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***ER ID NO.*** 73708 ***Date Received:*** 1/30/2003 ***Processor:*** YCA ***Page Count:*** 4

***Privileged: (Y/N)*** N ***Record Category:*** P

***FileFolder:*** N/A

***Correction: (Y/N)*** N ***Corrected No.*** 0 ***Corrected By Number:*** 0

***Administrative Record: (Y/N)*** Y

***Refilmed: (Y/N)*** N ***Old ER ID Number:*** 0 ***New ER ID Number:*** 0

***Miscellaneous Comments:***

REFERENCE CITED

30944

## Waste Management



# Effects of Pocket Gopher Burrowing on Cesium-133 Distribution on Engineered Test Plots

G. J. Gonzales,* M. T. Saladen, and T. E. Hakonson


## ABSTRACT

**Very low levels of radionuclides exist on soil surfaces from atmospheric fallout following weapons testing or from stack discharges, and from exposure of some of the older waste storage and disposal sites worldwide. Biological factors including vegetation and animal burrowing can influence the fate of these surface contaminants. Animal burrowing introduces variability in radionuclide migration that confounds estimation of nuclide migration pathways, risk assessment, and assessment of waste burial performance. A field study on the surface and subsurface erosional transport of surface-applied $^{133}$Cs as affected by pocket gopher (*Thomomys bottae*) burrowing was conducted on simulated waste landfill caps at the Los Alamos National Laboratory in north central New Mexico. Surface loss of Cs, adhered to five soil particle size ranges, was measured several times over an 18-mo period while simulated rainfalls were in progress. Gophers reduced Cs surface loss by significant amounts, 43%. Cesium surface loss on plots with only gophers was 0.8 kg totalled for the study period. This compared with 1.4 kg for control plots, 0.5 kg for vegetated plots, and 0.2 kg for plots with both gophers and vegetation. The change in Cs surface loss over time was significant ($P < 0.01$). Relatively little subsurface Cs was measured in plots containing only gophers (0.7 g kg$^{-1}$). Vegetation-bearing plots had significantly more total subsurface Cs ($\mu$ = 1.7 g kg$^{-1}$) than plots without vegetation ($\mu$ = 0.8 g kg$^{-1}$). An average of 97% of the subsurface Cs in plots with vegetation was located in the upper 15 cm of soil (SDR1 + SDR2) compared with 67% for plots without vegetation. Vegetation moderated the influence of gopher activity on the transport of Cs to soil subsurfaces, and stabilized subsurface Cs by concentrating it in the rhizosphere. Gopher activity may have caused Cs transport to depths below that sampled, 30 cm. The results provide distribution coefficients for models of contaminant migration where animal burrowing occurs.**


VERY LOW LEVELS of radionuclides exist on soil surfaces from global atmospheric fallout resulting from weapons testing, accidents such as Chernobyl, or from stack discharges (Bell et al., 1993). They also may exist resulting from exposure of some of the older waste storage and disposal facilities worldwide. This includes waste landfills that have been used for disposal of radioactive and hazardous waste. Because waste at storage and disposal facilities was buried as shallow as one meter, waste cells can become exposed by accelerated soil erosion, accidental breach of waste cells by machinery, or burrowing by rodents (Hakonson et al., 1982a; Wenzel et al., 1987; Garner, 1971). Migration of radionuclides that are present on the soil surface is often governed by erosional factors in the contaminated area (Fowler et al., 1978). These include the amount and intensity of erosion and runoff, the amount of water that infiltrates into the soil, and biological factors including vegetative cover and animal burrowing (Bell et al., 1993; Arthur and Markham, 1983; Landeen and Mitchell, 1981). While burrowing by fossorial animals can play an important role in the water balance of a site (Sejkora and Alldredge, 1989; Nyhan et al., 1990; Hakonson et al., 1992), the influence of burrowing on hydrologic erosion of radionuclides is poorly understood (Hakonson et al., 1982b).

Although studies on current and decommissioned low-level radioactive waste (LLW) burial sites in the western USA have shown that radionuclides present in the waste can be mobilized by burrowing animals that penetrate through trench covers and backfill (Klepper et al., 1979; Hakonson et al., 1982a,b; Hakonson and Gladney, 1982), the large spatial heterogeneity of contaminated soils disturbed by burrowing animals complicates contaminant migration such that there is insufficient data for input to models attempting to predict contaminant fate and associated risk (White et al., 1990). Past investigations have focused on the potential for animal activity to translocate buried waste material to the surface, however less emphasis has been placed on the fate of that waste once deposited on the surface (Arthur and Markham, 1983; Winsor and Whicker, 1980). The need for this information from a regulatory standpoint stems from the requirement (USEPA, 1989; USDOE, 1989) to assess contaminant migration pathways, estimate risks to potential receptors, and select remediation alternatives as a part of the U.S. Department of Energy (DOE) Environmental Restoration Program.

The pocket gopher is one such burrowing animal that

Los Alamos Natl. Lab., P.O. Box 1663, Los Alamos, NM 87545. G.J. Gonzales, Mail Stop K557, Hazards and Ecol. Risk Analysis, Probabilistic Risk and Hazard Analysis Group, TSA-11, Technology and Safety Assessment Div.; M.T. Saladen and T.E. Hakonson, Earth and Environ. Sci. Div., Environ. Sci. Group; M.T. Saladen, LANL, MS K490, Environment, Safety, and Health Div.; T.E. Hakonson, Center for Ecol. Risk Assessment and Management, Colorado State Univ., Fort Collins, CO 80302. Work supported by U.S. DOE contract W-7405-ENG-36, Office of Health and Environmental Restoration, Washington, DC. Received 24 June 1994. *Corresponding author (gonzales_g@lanl.gov).

Published in J. Environ. Qual. 24:1056-1062 (1995).

Abbreviations: LLW, low-level radioactive waste; USDOE, U.S. Department of Energy; LANL, Los Alamos National Laboratory; S/C, silt/clay; SDR, soil depth ranges.

has invaded LLW burial sites, including at the Los Alamos National Laboratory (LANL) in north central New Mexico (Hakonson et al., 1984; Hakonson et al., 1982b). Most gophers show a preference for invading disturbed sites (Findley et al., 1975); however, the extent of their disturbance of waste sites is not well quantified. This might only be inferred from their distribution. Pocket gophers are found only in the western hemisphere and their geographic range is from Panama, to Cuba, to Alberta, Canada. They are represented by 8 genera, 30 species and approximately 300 subspecies (Findley et al., 1975). Within their geographic range, pocket gophers occupy a variety of different vegetation types and their distribution varies (Turner et al., 1983). The pocket gopher used in this study was *Thomomys bottae*. *Thomomys* sp. are referred to as northern pocket gophers. *Thomomys bottae* is found from the western edge of the eastern plains westward. This gopher occupies almost every habitat where suitable soil conditions exist. The exceptions are the higher elevations of the northern mountains where it is replaced by *T. talpoides*. *Thomomys talpoides* is the species of parks and meadows of middle elevations.

Maximum densities reported for various pocket gophers are highly variable. Densities of 40 to 49 $ha^{-1}$ are very common for *Thomomys*, but they may attain densities as high as 120 $ha^{-1}$ (Turner et al., 1983). Pocket gopher peak density occurs in the fall with the rearing of young (Findley et al., 1975).

The influence of burrowing animals on radionuclide distribution is thought to be closely linked to their effects on soil erosion. Of the burrowing animals, the pocket gopher is generally considered the greatest contributor to soil erosion. Burrowing activities of pocket gophers have seasonal trends that are dictated by soil moisture and temperature. Gophers have been noted to dig deeper during winter and summer to avoid extreme temperatures. Presumably burrowing activity is most intense when the soil is tractable and moderately wet (Miller, 1946). At LANL, gopher density is not well quantified, however their preference for disturbed sites and common inhabitation of waste landfills is well known. In studying tunnel casts of gophers at LANL, Hakonson et al. (1982b) reported an excavated soil mass of 1200 kg $ha^{-1}$ $yr^{-1}$, for an average excavation rate of about 30 kg $d^{-1}$ $ha^{-1}$. Displacement of that amount of soil created about 2800 m of tunnel system in the trench cap.

Burrowing activity generally ranges in depth from 15 cm to 1.5 m. In this study, gopher activity extended to 1.5 m (Sejkora and Alldredge, 1989). The depth of burrowing can have implications on the effectiveness of long term waste burial since waste has been buried as shallow as 1 to 3 m from the surface. Tunnel systems created by pocket gophers increase infiltration by decreasing bulk density. This can subject the trench to accelerated erosion. Surface contamination with LLW is then possible.

The objectives of this study were to evaluate the separate and combined influence of vegetation and animal burrowing on the hydrologic erosion of stable cesium ($^{133}Cs$) applied to the surface of simulated waste landfill caps that were exposed to simulated rainfall in the field. Interaction of soil texture and time was also separated. Detailed results on the hydrological and soil erosional response to the treatments are reported elsewhere (Sejkora and Alldredge, 1989).

## MATERIALS AND METHODS

### Erosion Study Plots

Eight field plots measuring 3.1 by 10.7 by 0.5 m were constructed at the LANL Experimental Engineered Test Facility. The plots were similar to those used in erosion research by the U.S. Department of Agriculture (Simanton and Renard, 1982). Plots contained 15 cm of topsoil backfill (Hackroy series sandy loam, clayey, mixed, mesic Lithic Haplustalf) underlain by 75 cm of crushed Bandelier tuff backfill (unaltered tuff consists of rock of compacted volcanic ash and dust). Undisturbed Bandelier tuff served as the base of the backfill. A surface grade of 4 to 5% was established. Each plot was engineered with a runoff catchment trough that lead to a central downspout and then to a runoff-measuring supercritical flume on a concrete pad. The supercritical flume, an open channel constructed of stainless steel, was fitted with an FW-1 water level recorder.

### Experimental Design

A balanced factorial design was used to establish two study blocks (replicates) of four plots (treatments). Replicates of four soil surface treatments were established on the plots including two control plots with no biological activity (BARE), two with vegetation (VEG), two with gopher introduction (GOPHER), and two plots with vegetation and gopher (VEG&GOPH).

### Treatment Application

The VEG plots were seeded to 26 g $m^{-2}$ alfalfa (*Medicago sativa* L.) and 2 g $m^{-2}$ barley (*Hordeum vulgare* L.). Barley was selected as an annual plant that establishes cover and root systems quickly thus exerting its effect as a treatment relatively early in the study. Alfalfa was selected as a plant that would exert the longer term effects of a perennial. All plots were fertilized with 18-26-6 (N-P-K) at 45 g $m^{-2}$.

Shortly after seedling establishment, 4.5 kg $^{133}Cs$, as Cs chloride, was dissolved in 100 L of water, and the 100 L of solution was sprayed onto each of eight study plots (172 $gm^{-2}$) using a calibrated, nozzle-hooded power sprayer. In order to have a clear representation of Cs distribution that was not subject to inaccuracy caused by analytical sensitivity, a quantity of Cs was chosen based on previous experience that could be easily detected for at least 1.5 yr. The depth of solution penetration was estimated at 18 cm.

Pocket gophers were live-trapped from adjacent areas using traps similar to those described by Hart (1973). Thirty days after seeding VEG and VEG&GOPH plots, a single pocket gopher was introduced into each GOPHER and VEG&GOPH plot. Corrugated metal used to form the walls of the plots were buried 0.15 m as borders to prevent gopher escape. Gopher diet was supplemented with an artificial diet of protein pellets and root crops. Carrot (*Daucas carota* L.), potato (*Solanum tuberosum* L.), and turnip (*Brassica rapa* L.) were buried systematically in a grid pattern in an attempt to simulate burrowing activity throughout plots. The visual appearance of mounds and the disappearance of the supplied food materials was used as an indication of animal activity.

A rotating boom rainfall simulator (Howard Larsen, USDA-

ARS, Tumbstone, AZ; Renard, 1985) was used to apply 6 cm of water (2 $m^3$ total) to each plot over a 1-h period at 0.5, 1, 2, 3, 10.25, 12.5 and 14.25 mo after the soil was tagged with Cs. In the region of the study area, a rainfall intensity of 1.5 cm per 15 min has a return period of 3 yr (Bowen, 1990). The artificial rainfall intensity simulated these high intensity natural rainfalls. Intensities in this range are the most likely to mobilize contaminants on soil surfaces or in exposed landfills.

The first rainfall event (0.5 mo post-Cs application) was 2 wk prior to gopher introduction. The event was performed as a soil conditioning run. Since gophers had not been introduced and vegetation was not fully established; i.e., the biointrusion treatment was not yet affecting Cs erosion, data from that event were not included in computation of the results where the main effect was being measured.

The slope of the plots (5%) directed runoff to the runoff catchment troughs at the downhill end of each plot. The catchment trough, extending the entire width of the plot, then channeled runoff through the central downspout to the flume, which has a capacity of approximately 4 L $s^{-1}$. Thus, the FW-1 recorder plotted instantaneous and cumulative runoff hydrographs.

Just prior to each rainfall simulation event, plots with vegetative cover were mowed to a height of 10 cm (and all clippings removed), resulting in an average vegetative cover of about 30% during each rainfall event.

### Cesium and Sediment Sample Collection, Preparation, and Analysis

After runoff hydrographs had stabilized, between 10 and 20 min into each 1 h long rainfall, a 1-L sample of surface runoff (liquids and solids) was collected at the outflow from the flumes. A second steady-state sample was collected at about 50 min into an event. These were considered subsamples. Sediment in each sample was separated from liquids, dried, and sieved into the following size range fractions: <53 μ (silt/clay), 53 to 105 μ (very fine sand), 106 to 246 μ (fine sand), 247 to 499 μ (medium sand), and >500 μ (coarse sand). Particles collected on each sieve were dried and the mass of each fraction was determined using an analytical balance (Sejkora and Alldredge, 1989). Cesium was measured by neutron activation followed by photon counting for the 605 KeV gamma ray from $^{134}Cs$ with a NaI (Tl) detector coupled to a multi-channel analyzer. Cesium concentration was recorded and Cs mass was computed as the product of sediment mass and Cs concentration.

Approximately 14 mo after Cs application, soil samples were collected from four soil depth ranges (SDR): 0.1 to 7.5 cm (SDR1), 7.6 to 15.0 cm (SDR2), 15.1 to 22.5 cm (SDR3), and 22.6 to 30.0 cm (SDR4), and analyzed for Cs concentration. Cesium was measured by neutron activation followed by photon counting for the 605 KeV gamma ray from $^{134}Cs$ with a NaI (Tl) detector coupled to a multi-channel analyzer.

### Data Analyses

Cesium data were analyzed for treatment effects using one-way and multi-way analysis of variance. Differences between treatment means were evaluated for statistical significance using Duncan's New Multiple Range Test. Normal, log/normal and log/log linear regression analyses were performed to examine relationships between Cs surface loss and the independent variables time and cumulative applied rainfall.

## RESULTS AND DISCUSSION

## Surface Transport

### Main Treatment Effect

Notes: (i) As previously noted Cs data from the first rainfall, an event intended to condition the soil to simulated rainfall, were not included in computation of the results where main treatment effect was being measured; (ii) acronyms are used as follows: BARE refers to plots that neither were artificially vegetated nor did they receive gopher introduction; VEG refers to plots on which vegetation was artificially established; GOPHER refers to plots onto which a gopher was introduced and gopher burrowing was verified; VEG&GOPH refers to plots that received both vegetation establishment and gopher introduction.

The main effects of plant and animal surface treatments on Cs loss was significant ($P < 0.05$). Cesium loss was inversely related to the presence of vegetation and animal burrowing. Mean ($n = 2$) Cs loss from BARE plots totalled for Events 2 to 7, 1.4 kg, was the highest of the four main treatment effects (Table 1). Mean ($n = 2$) Cs loss from GOPHER plots, 0.8 kg, was significantly ($\alpha = 0.05$) lower than BARE and significantly higher than VEG, 0.5 kg, and VEG&GOPH, 0.2 kg (Table 1).

Plots with vegetation lost 36% of the Cs that BARE plots did, and vegetation-containing plots (VEG and VEG&GOPH) averaged 32% of the Cs surface loss for plots not treated with vegetative cover (BARE and GOPHER). Vegetative cover was effective at reducing Cs loss as evidenced by a 64% reduction in Cs loss for VEG compared to BARE (Table 1). This treatment effect,

**Table 1. Mean ($n = 2$) $^{133}Cs$ mass (kg) lost and cumulative percentage of Cs recovered (in parentheses) from plots in surface runoff and sediment, and in soil subsurface, following treatment of engineered field test plots for 1.5 yr with four combinations of rodent burrowing (pocket gopher) and vegetative cover (alfalfa-barley mix).**

| | Plot surface treatment | | | |
|---|---|---|---|---|
| Event | Bare | Gopher | Vegetated | Vegetated and Gopher |
| 1 | 0.25 (5.6%) | 0.33 (7.8%) | 0.38 (8.5%) | 0.39 (8.7%) |
| 2 | 0.33 (13.0%) | 0.38 (16.4%) | 0.17 (12.2%) | 0.15 (12.0%) |
| 3 | 0.33 (20.3%) | 0.21 (21.2%) | 0.09 (14.3%) | 0.04 (12.9%) |
| 4 | 0.23 (25.4%) | 0.08 (23.0%) | 0.09 (16.3%) | 0.03 (13.6%) |
| 5 | 0.22 (30.2%) | 0.08 (24.8%) | 0.03 (17.0%) | 0.01 (13.7%) |
| 6 | 0.20 (34.6%) | 0.04 (25.8%) | 0.04 (17.9%) | 0.01 (13.9%) |
| 7 | 0.15 (37.9%) | 0.02 (26.2%) | 0.04 (18.7%) | 0.01 (14.0%) |
| 2–7 Total | 1.4a† (37.9%) | 0.8b (26.2%) | 0.5c (18.7%) | 0.2d (14.0%) |
| Subsurface | 1.17 (63.9%) | 0.98 (47.9%) | 1.83 (59.5%) | 2.68 (73.7%) |

† Subtotals with different letters are different at the 0.05 level of significance.

like that of gophers, was probably related to the effects of vegetative cover on soil erosion as VEG plots had a 72% decrease in soil loss compared with BARE plots (Sejkora and Alldredge, 1989). Most long-term surface transport of contaminants occurs through sedimentation rather through dissolved solution transport. The mechanisms by which vegetation reduces erosion of soil-adhered chemicals or particulates, such as reduction of runoff velocity or protection from raindrop splash erosion, are well known (Laycock and Richardson, 1975; Moneirri et al., 1979; Dreicer et al., 1983).

Plots containing only gopher burrowing as the surface treatment averaged 57% less Cs loss than control plots (BARE). This may have resulted from several factors. Gopher-containing plots had 21% less hydrologic surface runoff and 42% less soil erosion than did plots without gophers (Sejkora and Alldredge, 1989). Since most long-term surface transport of nuclides occurs through sedimentation rather than dissolved solution transport, the influence of gophers on soil erosion was likely more responsible for the reduction in Cs loss than other factors.

Secondly, when gophers burrow they push and throw subsurface soil to the surface. This could (i) dilute the Cs initially concentrated at the surface by mixing untagged subsurface soil or subsurface soil lower in Cs concentration with Cs-tagged surface soil and (ii) cover surface-deposited Cs with untagged soil mounds making the Cs unavailable for erosion. Data on Cs concentration in eroded soil generally supports this latter explanation. Plots containing gophers averaged 18% lower Cs concentration on eroded soil than on plots with no gophers. Cesium concentration values for the silt/clay (S/C) fraction averaged for Events 2 to 7 were $4.9^{a}$, $5.1^{a}$, $4.0^{b}$, and $4.2^{b}$ kg Cs $kg^{-1}$ S/C soil for BARE, VEG, GOPHER, and VEG&GOPH, respectively.

Finally, gophers established a series of underground tunnels that extended to soil surfaces. These tunnels probably channeled surface-applied Cs to soil subsurfaces, making the chemical unavailable to surface erosion processes, further explaining a lower mass of Cs loss from gopher-containing plots. These effects would apply to many surface deposited contaminants (Findley et al., 1975).

Treating plots with both vegetative cover and gopher introduction appears to have affected Cs loss in an additive manner; i.e., the difference in Cs mass lost between VEG&GOPH and BARE ($\Delta$ − 1.2 kg) was approximately equal to the sum of the differences for VEG and GOPHER (−1.3 kg). As discussed above, however, the mode by which vegetative cover and gopher burrowing affect Cs loss is different.

## Temporal Cesium Loss

Understanding how time affects contaminant distribution is important to building models that estimate contaminant fate in real environments (Dahlman et al., 1980). In this study, the influence of time on Cs surface loss was highly significant ($F$ = 69.0). Figure 1 shows the change in Cs surface loss summed for each main treatment over the duration of the study.

After large changes in Cs loss initially, the plots in Fig. 1 are generally parallel, indicating no major differences in the rate of loss in Cs among treatments. The large change that occurred from the first to the second event was probably caused by a flush of relatively mobile Cs during the first event. From the first to the second event, vegetated plots (VEG and VEG&GOPH) experienced a substantial decrease in Cs loss (−58%) whereas nonvegetated plots experienced an increase (+18%; Table 1). This may indicate that vegetation was exerting its effect since at least the second artificial rainfall, which occurred 1 mo following Cs application. Following the first event, most Cs was probably adsorbed onto soil particles, especially the silt and clay fraction (Nyhan et al., 1990; Marshall and Holmes, 1979). Thus, transport of Cs from Event 2 forward would have occurred largely as transport of the soil material to which it was bound. Cesium concentration on surface-eroded soil was about equal for all treatments by the time of the second event, but Cs mass was substantially different among treatments (Table 1). This may be evidence that the influence of the main treatments on soil erosion was the dominant factor in controlling Cs loss from plot surfaces.

## Soil Particle Size Effects

It has long been known that distribution of contaminants in soils is largely influenced by soil total surface area and surface charge of soil particles compared with contaminants. In this study, isolating Cs concentration and eroded sediment by soil particle size within each of the four surface treatments might show the influence that particle size distribution had on Cs distribution. The relative contribution to Cs concentration by the S/C soil particle fraction over time is presented in Table 2. Summed across time, the S/C fraction accounted for relatively large proportions of Cs concentration. This is also true for sediment loss on which Sejkora and Alldredge (1989) reported that of the total sediment eroded, the S/C fraction accounted for 24%, 46%, 58%, 55%,

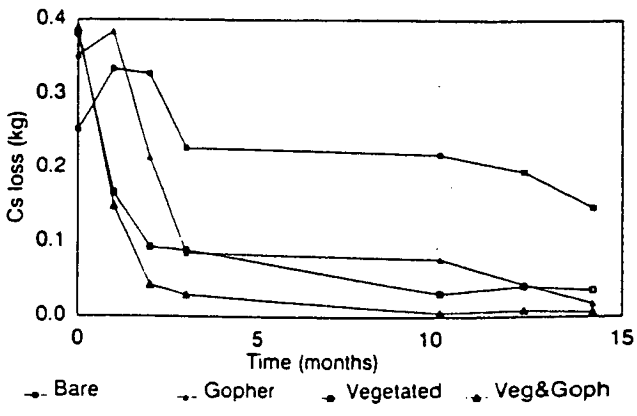


Fig. 1. Cesium-133 loss (kg) from plot surfaces as a function of time for each of four combinations of plot treatment. Treatments consisted of gopher burrowing and establishment of vegetative cover [alfalfa-barley mix]. Time units represent number of months after Cs was surface applied. Cumulative artificial rainfall values corresponding to time values are 0.6, 1.2, 1.8, 2.4, 3.0, 3.6, and 4.2 cm. Analysis of variance results are presented in Table 1.

**Table 2.** Proportion (%) of surface-eroded Cs concentration contributed by the silt-clay soil fraction of sediment collected during seven simulated rainfalls following surface-application of $^{137}$Cs and treatment with gopher burrowing and vegetative cover for 1.5 yr.

| Event | Plot surface treatment | | | | |
|---|---|---|---|---|---|
| | Bare | Gopher | Vegetated | Vegetated & Gopher | μ |
| | % | | | | |
| 1 | 43 | 48 | 37 | 42 | 42 |
| 2 | 29 | 28 | 26 | 30 | 28 |
| 3 | 28 | 30 | 32 | 31 | 30 |
| 4 | 26 | 29 | 30 | 33 | 29 |
| 5 | 31 | 35 | 34 | 48 | 37 |
| 6 | 36 | 34 | 38 | 48 | 39 |
| 7 | 35 | 64 | 52 | 62 | 53 |
| $\mu_{1-7}$ | 33 | 38 | 36 | 42 | 37 |
| $\mu_{2-7}$ | 31 | 37 | 35 | 42 | 36 |

61%, 69%, and 77% for Events 1 through 7, respectively. It can be assumed that Cs concentration and sediment values associated with the S/C fraction are somewhat underestimated because typically S/C particles aggregate into conglomerates of sand (Hakonson et al., 1984). Although the proportion of Cs loss associated with the S/C fraction increased over time and the S/C fraction accounted for large proportions of Cs loss, total Cs loss decreased through time (Fig. 1). These decreases were caused by reduced sediment concentration in the runoff coupled with the reductions in cesium concentrations related to the presence of vegetative cover and gopher burrowing.

### Relational Explanation of Cesium Transport

Cumulative rainfall was slightly more closely related to Cs surface loss concentration than was time for all surface treatments as measured by linear correlation coefficients ($r$). Cesium surface loss on plots void of gophers (BARE and VEG) best related to cumulative rainfall on a normal linear basis: $r_{BARE} = 0.97$; $r_{VEG} = 0.99$. For plots containing gophers (GOPHER and VEG-&GOPH), linear correlation of the natural log Cs concentration × natural log cumulative rainfall produced the best correlation coefficients: $r_{GOPHER} = 0.99$; $r_{VEG\&GOPH} = 0.99$. Log/normal correlations also produced high coefficients. Interacting additional independent variables did not improve the correlation coefficients. A pattern between season and Cs surface loss concentration was not apparent.

## Subsurface Transport

Vegetation-bearing plots (VEG and VEG&GOPH) had significantly more subsurface Cs (μ = 4.5 kg) at the end of the study than plots without vegetation (BARE and GOPHER, μ = 2.2 kg) (Table 3). This probably is related to surface soil erosion as affected by vegetation. It has long been established that plant cover reduces splash erosion, sheet erosion, and overland water flow (Dreicer et al., 1983; Jones et al., 1984; Nyhan and Lane, 1986). Through these means, vegetation probably reduced overland flow of Cs-containing soil particles, making more Cs that is adhered to soil particles available for movement into the subsoil.

Vegetation-bearing plots also differed in that a higher proportion of their measured subsurface Cs was located in the upper region of the sampled soil profile (Table 3). Ninety-seven percent of subsurface Cs for VEG and VEG&GOPH combined was located in the upper 15 cm of soil (SDR1 + SDR2) compared with 67% for that of BARE and GOPHER combined. This may be explained by soil-plant relationships. In the several days following a rainfall, water potential diffusion gradients from rhizosphere to plant root and plant-soil cation exchange processes may cause ions to concentrate in the rhizosphere (Cataldo, 1987; Russell and Barber, 1960; Crafts and Broyer, 1938). This rhizosphere effect was probably most exerted shortly after Cs application during which some Cs would have existed in solution. During this time in which Cs was retained in the rhizosphere zone as a dissolved ion, it was available for exchange with ions adhered to soil particles. Following this, vertical gradation of Cs presumably occurred throughout the duration of the study.

The relatively low Cs surface loss from gopher-active plots prompted the expectation that high proportions of the applied Cs would be located in the soil subsurface. However, GOPHER subsoils had only 22% of the applied Cs compared with 26, 41, and 60% for BARE, VEG, and VEG&GOPH subsoils, respectively. GOPHER plots also had 15% of their subsurface Cs in the deepest sampled soil unit, 22 to 30 cm, compared with 1.5, 0.6, and 0.8% for BARE, VEG, and VEG&GOPH, respectively. These two results suggest that gophers may have facilitated transport of Cs to greater depths than sampled, 30 cm. Presumably, this occurred by surface-applied Cs being washed into gopher tunnels that then channeled Cs suspensions to depths close to or below 30 cm, from where distribution to deeper zones may have occurred.

Soil moisture data supports the argument that gopher treatment facilitated transport of sediment-bound Cs to the deeper zones of the soil subsurface. The 22 to 30 cm subsoil range had 16.2% moisture for GOPHER plots compared with 15.1, 6.9, and 8.2% for BARE, VEG, and VEG&GOPH, respectively (Sejkora and Alldredge, 1989). Average soil moisture values for the 30 to 90 cm depth were 15.9, 15.2, 7.1, and 8.5% for

**Table 3.** Concentration of Cs (g Cs kg$^{-1}$ soil) in subsurface soil of plots treated with gopher burrowing and vegetative cover for 1.5 yr. Values in parentheses represent the proportion (%) of Cs found in each of four soil depth ranges.

| Surface treatment | Depth, cm | | | | Sum |
|---|---|---|---|---|---|
| | 1.0–7.5 | 7.6–15.0 | 15.1–22.5 | 22.6–30.0 | |
| Bare | 0.385 (44%) | 0.279 (32%) | 0.195 (22%) | 0.013 (2%) | 0.872 |
| Gopher | 0.331 (46%) | 0.081 (11%) | 0.203 (28%) | 0.111 (15%) | 0.726 |
| Vegetated | 1.041 (76%) | 0.294 (22%) | 0.022 (2%) | 0.008 (1%) | 1.365 |
| Vegetated and Gopher | 1.342 (67%) | 0.573 (29%) | 0.066 (3%) | 0.015 (1%) | 1.996 |

GOPHER, BARE, VEG, and VEG&GOPH, respectively. At the 22 to 30 cm depth, plots containing gophers differed from all other treatment plots in proportion of Cs, but differed only from plots containing vegetation for soil moisture. This indicates that soil moisture, and the influence of vegetation on soil moisture, were not the only factors influencing subsurface Cs distribution. That Cs concentration at 22 to 30 cm did not follow the pattern of soil moisture when comparing main treatment effects also supports the concept that Cs translocation was occurring through sedimentation rather than dissolved solution transport.

The presence of vegetation had an influence on how gopher activity affected subsurface Cs distribution. This was evident by examining the relative changes in Cs concentration that occurred between soil depth ranges (SDR; Fig. 2). Both replicate plots of GOPHER experienced substantial Cs increases from SDR2 (7.6 to 15.0 cm) to SDR3 (15.1 to 22.5 cm). The mean increase was 150% (Fig. 2). In comparison, VEG&GOPH and VEG experienced respective mean decreases of 89% and 93% for the same SDR increment. This implies that vegetation was effective in moderating the influence that gophers alone had on the vertical distribution of Cs.

## Cesium Mass Balance

Of the total quantity of Cs applied to plot surfaces, 4.5 kg, 64, 48, 60, and 74% was "recovered" as surface-eroded and subsurface Cs in BARE, GOPHER, VEG, and VEG&GOPH, respectively (Table 1). Plots containing only gophers had the lowest amount of recovered Cs. Fate of unrecovered Cs could have included migration of Cs to depths below that sampled (30 cm), Cs in runoff during natural rainfalls, and minimal uptake by vegetation and gophers.

The total amount of natural rainfall from the time when Cs was applied to the end of the study period was 32 cm. This total occurred in events involving approximately 68 d. In the 4 wk following Cs application, seven of the natural rainfall events produced 0.7, 2.0, 0.7,

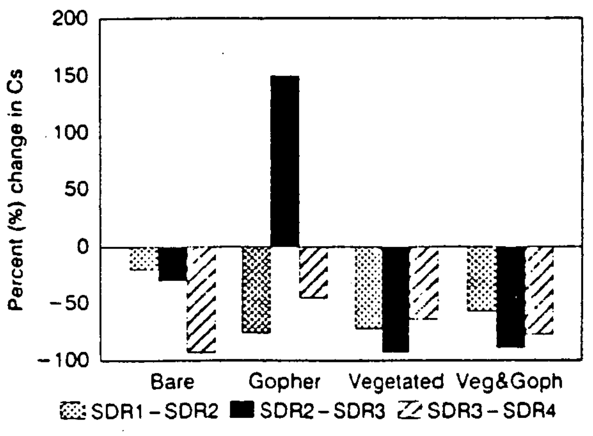


**Fig. 2. Proportional change (%) in $^{133}$Cs concentration between subsurface soil depth range (SDR) increments in engineered field test plots treated with four combinations of animal burrowing and vegetative cover. Soil depth ranges were: 0.1 to 7.5 cm (SDR1), 7.6 to 15.0 (SDR2), 15.1 to 22.5 (SDR3), and 22.6 to 30.0 cm (SDR4).**

1.1, 1.4, 1.3, and 2.5 cm within a 24-h period. Although the intensities of the natural rainfall events are unknown, averaged over 1 h the natural events noted above were >1.5 cm per 15 min. This was the intensity at which artificial rainfall was applied and which was capable of eroding soil-bound Cs. In the region of the study area, natural rainfall intensities of 1.5 cm per 15 min have a return period of 3 yr (Bowen, 1990). Thus, some loss of unrecovered Cs likely occurred through erosion during natural rainfall; however, because the intensities of the natural rainfalls that occurred during the study period are unknown, loss of unrecovered Cs through sediment transport during natural rainfalls cannot be estimated.

## CONCLUSION

Under conditions of high-intensity rainfall, proportionately more surface-applied Cs migrated to deeper soil zones in gopher-active plots than in plots without gophers. Gopher activity facilitated the movement of Cs to the soil subsurface from which further translocation may have occurred to depths below that measured in this study. Gopher tunnels probably channeled surface Cs to soil subsurfaces, explaining the relatively low measurements of Cs surface loss from gopher-containing plots compared with the control. Vegetation moderated the effect that gopher activity had on Cs surface loss and vegetation generally concentrated subsurface Cs at the plant rhizosphere depth. The net effect of these results is that relatively more soil-adhered contaminants deposited on the surface of waste burial caps where vegetation is present can be expected to remain on or in the burial zone, and would be more subject to leaching if gophers inhabit the site.

Perhaps most applicable are the results obtained where both vegetation and gopher activity were present because this treatment most closely represents the type of near-term conditions that exist on actual older waste burial systems at LANL. Excluding the initial event, plots treated with both vegetative cover and gopher burrowing lost surface Cs at an average rate of 17.6 g of Cs per centimeter of applied rainfall. Also, these plots had the highest recoverability of surface-applied Cs. These data may provide distribution coefficients for models on soil contaminant migration pathways, and risk assessments where contaminated soil is being affected by gopher burrowing.

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