a microwave oven for 5 min and then placed in a solution of 0.05% (w/v) trypan blue in lactoglycerol for 24 h (Phillips and Hayman, 1970). Roots were observed under 100× on a microscope and percentage of root area infected was estimated using the line intersect technique described in Giovannetti and Mosse (1980). Root area infected with mycorrhizae was estimated as % root area infected with mycorrhizae×root length/2.

2.9. 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 soil 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 grass tissue/Bq radioisotope g^{-1} dry soil. Mass balances for each experiment were calculated with the formula:

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

where

MB = mass balance or the percentage of ^{137}Cs or ^{90}Sr accounted for,

R_a = the Bq of ^{137}Cs or ^{90}Sr added to the soil,

R_{ps} = the Bq of ^{137}Cs or ^{90}Sr accumulated over the course of the experiment in plant shoots,

R_{pr} = the Bq of ^{137}Cs or ^{90}Sr accumulated over the course of the experiment plant roots and

R_s = the amount of ^{137}Cs or ^{90}Sr in the soil at the end of the experiment.

2.10. Statistical analysis

Data were 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 $p \leq 0.05$ using the Least Square Means test.

3. Results

The pH ranged from acid in the Lehew series (4.8) to basic in the Crenshaw series (7.4; Table 1). Soil carbon, nitrogen and extractable phosphorus ranged from a low of 0.35%, 0.05% and 3.2 g P mg^{-1} soil respectively, in the Lehew soil to a high of 2.02%, 0.19% and 28.3 g P mg^{-1} soil respectively, in the Crenshaw soil. Concentrations of all nutrients tested in these soils were adequate for plant growth.

The analysis of variance for plant biomass, concentration of ^{137}Cs or ^{90}Sr in plant tissue, % accumulation by plant tissue, bioconcentration ratio, aboveground biomass, root biomass, ^{137}Cs or ^{90}Sr in root tissue, ^{137}Cs or ^{90}Sr in the entire plant or ^{137}Cs or ^{90}Sr in soil indicated no significance ($p \leq 0.05$) for soil type×mycorrhizal inoculations×grass species, soil types× mycorrhizal inoculations or soil type×grass species interactions, therefore only mycorrhizal inoculations×grass species interactions will be discussed (Snedecor and Cochran, 1980).

The above ground biomass of bahia, johnson and switchgrass removed in three harvests, contained from 26.3 to 71.7% of the total amount of the ^{137}Cs and from 23.8 to 88.7% of the total amount of the ^{90}Sr added to the soil (Tables 2 and 3). Above-ground plant biomass did not differ between exposure to ^{137}Cs or ^{90}Sr over the course of the experiment. When bahia, johnson and switchgrass plants were inoculated with *G. mosseae* or *G. intraradices*, a greater percentage of their roots was found to contain mycorrhizae than when plants were not inoculated (Tables 2 and 3). When plants were inoculated with *G. mosseae* or *G. intraradices*, aboveground plant biomass, concentration of ^{137}Cs or ^{90}Sr in plant tissue, % accumulation of ^{137}Cs or ^{90}Sr from soil and the plant bioconcentration ratio in all three harvests increased compared to plants growing in control soil. When plants were inoculated with *G. mosseae*, aboveground plant biomass, concentration of ^{137}Cs or ^{90}Sr in plant tissue and % accumulation of ^{137}Cs or ^{90}Sr from

Table 1
Classification and nutrient concentration in Lehew, Crenshaw and Fullerton soils collected near the Oak Ridge Nuclear Facility, Tennessee

Soil series	Classification	pH	OM	C	N	P	K	Ca	Mg	Mn	Fe	Mn	Cu	Zn	B
			%			g element Mg^{-1} soil									
Lehew	loamy-skeletal, mixed mesic, typic dystrochrept	4.84	1.47	0.35	0.05	3.2	54	424	74	38	15	2.0	0.1	0.8	0.3
Crenshaw	clayey, kaolinitic, thermic typic paleudult	7.39	4.00	2.03	0.19	28.3	103	5622	164	18	5	18	0.1	1.5	1.3
Fullerton	clayey, kaolinitic thermic typic paleudult	5.68	3.86	0.91	0.10	5.7	78	603	98	118	20	118	0.5	1.0	0.4

Classifications are taken from soil survey of Anderson County, Tennessee (Monemaker et al., 1981). USDA National Resource Conservation Service.
$n=9$.

soil and in all three harvests increased compared to the *G. intraradices* amendment. As plants accumulated more ^{137}Cs or ^{90}Sr from these soils higher percentages of these radionuclides were stored in the aboveground tissues. Mass balance calculations accounted for 99.4% of the ^{137}Cs and 99.7% of the ^{90}Sr added to the soil.

4. Discussion

The concentration of ^{137}Cs or ^{90}Sr in plant tissues is comparable with other studies (Coughtrey et al., 1989; Salt et al., 1992, 1997; Murphy and Johnson, 1993). However, the proportion of ^{137}Cs or ^{90}Sr removed from the soil by these plants is substantially higher than other studies (Robinson and Stone, 1992; Salt et al., 1992, 1997; Entry et al., 1994). It is suggested that these plants extracted a high percentage of ^{137}Cs and ^{90}Sr from these soils because (1) density of roots was extremely high, (2) plants grew rapidly because growing conditions for these grasses and thus uptake of water and plant minerals was high, (3) concentrations of K and Ca in soil were low and (4) root colonization by mycorrhizal fungi was high. Inoculation of bahia, johnson and switchgrass grass with arbuscular mycorrhizae increased aboveground plant biomass, concentration of ^{137}Cs or ^{90}Sr in plant tissue and accumulation of ^{137}Cs or ^{90}Sr from soil. Inoculation with arbuscular mycorrhizae increased root biomass which resulted in greater quantities of ^{137}Cs and ^{90}Sr accumulation from the soil. In a modeling study based on data from experimental results, Kirk and Staunton (1989) found that the higher the density of roots in the soil the more ^{137}Cs was accumulated by a wide variety of grassland plants.

Although the ability to accumulate radionuclides varies among a wide array of plant species occupying different habitats, many plants growing on contaminated soils have been shown to accumulate radionuclides, especially ^{137}Cs and ^{90}Sr (Pinder et al., 1984; Coughtrey et al., 1989; Salt et al., 1992, 1997; Murphy and Johnson, 1993). Laboratory experiments indicate that certain plants may be able to remove radionuclides, especially ^{137}Cs and ^{90}Sr, from soil over a time period of 5–20 years. Nifontova et al. (1989) found that plants accumulated between 530 and 1500 Bq ^{137}Cs kg^{-1} plant material and between 300 and 1100 Bq ^{90}Sr kg^{-1} plant material over a 10 year period in 12 forest and 5 meadow plant communities containing between 250–300 kg ^{137}Cs and ^{90}Sr kg^{-1} soil in the vicinity of the Beloyarsk atomic power station in the Urals pine mountain region of Russia. Wallace and Romney (1972) found that a large number of plant species in the desert area near the Nevada Test Site, USA, accumulated from 162 to 944 Bq ^{90}Sr g^{-1} plant material from soil containing 3200 Bq ^{90}Sr g^{-1}. Several reports have documented the accumulation of ^{137}Cs and ^{90}Sr in grasses and other herbaceous plants in the field. Dahlman et al. (1969) reported that *Festuca arundinacea* accumulated 42 143 kBq g^{-1} plant material of ^{137}Cs m^{-2} in 8 months, in an area where the total amount of ^{137}Cs in above-ground runoff and sediment was less than 444 kBq ^{137}Cs g^{-1} soil. Salt et al. (1992) reported that *Lolium perenne, Festuca rubra, Trifolium repens* and *Cerastium fontanum* accumulated from 3.1 to 6.5% of the ^{134}Cs g^{-1} from a re-seeded pasture soil in Scotland. Coughtrey et al. (1989) found that a *Festuca/Agrostis* plant community in the UK accumulated 4–19% of the ^{137}Cs deposited by Chernobyl fallout. The objective of the above studies was to document ^{137}Cs and ^{90}Sr uptake by plants in relation to contamination of grazing animals and incorporation of radionuclides into the food chain and not phytoremediation. In order to make phytoremediation of radionuclides, or other elements that are considered pollutants, practical one must maximize root density, plant growing conditions and availability of the contaminant to the plant (Entry et al., 1996). Even though a majority of plants growing in soils contaminated with ^{137}Cs and ^{90}Sr are able to accumulate these radionuclides, not all plants are able maximize accumulation when put in cultivation. To adequately test the feasibility of phytoremediation, experiments with soils contaminated with ^{137}Cs and ^{90}Sr must be tested in the field.

Table 2
^{137}Cs accumulation in grasses inoculated with arbuscular mycorrhizae fungi planted in ^{137}Cs contaminated soil[a,b,c]

Fungi	Plant species	Harvest 1 (8 weeks)				Harvest 2 (16 weeks)				Harvest 3 (24 weeks)				Total						
		Plant biomass	Concentration	^{137}Cs recovered after 1 harvest[b]	Bioconcentration ratio	Plant biomass	Concentration	^{137}Cs recovered after 2 harvests[b]	Bioconcentration ratio	Plant biomass	Concentration	^{137}Cs recovered after 3 harvests[b]	Bioconcentration ratio	Above ground biomass	Root biomass	^{137}Cs in roots	Plant biomass	^{137}Cs in plant	^{137}Cs in soil	Mycorrhizal infection
		g^{-1}	Bq g^{-1}	%	d	g^{-1}	Bq g^{-1}	%	d	g^{-1}	Bq g^{-1}	%	d	g^{-1}	g^{-1}	%	g^{-1}	%	%	%
None	Bahia grass	1.43 d	380 b	8.2 c	5.4 c	1.03 c	390 b	18.3 e	4.2 b	0.79 b	397 b	26.3 e	3.5 b	3.66 d	1.63 c	15.6 b	5.30 b	41.9 b	57.6 a	54.0 c
None	Johnson grass	3.59 a	353 b	16.0 bc	12.6 a	1.95 a	388 b	34.9 c	8.6 a	1.05 a	401 b	45.5 bc	5.3 b	6.60 a	3.07 a	27.9 a	9.67 a	73.4 a	26.0 c	54.4 c
None	Switch grass	2.04 c	339 b	8.9 c	5.9 c	1.40 b	391 b	22.0 e	5.9 b	0.79 b	482 ab	31.8 d	4.4 b	4.23 c	1.71 c	16.0 b	5.94 b	47.8 b	51.8 a	54.7 c
Glomus mosseae	Bahia grass	1.19 d	869 a	13.1 c	10.6 b	1.57 b	467 a	31.7 c	8.2 a	0.77 b	521 a	41.7 c	5.1 b	3.54 bc	1.61 c	15.6 b	5.15 b	57.3 a	42.2 b	86.7 a
Glomus mosseae	Johnson grass	2.78 b	856 a	30.1 a	23.7 a	2.09 a	479 a	55.8 a	13.2 a	1.00 a	556 a	70.1 a	8.8 a	5.88 b	2.78 a	24.7 a	8.73 a	94.8 a	4.6 d	87.2 a
Glomus mosseae	Switch grass	1.95 c	889 a	21.9 b	17.3 b	2.03 a	470 a	46.0 b	11.0 a	0.76 b	498 a	55.4 b	6.0 ab	4.74 c	1.99 b	18.8 b	6.73 b	74.2 a	25.3 c	86.9 a
Glomus intraradices	Babia grass	1.67 c	868 a	18.4 bc	14.5 b	1.65 b	475 a	38.3 bc	9.2 a	0.76 b	439 b	46.7 bc	4.4 b	4.09 c	1.61 c	16.1 b	5.70 b	62.8 b	37.0 bc	70.1 b
Glomus intraradices	Johnson grass	3.80 a	823 a	33.6 a	31.2 a	2.09 a	444 a	57.0 a	13.4 a	1.05 a	555 a	71.7 a	8.8 a	6.95 a	2.28 b	17.6 b	9.24 a	89.3 a	10.2 d	70.4 b
Glomus intraradices	Switch grass	1.89 c	880 a	22.9 b	16.6 b	1.70 b	471 a	43.1 b	9.5 a	0.78 b	439 b	51.9 b	4.6 b	4.38 c	1.51 c	14.9 b	5.90 b	66.8 b	32.8 bc	73.0 b

[a] Within each column, values followed by the same letter are not significantly different as determined by the least squared means test ($p \leq 0.05$) $n = 9$ for all values.
[b] ^{137}Cs recovered = %of the total amount of radionuclotide added to the soil that was accumulated by the plant after 1, 2, or 3 harvests.
[c] Concentration = Bq radionuclotide g^{-1} plant tissue.
[d] Bioconcentration ratio = Bq radionuclotide in plant tissue/Bq radionuclotide g^{-1} in soil.
[e] 3967 Bq 137Cs was added to 300 g equivalent dry weight of soil.
[f] The analysis of variance for plant biomass, concentration of ^{137}Cs or ^{90}Sr in plant tissue, % accumulation by plant tissue, bioconcentration ratio, aboveground biomass, root biomass, ^{137}Cs or ^{90}Sr in root tissue, ^{137}Cs or ^{137}Cs in the entire plant or ^{137}Cs or ^{90}Sr in soil indicated no significance ($p \leq 0.05$) for soil type×soil amendments×grass species, soil types×soil amendments or soil type×grass species interactions, therefore only soil amendments×grass species interactions may be discussed (Snedecor and Cochran, 1980).

Table 3
^{90}Sr accumulation in grasses inoculated with arbuscular mycorrhizae fungi planted in ^{90}Sr contaminated soil[a,b,c]

Fungi	Plant species	Harvest 1				Harvest 2				Harvest 3				Total						
		Plant biomass	Concentration	^{90}Sr recovered after 1 harvest[b]	Bioconcentration ratio	Plant biomass	Concentration	^{90}Sr recovered after 2 harvests[b]	Bioconcentration ratio	Plant biomass	Concentration	^{90}Sr recovered after 3 harvests[b]	Bioconcentration ratio	Aboveground biomass	Root biomass	^{90}Sr in roots	Plant biomass	^{90}Sr in plant	^{90}Sr in soil	Mycorrhizal infection
		g^{-1}	Bq g^{-1}	%	d	g^{-1}	Bq g^{-1}	%	d	g^{-1}	Bq g^{-1}	%	d	g^{-1}	g^{-1}	%	g^{-1}	%	%	%
None	Bahia grass	1.36 d	362 c	11.4 c	4.4 c	1.03 c	371 d	20.4 f	4.0 b	0.72 b	327 c	23.8 e	2.5 a	3.11 d	0.93 d	6.2 b	4.04 c	30.0 b	69.6 a	50.5 c
None	Johnson grass	3.24 a	395 b	26.0 b	11.4 b	1.99 b	443 c	46.6 d	10.0 a	1.11 a	363 bc	52.6 c	5.1 a	6.35 a	1.94 a	13.4 a	8.29 a	66.0 a	33.4 c	48.3 c
None	Switch grass	1.57 c	477 b	17.4 c	6.7 c	1.57 c	388 d	31.9 e	6.5 ab	0.83 ab	383 b	36.8 d	3.7 a	3.99 c	1.54 b	10.2 ab	5.53 b	47.0 b	56.6 b	49.9 c
Glomus mosseae	Bahia grass	1.67 c	620 b	23.1 b	9.2 b	1.38 b	463 c	38.0 d	7.0 ab	0.76 b	342 b	42.0 cd	3.1 a	3.82 c	1.56 b	8.6 b	8.98 a	50.6 a	49.0 b	85.3 a
Glomus mosseae	Johnson grass	3.74 a	561 ab	48.3 a	18.7 a	2.07 a	608 bc	77.2 b	15.1 a	1.06 a	213 c	79.4 a	3.1 a	6.87 a	2.11 a	8.2 b	8.98 a	88.0 a	11.0 e	85.2 a
Glomus mosseae	Switch grass	2.04 b	694 a	30.8 b	12.6 ab	1.76 a	687 b	56.3 c	13.7 a	0.91 a	460 a	63.4 b	5.6 a	4.89 b	1.87 a	16.3 a	6.76 b	79.7 a	19.9 d	84.7 a
Glomus intraradices	Bahia grass	1.66 c	647 b	25.8 b	9.6 b	1.32 bc	705 b	47.4 d	10.3 a	0.77 b	268 c	50.1 c	2.6 a	3.75 c	1.35 c	7.5 b	5.10 b	57.6 b	42.0 b	72.8 b
Glomus intraradices	Johnson grass	3.39 a	632 b	50.3 a	19.1 a	2.36 a	609 bc	83.6 a	17.5 a	1.02 a	342 b	88.7 a	5.4 a	6.78 a	2.14 a	12.5 a	8.91 a	98.7 a	0.0 f	75.5 b
Glomus intraradices	Switch grass	1.60 c	711 a	26.5 b	10.2 b	1.65 b	768 a	56.1 c	14.1 a	0.85 ab	429 a	62.0 b	4.8 a	4.10 c	1.59 b	13.0 a	5.69 b	93.4 a	6.1 e	76.7 b

[a] Within each column, values followed by the same letter are not significantly different as determined by the least squared means test ($p \leq 0.05$) $n = 9$ for all values.
[b] ^{90}Sr recovered = % of the total amount of radionuclotide added to the soil that was accumulated by the plant after 1, 2, or 3 harvests.
[c] Concentration = Bq radionuclotide g^{-1} plant tissue.
[d] Bioconcentration ratio = Bq radionuclotide in plant tissue/Bq radionuclotide g^{-1} in soil.
[e] 4373 Bq ^{90}Sr was added to 300 g equivalent dry weight of soil. 14.5 Bq ^{90}Sr g^{-1} soil.
[f] The analysis of variance for plant biomass, concentration of ^{137}Cs or ^{90}Sr in plant tissue, % accumulation by plant tissue, bioconcentration ratio, aboveground biomass, root biomass, ^{137}Cs ^{90}Sr in root tissue, ^{137}Cs or ^{90}Sr in the entire plant or ^{137}Cs or ^{90}Sr in soil indicated no significance ($p \leq 0.05$) for soil type×soil amendments×grass species, soil types×soil amendments or soil type×grass species interactions, therefore only soil amendments×grass species interactions may be discussed (Snedecor and Cochran, 1980).

Entry, J.A., Vance, N.C., Hamilton, M.A., Zabowski, D., Watrud, L.S., Adriano, D.C., 1996. Phytoremediation of soil contaminated with low concentrations of radionuclides. Water, Air and Soil Pollution 88, 168–176.

Giovannetti, M., Mosse, B., 1980. An evaluation technique for measuring vesicular arbuscular mycorrhizae infection in roots. New Phytologist 84, 489–500.

Hoffman, F.O., Bergstrom, U., Gyllander, C.A., Wilikins, A.B., 1984. Comparisons of the predictions from internationally recognized assessment models for the transfer of selected radionuclides through terrestrial food chains. Nuclear Safety 25, 533–546.

Kirk, G.J.D., Staunton, S., 1989. On predicting the fate of radioactive cesium in soil beneath grassland. Journal of Soil Science 40, 71–84.

Kirk, R.E., 1982. Experimental Design. Brooks, Monterey, CA.

Lange, R., Dickerson, M.H., Gudiksen, P.H., 1988. Dose estimates from the Chernobyl accident. Nuclear Technology 82, 311–323.

Lowe, V.P.W., Horrill, A.D., 1991. Caesium concentration factors in wild herbivores and the fox (*Vulpes vulpes* L.). Environmental Pollution 70, 93–107.

McLean, R.L., 1982. Soil pH and lime requirement. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy, Madison, WI, pp. 539–577.

Monemaker, R.H., Conner, C.T., Mckinney, D., Monteith, S.E., Ottinger, S.A., Treudway, W.D., 1981. Soil survey of Anderson county, Tennesee. USDA National Resource Conservation Service, p. 165.

Murphy, C.E., Johnson, T.L., 1993. Vegetative uptake of technetium-99 from buried, solidified, low level radioactive waste. Journal of Environmental Quality 22, 793–799.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy, Madison, WI, pp. 539–577.

Ohnuki, T., Kozai, N., 1994. Sorption characteristics of radioactive cesium and strontium on smectite. Radiochimica Acta. 67, 327–331.

Pinder, III, J.E., McLeod, K.W., Alberts, J.J., Adriano, D.C., Corey, J.C., 1984. Uptake of ^{244}Cm and ^{238}Pu and other radionuclides by trees inhabitating a contaminated floodplain. Health Physics 47, 375–384.

Prister, B., Loshchilov, N., Perepelyatnikova, L., Perepelyatnikova, G., Bondar, P., 1992. Efficiency of measures aimed at decreasing the contamination of agricultural products in areas contaminated by the Chernyobl NPP accident. Science of the Total Environment 112, 79–87.

Nifontova, M.G., Kulikov, G.I., Tarshis, G.I., D'yachenko, D., 1989. Radioecological study of natural ecosystems in the vicinity of atomic power stations. Ekologiya 3, 40–45.

Pennttila, S., Kairesalo, T., Uusi-Rauva, A., 1993. The occurrence and bioavailability of radioactive ^{137}Cs in small forest lakes in southern Finland. Environmental Pollution 82, 47–55.

Phillips, J.M., Hayman, D.S., 1970. Improved procedures for clearing roots and staining parasitic and vesicular arbuscular mycorrhizal fungi for rapid assessment of infection. Transactions of the British Mycological Society 55, 158–160.

Rameback, H., Albission, Y., Skalberg, M., Werme, I., 1994. Release and diffusion of ^{90}Sr from spent UO_2 fuel in bentonite clay. Radiochimica Acta 67, 405–408.

Rickard, W.H., Ebrhard, L.E., 1993. Strontium-90 in Canada goose eggshells: nonfatal monitoring for contamination in wildlife. Northwest Science 67, 25–31.

Robison, W.L., Stone, E.L., 1992. The effect of potassium on the uptake of ^{137}Cs in food crops grown on coral soils: Coconut at Bikini Atoll. Health Physics 62, 496–511.

Rogers, R.D., Williams, S.E., 1986. Vesicular-arbuscular mycorrhizae: influence on plant uptake of cesium and cobalt. Soil Biology and Biochemistry 4, 371–376.

Sanzharova, D.I., Aleksakhin, R.M., 1982. Uptake of ^{22}Na, ^{32}P, ^{65}Zn, ^{90}Sr and ^{106}Ru by crops. Pochvovedeniye 9, 59–64.

Salt, C.A., Kay, J.W., Donaldson, L., Woolsey, J.M., 1997. The influence of defoliation intensity, season, and leaf age on radiocaesium concentrations in *Agrostis capillaris*. Journal of Applied Ecology 34, 1177–1189.

Salt, C.A., Mayes, E.S., Elston, D.A., 1992. Effects of season, grazing intensity and diet composition on the radiocaesium intake by sheep on a re-seeded hill pasture. Journal of Applied Ecology 29, 378–387.

Smith, S.E., Read, D.J., 1997. Mineral nutrition, heavy metal accumulation and water relations of VA mycorrhizal plants. In: Mycorrhizal Symbiosis. Academic Press, San Diego, CA. p. 605.

Snedecor W.G., Cochran W.G., 1980. Statistical Methods. 7th Edition. Iowa State University Press, Ames, IA.

Van den Driesshe, R., 1987. Importance of current photosynthate to new root growth in planted conifer seedlings. Canadian Journal of Forest Research 17, 776–781.

Vereoglou, D.S., Barbayiannis, N., Zalidis, G.C., Kalpakis, S., Batianis, E., 1995. Transfer factors for ^{90}Sr as influenced by species Ca uptake and soil Ca availability. Plant and Soil. 175, 225–232.

Walker, R.K., Gessel, S., Held, E.E., 1997. The ecosystem study on Ronglap Atoll. Health Physics. 73, 223–233.

Wallace, A., Romney, E.M., 1972. Radioecology and Ecophysiology of desert plants at the Nevada Test Site. Environmental Radiation Division. Laboratory of Nuclear Medicine University of California, Riverside, CA.

Whicker, F.W., Pinder, J.E., Bowling, J.W., Alberts, J.J., Brisbin, L., Jr., 1990. Distribution of radionuclides in an abandon reactor cooling reservoir. Ecological Monographs 60, 471–496.