Title

Radionuclide transport from soil to air, native vegetation, Kangaroo Rats and grazing cattle on the NTS. Describes uptake of radionuclides, especially Plutonium, from soils to plants, to native mammals and grazing cattle.

Author

Various

101565

Document Date

12/30/88

ERC Index number

05.09.609

Document Type

Published Article (scientific or technical journals)

Box Number

1666-1

Recipients

Scientific Communities

Health Physics Vol. 55, No. 6 (December), pp. 869–887, 1988
Printed in the U.S.A.

0017-9078/88 $3.00 + .00

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● *Paper*

RADIONUCLIDE TRANSPORT FROM SOIL TO AIR, NATIVE VEGETATION, KANGAROO RATS AND GRAZING CATTLE ON THE NEVADA TEST SITE*

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(*Received* 12 *May* 1987; *accepted* 4 *September* 1988)

***Abstract*—Between 1970 and 1986 the Nevada Applied Ecology Group (NAEG), U.S. Department of Energy, conducted environmental radionuclide studies at weapons-testing sites on or adjacent to the Nevada Test Site. In this paper, NAEG studies conducted at two nuclear (fission) sites (NS201, NS219) and two nonnuclear (nonfission) sites (Area 13 [Project 57] and Clean Slate 2) are reviewed, synthesized and compared regarding (1) soil particle-size distribution and physical-chemical characteristics of $^{239+240}$Pu-bearing radioactive particles, (2) $^{239+240}$Pu resuspension rates and (3) transuranic and fission-product radionuclide transfers from soil to native vegetation, kangaroo rats and grazing cattle.**

The data indicate that transuranic radionuclides were transferred more readily on the average from soil to air, the external surfaces of native vegetation and to tissues of kangaroo rats at Area 13 than at NS201 or NS219. The $^{239+240}$Pu resuspension factor for undisturbed soil at Area 13 was three to four orders-of-magnitude larger than at

* This research was supported by the Nevada Applied Ecology Group, U.S. Department of Energy, Nevada Operations Office, Las Vegas, NV.

NS201 and NS219, the geometric mean (GM) vegetation-over-soil $^{239+240}$Pu concentration ratio was from ten to 100 times larger than at NS201, and the GM GI-over-soil, carcass-over-soil and pelt-over-soil $^{239+240}$Pu ratios for kangaroo rats were about ten times larger than at NS201. These results are consistent with the finding that Area 13, compared with NS201 or NS219, has a higher percentage of radioactivity associated with smaller soil particles and a larger percentage of resuspendable and respirable soil. However, the resuspension factor increased by a factor of 27 at NS201 when the surface soil was disturbed, and by a factor of 12 at NS219 following a wildfire.

The average (GM) concentration of $^{239+240}$Pu for the GI (and contents) of Area 13 kangaroo rats and for the rumen contents of beef cattle that grazed Area 13 were very similar (400 vs. 440 Bq kg^{-1} dry wt, respectively) although the variability between individuals was very large. The GM carcass-over-GI $^{239+240}$Pu concentration ratio for kangaroo rats at Area 13, Clean Slate 2, and NS201 were similar in value ($\sim 2 \times 10^{-2}$), as were the GM GI-over-vegetation concentration ratios ($\sim 2 \times 10^{0}$) (no statistical differences). The GM carcass-over-GI ratio for Area 13 kangaroo rats (2×10^{-2}) was 30 times larger (statistically significant) than the approximate calculated GM carcass-over-rumen concentration ratio (7×10^{-4}) for the beef cattle that grazed Area 13, indicating the possibility of greater transfer of $^{239+240}$Pu to tissues of kangaroo rats than to tissues of beef cattle.

At NS201, the data indicated that the bioavailability of radionuclides to the carcass of kangaroo rats was ^{90}Sr > ^{137}Cs > ^{238}Pu > ^{241}Am > $^{239+240}$Pu. The GM carcass-over-GI ratio for ^{90}Sr was about six times larger than for ^{137}Cs, about 30 times larger than for ^{238}Pu and about 60 times larger than for ^{241}Am and $^{239+240}$Pu (statistical differences). Also, the GM $^{239+240}$Pu-over-^{238}Pu ratios for pelt and GI were three to four times larger (statistically significant) than that for carcass, and the GM $^{239+240}$Pu-over-^{241}Am ratio for pelt was about two times larger (statistically significant) than that for carcass.

INTRODUCTION

THE NEVADA Applied Ecology Group (NAEG) conducted environmental radionuclide studies on the Nevada Test Site (NTS), the Tonopah Test Range and the Nellis Bombing and Gunnery Range between 1970 and 1986. The objectives of the NAEG included determining concentrations of radionuclides in ecosystem components (soil, air, native vegetation, small mammals and grazing cattle), quantifying the rates that radionuclides move from soil to the other components and developing radionuclide transport and dose-to-man models.

In this paper we focus on NAEG studies conducted at Nuclear Sites 201 and 219 and nonnuclear sites Area 13 (Project 57) and Clean Slate 2, all of which are in Great Basin desert environments. At nuclear sites, a nuclear device was detonated causing a nuclear reaction with accompanying very high temperatures and local contamination by fission and activation products and by residual transuranic radionuclides. At nonnuclear (safety-shot) sites, chemical explosions dispersed transuranic contamination, but little if any fission or activation-product contamination was produced. Data from the two nuclear and two nonnuclear sites are synthesized and compared here regarding soil physical-chemical characteristics and soil particle-size distributions, resuspension factors and the transfer of transuranic and fission-product radionuclides from soil to native vegetation, kangaroo rats (*Dipodomys* spp.) and grazing cattle. This synthesis should be useful for the continuing development of radionuclide transport and dose models for the NTS environs.

This paper complements a recent paper (Gilbert et al. 1988) that estimated the fraction of $^{239+240}$Pu transferred from soil to muscle, bone and other tissues of grazing cattle, and a paper (Romney et al. 1987b) that reviewed findings on the distribution and availability of $^{239+240}$Pu and ^{241}Am at NAEG nonnuclear study sites. Those readers requiring detailed information about NAEG studies should consult Howard (1984) and the NAEG technical reports referenced here. A listing of NAEG journal papers and technical reports is given in Chilton and Cox (1988).

The NAEG studies form a valuable baseline for the Basic Environmental Compliance and Monitoring Program (BECAMP) that was initiated in 1986 by DOE, Nevada Operations Office, to assess changes over time in the radiological and ecological condition of the NTS and surrounding areas. BECAMP studies will also provide information needed for compliance with environmental laws dealing with hazardous wastes, endangered plant and animal species and the preservation of historic sites.

As the analytical method used did not separate the Pu isotopes, ^{239}Pu is used here to represent the combination of ^{239}Pu and ^{240}Pu.

STUDY AREAS

Nuclear Site 201 (NS201), also known as Little Feller II, is located in Area 18 on the NTS in an arid region of steep hill slopes, drainage channels, rock outcrops, rocky soils and low growing shrubs. In 1962, a very low yield nuclear device was detonated near the ground surface, resulting in an elongated pattern of soil and vegetation radionuclide contamination. The spatial pattern of ^{241}Am concentrations in surface soil (0- to 5-cm depth) was estimated by Gilbert and Simpson (1985) (shown here in Fig. 1) and by McArthur and Meed (1988). The estimated patterns for ^{239}Pu + ^{241}Am and ^{137}Cs in surface soil (given by Gilbert et al. 1987) are similar to that for ^{241}Am.

Nuclear Site 219 (NS219), also known as Palanquin, is located on Pahute Mesa in the northern part of the NTS. The area is characterized by rolling mesa tops consisting primarily of lava outcroppings interspersed with shallow alluvial soils (O'Farrell and Sauls 1987). In 1965, a small nuclear device that had been buried in hard volcanic rock was exploded. The explosion created a crater, and some radioactivity was released aboveground, causing radiation damage or death to shrubs in an elongated 3-km^2 area north of the detonation point (ground zero; GZ) in patterns described by Rhoads and Platt (1971).

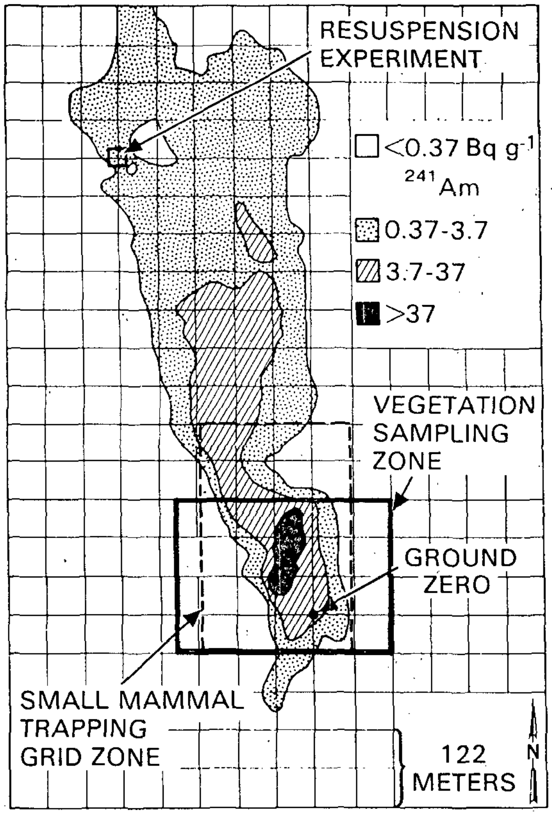


Fig. 1. Estimated concentration contours of ^{241}Am in surface soil at NS201 as determined from ^{241}Am concentrations in soil samples. Also shown are the location of vegetation, small-mammal and resuspension studies. Adapted from Fig. 10 in Gilbert and Simpson (1985).

This damaged area became a grassland of perennial and annual grasses. The spatial patterns of ^{239}Pu + ^{241}Am and ^{90}Sr concentrations in surface soil were estimated by Gilbert et al. (1987) and McArthur and Meed (1988).

Area 13 is a flat, arid, treeless region within Emigrant Valley on the Nellis Bombing and Gunnery Range northeast of the NTS. In 1957, at the Project 57 site, an assembly of nuclear materials was dispersed with a chemical explosion at ground level. The estimated spatial pattern of ^{241}Am contamination in surface soil is shown in Fig. 2. The pattern for ^{239}Pu, which is very similar to that for ^{241}Am, was estimated by Delfiner and Gilbert (1978). The results of an aerial radiological survey of Area 13 for ^{241}Am and ^{239}Pu were reported by Fritzsche (1979). Shrubs are the dominant vegetation type (Romney et al. 1974).

Clean Slate 2 is located on Cactus Flat north of the NTS on the Tonopah Test Range. This region is flat, arid, sandy and treeless, with low-growing shrubs and grasses (Romney et al. 1975). In 1963, an explosive device was detonated near to an assembly of Pu at the ground surface. The spatial patterns of ^{241}Am and ^{239}Pu concentrations in surface soil have been estimated from soil (Gilbert et al. 1975) and aerial (Jobst 1979) measurements.

METHODS AND DATA

Soil

The NAEG collected soil samples to estimate the spatial pattern and inventory of radionuclides in surface soil and to study the relationships among radionuclide concentrations in soil, air, vegetation, small mammals and cattle. In this paper the study of relationships is emphasized.

At NS201, surface-soil samples were collected at more than 700 locations on a variable-size grid pattern that ranged from 7.6-m spacing near GZ to 61-m spacing at greater distance from GZ (see Fig. 1 in Gilbert et al. 1987). Samples were obtained using a 12.7-cm diameter by 5-cm-deep sampling ring inserted flush into the soil. Analytical results from these samples were used to estimate the spatial pattern of ^{241}Am shown in Fig. 1 and the spatial patterns of ^{137}Cs and ^{239}Pu + ^{241}Am reported by Gilbert et al. (1987). In this paper we use only the soil samples that were collected at locations within the vegetation sampling zone (Fig. 1). The ^{239}Pu and ^{137}Cs concentrations for these soil samples are plotted in Fig. 3.

At NS219, 89 samples were collected on a variable-size grid pattern (122-m spacing near GZ, 488-m spacing at greater distance; Gilbert et al. 1987, Figs. 18 and 19) using the same methods that were used at NS201. At Area 13 and Clean Slate 2, 180 and 88 soil samples, respectively, were collected at randomly selected locations within geo-

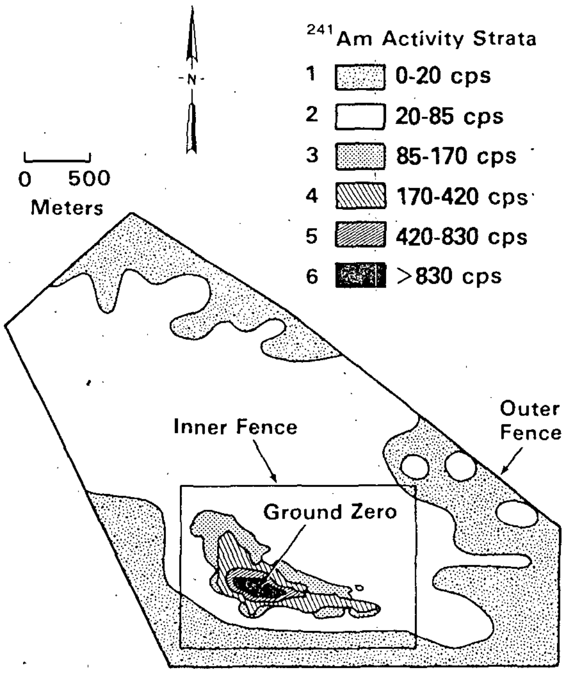
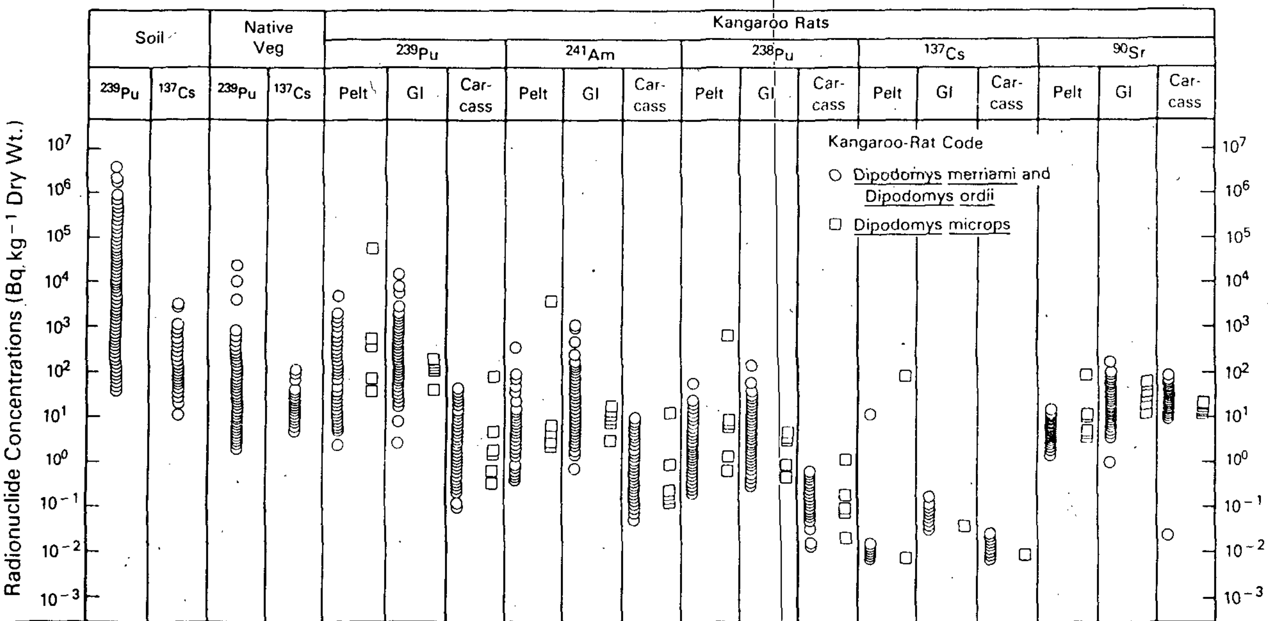


Fig. 2. Americium-241 activity (counts per second [cps]) strata for surface soil at Area 13 (Project 57) as determined using the FIDLER (*F*ield *I*nstrument for the *D*etection of *L*ow *E*nergy *R*adiation) in-situ detector (Tinney 1968) held at 0.3-m height above the ground surface. Adapted from Fig. 5 in Gilbert and Eberhardt (1974).

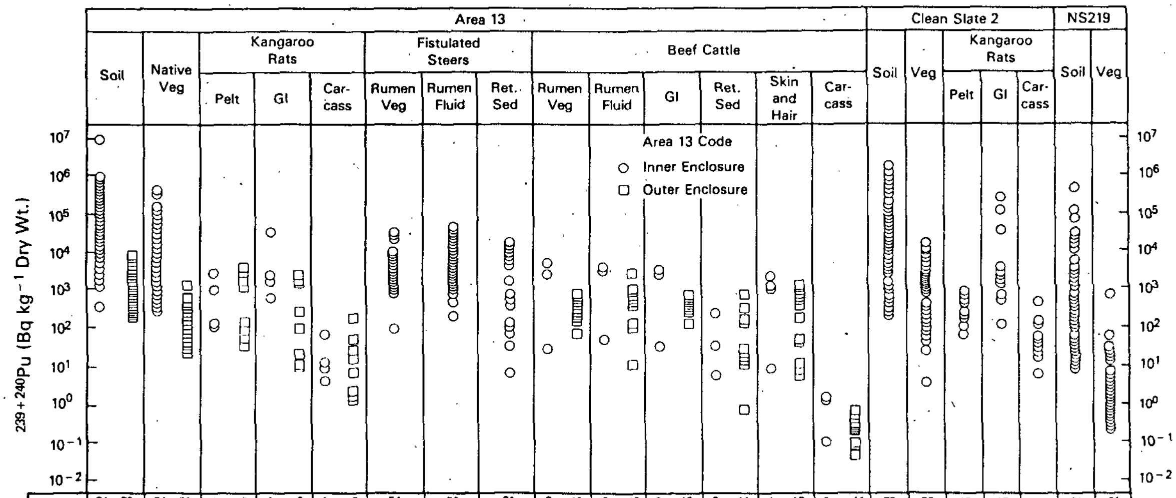


	Soil ^{239}Pu	Soil ^{137}Cs	Native Veg ^{239}Pu	Native Veg ^{137}Cs	^{239}Pu Pelt	^{239}Pu GI	^{239}Pu Carcass	^{241}Am Pelt	^{241}Am GI	^{241}Am Carcass	^{238}Pu Pelt	^{238}Pu GI	^{238}Pu Carcass	^{137}Cs Pelt	^{137}Cs GI	^{137}Cs Carcass	^{90}Sr Pelt	^{90}Sr GI	^{90}Sr Carcass
n	87	61	87	61	53 6	53 6	53 6	36 5	53 6	50 6	52 6	51 6	48 6	12 2	10 1	11 1	53 6	52 6	53 6
GM ○	6200	140	30	8.4	46	110	1.3	7.2	17	0.30	1.3	4.0	0.14	0.028	0.081	0.026	5.8	21	22
GM □					180	72	1.7	20	9.1	0.27	4.4	2.5	0.12	0.81	0.049	0.0096	12	32	17
GSD ○	24	3.5	6.3	1.7	5.4	5.5	4.2	5.7	4.9	3.5	3.7	3.6	2.5	17	1.6	9.8	1.7	2.5	2.9
GSD □					16	1.9	7.0	23	1.9	5.6	14	2.5	3.8	760	---	---	3.3	1.8	1.1
GSE ○	1.4	1.2	1.2	1.1	1.3	1.3	1.2	1.3	1.2	1.2	1.2	1.2	1.1	2.3	1.2	2.0	1.1	1.1	1.2
GSE □					3.1	1.3	2.2	4.1	1.3	2.0	2.9	1.5	1.7	109	---	---	1.6	1.3	1.0

Fig. 3. Radionuclide concentrations (Bq kg^{-1} dry wt) for soil, native vegetation and tissues of kangaroo rats (*Dipodomys* spp.) at NS201 (1 Bq = becquerel = 1 s^{-1} = 2.7×10^{-11} Ci), n = number of samples or animals, GM = geometric mean (Bq kg^{-1} dry wt), GSD = geometric standard deviation (dimensionless), GSE = geometric standard error (dimensionless). GM = exp($y$bar), GSD = exp(s), GSE = exp($s/\sqrt{n}$), where $y$bar and s are the arithmetic mean and standard deviation, respectively, of the natural logarithms of the data. The GM estimates the median concentration. The GSD and GSE characterize the multiplicative variability of the measurements and of the estimated GM, respectively. The GSE may be used to place confidence intervals on the GM (Gilbert 1987). The soil and vegetation data are for locations within the vegetation sampling zone (Fig. 1) where radionuclide measurements were made for both soil and vegetation.

graphical ^{241}Am activity strata. The Area 13 strata are shown in Fig. 2. The strata for Clean State 2 were reported by Gilbert et al. (1975). The ^{239}Pu concentrations for soil samples collected at vegetation sampling locations at Area 13, Clean Slate 2, and NS219 are plotted in Fig. 4. Table

four surface-soil samples and one profile at NS219 and 12 surface samples at Area 13). The profiles at NS201 were collected within the vegetation sampling zone (Fig. 1). The samples at NS219 were at distances of from 383 m to 3979 m down the fallout plume from GZ. At Area



		Area 13 Soil	Area 13 Native Veg	Area 13 Kangaroo Rats Pelt	Area 13 Kangaroo Rats GI	Area 13 Kangaroo Rats Carcass	Area 13 Fistulated Steers Rumen Veg	Area 13 Fistulated Steers Rumen Fluid	Area 13 Fistulated Steers Ret. Sed	Area 13 Beef Cattle Rumen Veg	Area 13 Beef Cattle Rumen Fluid	Area 13 Beef Cattle GI	Area 13 Beef Cattle Ret. Sed	Area 13 Beef Cattle Skin and Hair	Area 13 Beef Cattle Carcass	Clean Slate 2 Soil	Clean Slate 2 Veg	Clean Slate 2 Kangaroo Rats Pelt	Clean Slate 2 Kangaroo Rats GI	Clean Slate 2 Kangaroo Rats Carcass	NS219 Soil	NS219 Veg
n		84 50	84 50	4 9	4 9	4 8	54	56	21	3 12	3 13	3 12	3 11	4 13	3 11	75	75	15	15	14	61	61
GM	○	57,000	6600	360	2600	13	3200	4000	610	760	790	790	34	390	0.58	28,000	790	260	2500	45	610	1.8
	□	1100	180	380	170	11				330	220	380	32	160	0.23							
GSD	○	5.8	4.7	4.9	5.5	3.2	2.7	3.5	7.7	16	12	14	6.4	13	4.4	8.9	6.1	2.2	8.5	2.9	13	5.0
	□	2.6	2.5	6.3	9.9	5.5				2.0	9.7	1.7	6.9	7.2	2.4							
GSE	○	1.2	1.2	2.2	2.3	1.8	1.1	1.2	1.6	5.0	4.1	4.5	2.9	3.6	2.4	1.3	1.2	1.2	1.7	1.3	1.4	1.2
	□	1.1	1.1	1.8	2.1	1.8				1.2	1.9	1.2	1.8	1.7	1.3							

Fig. 4. Plutonium concentrations (Bq kg^{-1} dry wt) for soil, native vegetation, fistulated steers, beef cattle, and kangaroo rats (*Dipodomys microps*) at Area 13, Clean Slate 2 and NS219. *n*, GM, GSD and GSE are defined in the caption of Fig. 3. GI for a beef cow is the mean of its rumen vegetation and rumen fluid concentrations. Carcass for a beef cow is 0.75(muscle concentration) + 0.25(bone concentration) (see text). Soil and vegetation data are for locations within the vegetation sampling zone (Fig. 1) where ^{239}Pu was measured for both soil and vegetation. Outer-enclosure Area 13 kangaroo rats had centers of activity in strata 1 or 2. Inner-enclosure kangaroo rats had centers of activity in strata 3 or 4 (Fig. 2).

Air

At NS201, soil resuspension experiments were conducted at a location 732-m north and 305-m west of GZ (Fig. 1) (Shinn and Homan 1982). The experiments were conducted from 21 August to 22 September 1980 in a region chosen for its relatively smooth terrain and uniform ^{239}Pu and ^{241}Am soil concentrations and ease of access from improved roads. Three high-volume (100 m^3 h^{-1}) air samplers and two cascade impactors were used to characterize the ^{239}Pu aerosol for undisturbed and hand-raked soil surfaces. Also, a floorless wind tunnel was used to measure resuspension phenomena under steady-state wind speed conditions. Special radiochemical methods (after Wessman and Leventhal 1977) were used on the air filters to determine ^{239}Pu concentrations using isotope dilution and alpha spectrometry.

At NS219, ^{239}Pu aerosol studies were conducted similarly to those at NS201. One high-volume air sampler and two cascade impactors were located 305-m due north of GZ in an area undisturbed by blast effects. The samples were operated during 1983 (Table 1) to compare with measurements made at the same location in September–October 1977, following a grassland wildfire that had swept through the area.

At Area 13, an ultra-high-volume air sampler (1700 m^3 h^{-1}) was operated for 24-h periods five times each

low soil concentrations south of GZ just outside the outer fence. Also, cascade impactors were used in April and July 1974 near GZ in the inner fenced area. No resuspension data were collected at Clean Slate 2.

Vegetation

At Area 13 and Clean Slate 2, leaves and stems were collected at random places from usually a single shrub at each soil-sample location. At NS201, this same sampling procedure was used at 88 soil-sample locations within the vegetation sampling area shown in Fig. 1. The NS201 vegetation data are shown in Fig. 3. The sampled shrub at each location was selected at random from among the shrubs within 3 m of the soil-sample location. If no shrub was within the 3-m sampling zone, an event that occurred at fewer than 50% of the locations, the nearest shrub was selected.

At NS219, composite perennial bunch-grass samples were collected at most of the 89 soil-sample locations throughout the fallout pattern (Romney et al. 1987a; Gilbert et al. 1987). At each location at NS219, the bunch grass was clipped (down to the crown mat) from several grass clumps and composited. Sample collection dates for all sites are given in Table 1.

All vegetation samples were charred, ashed at 450°, dissolved and assayed for the major γ-emitting radionu-

Table 1. Sample collection dates at study sites NS201, NS219, Area 13 and Clean Slate 2.

Study Site	Soil	Air	Native Vegetation	Kangaroo Rats	Grazing Cattle
NS201	August 1976 to October 1977*	August - September 1980	July 1977	April 1977 to September 1980*	No data
NS219	June - October 1980	September - October 1977† January - December 1983	September 1980	May 1980 to June 1982	No data
Area 13	January - February 1973	February - July 1973	January - April 1973	March 1973 to June 1974	May 1973 to January 1976
Clean Slate 2	November - December 1973	No data	November 1973	March - August 1974 August 1975	No data

* Intermittent sampling over time.
† Following a grassland wildfire.

using methods described by Wessman et al. (1982). In Fig. 3 are shown the vegetation ^{239}Pu and ^{137}Cs measurements for locations at NS201 where both soil and vegetation samples were collected. The vegetation ^{239}Pu data at Area 13, Clean Slate 2, and NS219 are shown in Fig. 4. A vegetation-over-soil radionuclide concentration ratio was computed for each vegetation sample by dividing the vegetation radionuclide concentration by that of the nearest surface-soil sample.

Kangaroo rats

At NS201, small mammals were captured using Sherman live traps arranged in a rectangular grid (16 lines, each with 25 traps; 15.2-m spacing between lines and traps) located in the GZ area (Fig. 1). Radionuclide concentrations were reported by Moor et al. (1976a, 1976b) and Moor and Bradley (1987) for the pelt, the intact gastrointestinal tract and its contents (henceforth denoted by GI) and carcass (all internal organs except the GI) of sacrificed kangaroo rats (*Dipodomys merriami*, *D. ordii* and *D. microps*). Seventy-five percent of the sacrificed animals had been residents for three to six months. The remaining animals were present fewer than three months. Pelts were analyzed for ^{241}Am using γ spectrometry. Radiochemistry was used to determine ^{241}Am for GI and carcass and ^{239}Pu, ^{238}Pu and ^{90}Sr for all three tissues (Fig. 3).

Small-mammal live trapping was conducted at Area 13 and Clean Slate 2 on 3.9-hectare trapping grids of 200 Sherman live traps (Moor and Bradley 1974; Bradley and Moor 1975). These grids covered the GZ areas and contiguous areas of lower radionuclide concentrations. *Dipodomys microps* animals that were residents more than six months were removed for radiochemical analyses of their pelt, GI and carcass. The ^{239}Pu measurements for these tissues are shown in Fig. 4.

Small mammal studies were also conducted at NS219 (O'Farrell and Sauls 1987), but most radionuclide measurements in the sacrificed animals were below measurement detection limits and hence were not used in this paper. At NS201, NS219 and Area 13, the time period of small-mammal trapping overlapped (or nearly so) with that of soil and vegetation sampling.

During autopsy of small mammals, efforts were made to reduce the possibility of cross contamination (Moor and Bradley 1987). These efforts included using a new pair of latex surgeon's gloves for each animal and separate instruments for each tissue. Each pelt, GI and carcass tissue was placed in a separate plastic bag, frozen and shipped in dry ice to the radioanalysis laboratory where the samples were dried, ashed and assayed for the major γ-emitting radionuclides. Carcass-over-GI, carcass-over-pelt and GI-over-pelt ratios of radionuclide concentrations were computed for each animal.

For Area 13, Clean Slate 2 and NS201, tissue-over-soil ratios of ^{239}Pu concentrations for kangaroo rats were obtained to estimate the average tissue-over-soil concentration ratio for each study area as follows. First, we used universal kriging (Barnes et al. 1977; Gilbert and Simpson 1985) on the logarithms of ^{239}Pu concentrations of surface-soil samples to estimate logarithmic-average soil concentrations for 30-m by 30-m blocks at Area 13 and Clean Slate 2 and for 15-m by 15-m blocks at NS201. Second, these block averages were exponentiated to obtain block averages (medians) in the original (untransformed) scale. Third, the tissue radionuclide concentration for each animal was divided by the median soil concentration for the block that contained the animal's computed center of activity (Area 13 and Clean Slate 2) or location of last capture (NS201). The geometric mean (GM, defined in the caption to Fig. 3) of the individual ratios was calculated to estimate the average (median) tissue-over-soil concentration ratio. An analogous procedure was used to obtain GM tissue-over-vegetation concentration ratios.

We note that the GM rather than the arithmetic mean is used throughout this paper to estimate averages of measurements and ratios because it is more robust to (less affected by) a few individual values that are unusually large.

Cattle

As discussed by Gilbert et al. (1988) and in greater detail by Smith (1979), a reproducing herd of beef cattle grazed the Area 13 study site over a three-year period (Table 1). In May 1973, nine pregnant beef cows (three in each trimester of pregnancy) from a control herd pastured near Kingman, AZ, were placed within either an inner-fenced enclosure (one cow) or an outer-fenced enclosure (eight cows) at the study site (Fig. 2). Individuals grazed the enclosures for up to 1064 d. No supplemental feeding was provided, and uncontaminated water was available *ad libitum*. Cattle were periodically removed and sacrificed and samples of muscle, femur, vertebra, liver, kidney, lungs, tracheobronchial lymph nodes, blood cells, blood serum, gonads, skin and hair, rumen vegetation, rumen fluid and reticulum sediment were assayed for ^{239}Pu, ^{241}Am, ^{238}Pu and other radionuclides. These data are given by Smith (1979) and were used by Gilbert et al. (1988) to estimate the fraction of ^{239}Pu that was transferred from soil to the tissues of these cattle.

Diet information (discussed below) was obtained by examining the rumen contents (vegetation and fluid) of grazing cattle at their time of sacrifice and of four rumen-fistulated steers that grazed the inner-fenced enclosure for 24-h periods on 15 occasions at monthly or quarterly intervals during the grazing experiment. The rumen-fistulated steers were placed in Area 13 for a 48-h acclimation period and their rumens were emptied before their 24-h grazing periods began. The ^{239}Pu measurements needed for this paper (rumen vegetation, rumen fluid and reticulum sediment for steers and beef cattle, and skin and hair for cattle) are shown in Fig. 4.

In the Results and Discussion section, we compare carcass-over-GI radionuclide concentration ratios for kangaroo rats with carcass-over-rumen ratios for cattle. Radionuclide measurements of each kangaroo-rat carcass were obtained on the entire carcass as mentioned above. However, as only the major organs of the cattle were sampled and analyzed for radionuclides, we did not have measurements for the total composited carcass of cattle. Therefore, we chose to approximate the carcass concentrations of each sacrificed cow by computing 0.75 $\times$ (muscle concentration) + 0.25 $\times$ (bone concentration), where "bone concentration" was the mean of the femur and vertebra ^{239}Pu concentrations for the cow (no other bones were assayed). (The muscle, femur and vertebra data were reported by Smith [1979] and Gilbert et al. [1988].) The factors 0.75 and 0.25 were obtained by assuming the weight of the skeleton and muscle of cattle was 15% and 45%, respectively, of the total weight of the cow: $45/(15 + 45) = 0.75$ and $15/(15 + 45) = 0.25$. The resulting calculated cattle carcass concentrations are displayed in Fig. 4. As these cattle carcass data are only approximate, the comparisons made below between kangaroo rats and cattle should only be used to generate hypotheses for further study rather than to reach firm conclusions regarding differences or similarities.

Each cow's rumen concentration (needed for estimating rumen-over-soil, rumen-over-vegetation and carcass-over-rumen ratios) was obtained by computing the mean of the rumen fluid and rumen vegetation dry-weight concentrations for the cow. This simple average was used because the rumen-vegetation and rumen-fluid ^{239}Pu concentrations for a cow were usually very similar in value. The computed ^{239}Pu rumen ("GI") concentrations are shown in Fig. 4. The tissue-over-soil and tissue-over-vegetation concentration ratios for each cow were obtained by dividing the tissue concentration of the cow by the area-weighted GM of the measured surface-soil or shrub-vegetation concentrations for the fenced enclosure within which the cow grazed. These area-weighted GMs (areas of strata in Fig. 2) are 13,000 and 1,400 Bq kg^{-1} for the inner and outer enclosures, respectively. The GMs for soil and vegetation shown in Figs. 3 and 4 are unweighted means.

In addition to the grazing study in Area 13, the NAEG conducted laboratory studies on ruminant animals (mostly cattle and swine) concerning the metabolism, alimentary solubility and tissue uptake and distribution of ^{239}Pu, ^{241}Am and other radionuclides (Black and Smith 1984; Smith and Black 1984; Howard 1984; Eisele and Chertok 1987).

In this paper, all rumen-fluid, rumen-vegetation and rumen-sediment radionuclide measurements, as well as all soil-, vegetation-, air-, small-mammal- and cattle-tissue measurements used to compute concentration ratios were on a dry-weight basis. Statistical tests were conducted to assess the statistical significance of observed differences in GMs. This was done using paired and two-sample t tests (Snedecor and Cochran 1980, pp. 85, 97) and Bonferroni t tests (Miller 1966) conducted on the logarithms of the data.

RESULTS AND DISCUSSION

Soil-particle studies

At both NS201 and NS219, studies by Lee and Tamura (1981) and Lee et al. (1987a, 1987b) indicated that most of the radionuclides were incorporated into particles of silicate glass. At NS201, the radioactivity occurred as either spherical glass particles (usually solid) or glass coatings (often containing gas voids) on sand particles. At NS219, the radioactive particles were silicate glass that were sponge-like, highly porous and very fragile. At the Area 13 site, the nonfission explosion did not yield sufficiently high temperatures to produce silicate glass particles. Instead, the ^{239}Pu occurred predominately as high-density oxide particles (Tamura 1975, 1976, 1978).

The soil particle-size fraction containing the most radioactivity was the 2000- to 50,000-μm diameter fraction at NS219, the smaller 100- to 2000-μm fraction at NS201 and the still smaller 20- to 53-μm fraction at Area 13. Information of this type was not obtained at Clean Slate 2. At NS219 and NS201, the respirable soil fraction (<5 μm) contained 1% or less of the total soil radioactivity compared with about 5% at Area 13. Of the samples collected, the maximum percentage of the total-soil radioactivity contained in the resuspendable (<100 μm) fraction was 13% at NS219 (Lee and Tamura 1981) compared with a maximum of 5% for NS201 (Lee et al. 1987a). At Area 13, the mean percentage of total-soil ^{239}Pu in the resuspendable soil fraction was 88% (min = 73%, max = 99%; n = 10) (Tamura 1975, 1976). The 88% value was obtained assuming there was negligible amounts of ^{239}Pu in the >2000-μm fraction (that fraction was not analyzed). This assumption seemed reasonable, since negligible amounts of ^{239}Pu were in the smaller 840- to 2000-μm fraction.

These results indicate Area 13 has more potential for transport of ^{239}Pu via resuspension than NS201 or NS219. Additional evidence for this is the presence of "blow sand" mounds (accumulations of blow sand around the base of shrubs and grass clumps) in Area 13 and Clean Slate 2, but not at NS201 and NS219. Essington et al. (1977) and Gilbert and Essington (1977) reported that these clumps, which result from wind action and the burrowing activities of small mammals, have higher concentrations of transuranic radionuclides than underlying soil or surrounding desert pavement. The soil-profile samples collected in desert pavement areas and in mounds indicated that most ^{239}Pu and ^{241}Am was in the top 5-cm of soil (~95% at Area 13 and NS219; somewhat less at NS201 and Clean Slate 2) (Essington and Fowler 1976; Essington 1982, 1987a, 1987b; Gilbert et al. 1975).

Resuspension studies

The resuspension studies also supported the hypothesis of a higher potential for radionuclide transport at Area 13 than at NS201 or NS219. For ^{239}Pu, the resuspension factor, defined as the ratio of the measured aerosol concentration (Bq m^{-3}) to the total surface-soil contamination level (Bq m^{-2}) was four orders of magnitude larger at Area 13 (9×10^{-9} m^{-1}) than at NS219 (2×10^{-13} m^{-1}) (Shinn et al. 1986), and three orders of magnitude larger than at NS201 (4×10^{-12} m^{-1}) (Shinn and Homan 1982). Also, at NS201 and NS219, Shinn et al. (1986) found that the enhancement factor, defined as the ratio of specific activity in the aerosols (Bq g^{-1} of suspended dust) to specific activity in surface soil (Bq g^{-1} soil), was 0.02 and 0.002, respectively. Enhancement factors for Area 13 and Clean Slate 2 are not available, but this factor at two similar nonnuclear sites on the NTS (the GMX site in Area 5 and Plutonium Valley in Area 11) was reported by Shinn et al. (1986) to be about 1.0. These differences in resuspension and enhancement factors are believed to occur because much, if not most, of the ^{239}Pu at NS201 and NS219 is associated with silicate materials which are not resuspendable (Shinn et al. 1986).

The extent to which these resuspension conclusions depend on the specific locations of the air samplers at the study sites remains to be determined. Also, the resuspension studies were conducted in different years (see Table 1). Hence, differences in rainfall and wind conditions in the different years could account for part of the differences between study sites.

The resuspension results discussed above for NS201 and NS219 are for undisturbed soil surfaces. Evidence was obtained for increased resuspension at these sites when the surface soil was disturbed. At NS201, when the soil surface was hand raked to loosen the soil and to remove the pebbles that formed a desert pavement, the ^{239}Pu aerosol concentration increased by a factor of 27 (to 4×10^{-5} Bq m^{-3}) and the Pu specific activity at 1.2-m height increased by a factor of 18 (to 1.3 Bq g^{-1}) (Shinn and Homan 1982). These same relationships were observed in the wind tunnel at NS201. At NS219, Shinn et al. (1986) found that a grassland wildfire in 1977 increased the ^{239}Pu aerosol-specific activity (Bq g^{-1}) by a factor of three and the ^{239}Pu aerosol concentration by a factor of twelve for a few months during the dry season following the wildfire.

Another mechanism that could potentially increase the resuspension of radionuclides at NS201 and NS219 would be for the radioactive glass particles to be broken down into resuspendable size particles by weathering, traffic or wind erosion. At NS201, Lee et al. (1987a) found that impact grinding of the 0.25- to 2-mm fraction of a 0- to 2.5-cm soil sample for 1 h followed by sieving resulted in 85% of the ^{241}Am being retained with the 0.25- to 2-mm fraction. Only 4% of the ^{241}Am was associated with the <0.125-mm fraction generated by grinding. Lee et al. (1987a) concluded that soil at NS201 might have a lower probability than the soil at NS219 of producing respirable-size radioactive particles by saltation during wind erosion, because Lee and Tamura (1981) found the radioactive particles at NS219 to be very fragile and porous. However, the desert pavement in these areas may prevent saltation from occurring to any great extent. Also, Shinn and Homan (1982) could not detect saltation in the wind tunnel at NS201.

Tamura (1977) developed a soil Pu index to evaluate the potential exposure hazard in terms of resuspension and inhalation of Pu-contaminated particles in soil. The index, defined as the product of a soil activity factor, a lung depositional factor and a resuspendable activity factor, was about ten times larger at Area 13 compared with NS201 or NS219 (Lee and Tamura 1981).

Air-vegetation-soil relationships

Romney et al. (1975) concluded that radionuclide contamination of vegetation in the arid NTS environs is primarily by resuspension processes rather than by root uptake. Hence, areas that have larger resuspension factors should also have larger vegetation-over-soil concentration ratios. If so, we would expect that the average vegetation-over-soil ratio would be higher for Area 13 than for NS201 and NS219, assuming that the estimated resuspension factors at each of these study sites are valid at locations where vegetation samples were collected. The GMs for the vegetation and soil ^{239}Pu data plotted in Figs. 3 and 4 indicate that NS201 and NS219 do have smaller ratios. For Area 13 (Fig. 4), the vegetation GM divided by the soil GM is 6600/57,000 = 0.12 and 180/1100 = 0.16 for the inner and outer enclosures, respectively, as compared with 30/6200 = 0.0048 for NS201 (Fig. 3) and 1.8/610 = 0.0030 for NS219 (Fig. 4).

A closer look at the vegetation-over-soil data for Area 13 and NS201 is made in Fig. 5a, b, c where the vegetation-over-soil ratios of the ^{239}Pu and ^{137}Cs concentrations in Figs. 3 and 4 are plotted versus the soil concentration (the denominator of the ratio). The least-squares equations that were fitted to the data are also shown. These equations were obtained by regressing the natural logarithms of the ratios on the natural logarithms of the paired soil concentrations, then exponentiating the equation. The form

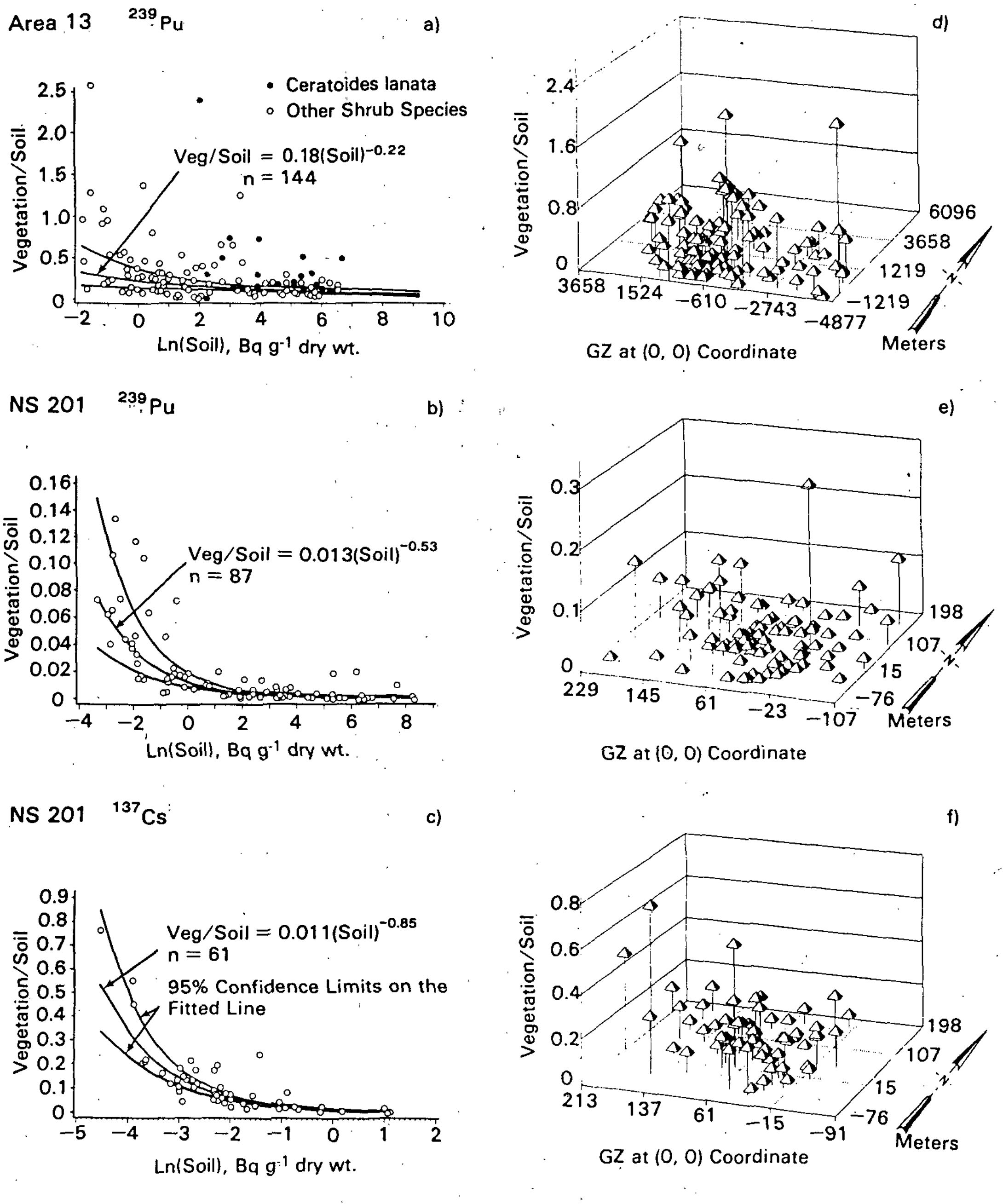


Fig. 5. (a, b, c) Regression of vegetation-over-soil concentration ratios of ^{239}Pu and ^{137}Cs on the ^{239}Pu and ^{137}Cs soil concentrations in the denominator of the ratios for Area 13 and NS201. (d, e, f) Vegetation-over-soil concentration ratios of ^{239}Pu and ^{137}Cs plotted at locations in Area 13 and NS201 where the samples were collected.

of the equations in Fig. 5a, b also applies to ^{241}Am since the correlation between ^{239}Pu and ^{241}Am concentrations for vegetation and soil at NS201 is very high (>0.98), as it is at the other three sites.

In Fig. 5a, b, the data indicates that most vegetation-over-soil ratios of ^{239}Pu concentrations at Area 13 were larger than those at NS201, which is consistent with the higher measured resuspension factor at Area 13. However, different vegetation species were collected at the two sites, which could be a contributing factor to the difference in vegetation-over-soil ratios. Of particular interest in this regard is winter fat (*Ceratoides lanata*), 23 samples of which were collected at Area 13 and none at NS201. This species has hairy fruiting bodies that tend to entrap resuspended soil. Also, the foliage of this plant is covered with a dense coating of star-shaped and unbranched hairs that may trap resuspended soil (Smith 1979). Indeed, Romney et al. (1975) found that the mean ^{239}Pu concentrations for *C. lanata* samples were larger than for samples of other species at Area 13. The vegetation-over-soil ratios for this species (identified in Fig. 5a) are among the larger ratios. However, most of the remaining ratios at Area 13 are still larger than those at NS201, which suggests that species differences alone cannot account for the larger ^{239}Pu vegetation-over-soil ratios at Area 13 compared to NS201.

The least-squares equation in Fig. 5a changes slightly to Veg/Soil = $0.18(\text{Soil})^{-0.30}$ if the *C. lanata* ratios are discarded. Dividing this equation by the NS201 equation for ^{239}Pu in Fig. 5b yields $14(\text{Soil})^{0.23}$. This result indicates that, on the average, the magnitude of the difference in ratios may increase from roughly a factor of ten at locations in both testing areas where the ^{239}Pu concentrations were approximately 1 Bq g^{-1}, to a factor of roughly 40 for locations where the concentrations were about 100 at the locations in Area 13 and NS201 where the paired soil and vegetation samples were collected. The higher ratios occur on the edges of the fallout plume, whether the edge is near or far from GZ. The high ratios on the edge near GZ may be due to wind transport of radioactive particles from the nearby GZ area. Romney et al. (1975) suggested that the high ratios farther down the fallout plume may be because of two related processes: a decrease in the average fallout-particle size with increasing distance downwind from GZ, and smaller particles further from GZ being more readily resuspended and retained on plant surfaces. Partial support for this latter hypothesis was obtained at NS219 by Lee and Tamura (1981), who found smaller radioactive particles at greater distances from GZ. However, Tamura (1975) found relatively uniform-sized particles at all distances from GZ in Area 13. At NS201, samples were not collected at sufficient distances from GZ to provide comparable information.

Another possible explanation for the increase in vegetation-over-soil ratios is that as soil concentrations decrease, root uptake may become a more important vegetation contamination mechanism relative to resuspension processes. However, if this phenomenon is occurring, resuspension processes are believed to be the more important mechanism since the vegetation-over-soil ratios at low soil concentrations are so large.

The vegetation-over-soil results also suggest that the resuspension enhancement factor defined above may change over space. To see this, note that the enhancement factor can be expressed as the product of the air-over-vegetation concentration ratio and the vegetation-over-soil concentration ratio. Hence, assuming equations of the form in Fig. 5a, b, c are applicable, we obtain

$$\text{Enhancement Factor} = (\text{Air/Veg})(\text{Veg/Soil})$$

grass, *Oryzopsis hymenoides*) were preferred (Smith 1979). Forbs usually made up 5% or less of the diet. The three shrub species above also accounted for about 90% of the vegetation samples collected by hand in Area 13.

At Area 13 the dominant captured small mammal was the kangaroo rat *D. microps*, and our analyses here are for the 13 animals of this species that were sacrificed (^{239}Pu data for these animals are in Fig. 4). Although botanical analyses of the GI contents of sacrificed kangaroo rats were not conducted, *D. microps* is known to consume primarily the interior portions of leaves on the upper twigs of *A. confertifolia*, but it may occasionally use leaves of *A. canescens* and *C. lanata* (Kenagy 1972, 1973). *D. microps* also eats seeds and some green plant material (Burt 1934).

It is also known that both kangaroo rats and cattle ingest soil either accidentally from the ground surface during foraging and other activities, or as soil surficially attached to ingested vegetation. Kangaroo rats engage in sand bathing to groom their pelage (Eisenberg 1963; Kenagy 1976), spend most of their time in burrows (Moor et al. 1977) and eat vegetation and/or seeds (Kenagy 1973) to which soil and accompanying radionuclides may be attached. French et al. (1965) estimated that under field conditions, *D. merriami* obtain 70–80% of their internal radionuclide burdens from ingesting contaminated soil particles. They found that the total sand consumed by *D. merriami* from digging and searching in the sand and by grooming their fur was 97 mg d^{-1} in one laboratory experiment and 291 mg d^{-1} in another experiment.

Cattle often roll in the dirt, and they lick off and ingest soil deposited on their snouts (Patzer et al. 1977). Blincoe et al. (1981) found at Area 13 that almost all (>97%) of the Pu ingested by rumen-fistulated steers was ingested with soil from the ground surface or with soil surficially attached to vegetation. Smith (1979) concluded on the basis of a special soil-in-ingesta study of some of the Area 13 cattle that they ingested an average of about 0.25 to 0.5 kg d^{-1} of soil from the soil surface. The amount

inner and outer enclosures (12 and 3, respectively), perhaps the best overall summary is to compare the GI GM for all 13 kangaroo rats with the GI GM for all 15 cattle. These GMs were 400 Bq kg^{-1} (GSE = 2.0) and 440 Bq kg^{-1} (GSE = 1.3) for kangaroo rats and cattle, respectively (not statistically different). Hence, although the variability in these data is high, the GM GI ^{239}Pu concentrations for the sampled cattle and kangaroo rats were very similar in value.

The reticulum sediment concentrations for beef cattle (Fig. 4) are about 10 times smaller than those for rumen GI (statistically different). This difference may be due to the sediment being perhaps composed of the larger and heavier ingested soil particles that contain lower concentrations of ^{239}Pu. Tamura (1976) found that the larger soil-size fractions (those greater than 125 μm geometric diameter) of surface soil contained less than an average of 2.5% of the ^{239}Pu in soil (Gilbert et al. 1988).

The GM ^{239}Pu concentrations for rumen vegetation and rumen fluid (Fig. 4) were ~5-times larger than the GMs for these types of samples for beef cattle (statistically significant differences). The GM reticulum sediment concentration for fistulated steers was also statistically larger. These differences might be due to an increased ingestion of soil by steers because of possibly more vigorous grazing due to their stressed condition (empty rumens) at the start of their 24-h grazing periods.

Fifty-nine kangaroo rats were removed from NS201 and sacrificed: *Dipodomys merriami* (41 animals), *D. ordii* (12) and *D. microps* (6). *Dipodomys merriami* eats primarily seeds in addition to green plants and insects (Soholt 1973; Reichman 1975; Bradley and Mauer 1971). In the spring, *D. merriami* may have a diet of nearly 40% green plant material (Kenagy 1972, 1973). *Dipodomys ordii* also eats seeds and green plants. At NS201, about 50% of the hand-sampled vegetation was *Chrysothamus visidiflorus*, with *A. canescens* and *Chrysothamus nauscosus* each accounting for another 24%. The ^{239}Pu measurements for these animals and the vegetation are given

At Clean Slate 2, *A. confertifolia* and *D. microps* were the dominant vegetation and small-mammal species, respectively, and they were the only species that were collected. Fifteen *D. microps* animals were removed and sacrificed. At NS219, all collected vegetation samples were bunch grasses *Oryzopsis hymenoides* and *Sitanion jubatum*. Figure 4 shows the ^{239}Pu data for collected vegetation at Clean Slate 2 and NS219 and for the *D. microps* samples from Clean Slate 2.

The GM ^{239}Pu concentration for the GI of *D. microps* at Clean Slate 2 (2500 Bq kg^{-1}) (Fig. 4) is similar to that for *D. microps* in the inner enclosure at Area 13 (2600 Bq kg^{-1}) (Fig. 4), but is an order of magnitude larger than at NS201 (72 Bq kg^{-1}) (Fig. 3), a statistically significant difference. The smaller GM at NS201 could be related to possibly less ingestion of ^{239}Pu with soil since the ^{239}Pu at NS201 is associated with silicate materials.

Tissue-over-tissue concentration ratios for kangaroo rats at NS201

In this section we use the kangaroo-rat data in Fig. 3 to compare ^{239}Pu, ^{238}Pu, ^{241}Am, ^{137}Cs and ^{90}Sr as concerns their carcass-over-GI, carcass-over-pelt and GI-over-pelt concentration ratios.

We see from Fig. 3 that, for each data set, the concentrations for the different animals vary over several orders of magnitude. Nevertheless, there are consistent patterns in the data. The GMs indicate that: 1) for all radionuclides except ^{90}Sr, the GM for carcass is smaller than that for GI; 2) carcass concentrations are highest for ^{90}Sr followed by ^{239}Pu, ^{241}Am, ^{238}Pu and ^{137}Cs, in that order; and 3) for *D. merriami* and *D. ordii*, the GI concentrations are higher than pelt concentrations for all radionuclides. A convenient way to summarize these patterns is to compute average concentration ratios. This was done by computing the concentration ratio for each animal and then computing the GM of those ratios. The ratios for the individual animals are plotted in Fig. 6.

The data in Fig. 3 and the ratios in Fig. 6 are for those animals with positive concentration measurements reported by the analytical laboratory (negative measurements were reported for some tissue samples, particularly pelt). The number of ^{137}Cs data is small because a zero ^{137}Cs concentration was reported for most samples. Hence, strictly speaking, the GM ratios for ^{137}Cs in Fig. 6 are for only those sacrificed kangaroo rats that had relatively large ^{137}Cs concentrations.

The GM carcass-over-GI ratio for ^{90}Sr (0.97) was statistically larger than the GM ratios for ^{137}Cs (0.17), ^{238}Pu (0.032), ^{241}Am (0.018) and ^{239}Pu (0.012). Also, the GM carcass-over-GI ratio for ^{238}Pu was statistically larger than the GM ratios for ^{241}Am and ^{239}Pu. This latter result agrees with studies by McLendon et al. (1976), Hanson (1975) and Little (1976) that suggested ^{238}Pu is more biologically available than ^{241}Am or ^{239}Pu. Similar relationships between these isotopes were observed for the carcass-over-pelt ratios (Fig. 6). The smaller GM concentrations of ^{241}Am, ^{238}Pu and ^{239}Pu in carcass compared to pelt is consistent with data obtained by Arthur

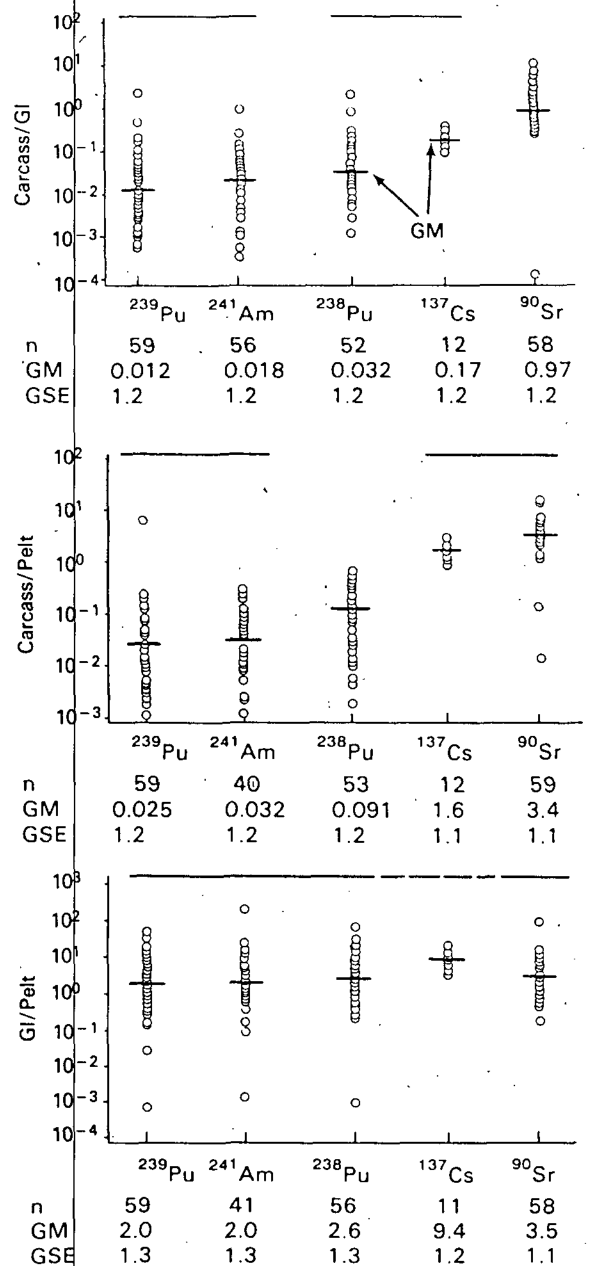


Fig. 6. Carcass-over-GI, carcass-over-pelt and GI-over-pelt ratios of radionuclide concentrations in kangaroo rats (*Dipodomys* spp.) at NS201. A line drawn over two or more data sets indicates no statistical difference ($p > 0.05$) between the geometric-mean ratios for those data sets. These comparisons were made using Bonferroni t tests (Miller 1966) conducted on the logarithms of the ratios.

et al. (1987), Halford (1987), Hakonson and Bostick (1976), Little (1980) and Garten (1981) for small mammals collected in various habitats. The GM GI-over-pelt ratios were all greater than one, and the GM GI-over-pelt ratio for ^{137}Cs was statistically larger than those for the other radionuclides by a factor of four or five. However, since most ^{137}Cs concentrations were reported as zero and hence could not be used here, this statistical difference may not reflect a true difference.

Comparing ^{239}Pu concentration ratios across sites

In this section we compare NS201, Area 13, and Clean Slate 2 with regard to tissue-over-tissue, tissue-over-vegetation (shrub) and tissue-over-soil ratios of ^{239}Pu concentrations for cattle and kangaroo rats. The ^{239}Pu data used to make these comparisons are from Figs. 3 and 4.

Tissue-over-tissue concentration ratios for kangaroo rats and cattle

In Table 2 are shown the GM tissue-over-tissue ^{239}Pu concentration ratios for kangaroo rats at Area 13, Clean Slate 2 and NS201 and for beef cattle at Area 13. The GM carcass-over-GI ratios for kangaroo rats at the three study sites were very similar in value, ranging from 0.012 (NS201) to 0.021 (Area 13), and were not statistically different. The Area 13 GM ratio for kangaroo rats (0.021) was about 30 times larger than the GM carcass-over-rumen ("GI") ratio (0.00073) for cattle at Area 13 (a statistically significant difference). This result leads one to consider a hypothesis that the transfer of ^{239}Pu from the GI to carcass was greater for kangaroo rats than for cattle at Area 13. However, caution is suggested in interpreting these results since, as described in the Methods and Data section, we could only approximate carcass concentrations for cattle.

The GM GI-over-pelt ^{239}Pu concentration ratio for kangaroo rats at Area 13 (GM = 1.1, Table 2) was not statistically different from the GM for Area 13 cattle (2.8) or NS201 kangaroo rats (2.0). However, these GMs were statistically smaller than the GM ratio (9.4) at Clean Slate 2 (Table 2). The larger ratio for Clean Slate 2 was caused in large part by the very large GI concentrations for three animals (see Fig. 4). These animals had centers of activity in the highest soil- and vegetation-concentration region at Clean Slate 2. Also, most of the animals at Clean State 2 had centers of activity in relatively high concentration areas. The GM ratio (9.4) was not statistically different from the GM GI-over-pelt ratio 7.4 (GSE = 1.7) for four animals at Area 13 that had centers of activity in the higher concentration region (inner fenced enclosure; strata 3 or 4; Fig. 2). The GM GI-over-pelt ratio for the nine outer-enclosure animals at Area 13 was 0.46 (GSE = 1.5). These results indicate that kangaroo rats that lived in the more highly contaminated environments at Area 13 and Clean Slate 2 may have had similar GM GI-over-pelt ratios (of size ~ 7–9) that were larger than GM ratios for animals in less contaminated areas. The similarity in GM GI-over-pelt ratios at Area 13 and NS201 reported in Table 2 (ratios of 1.1 and 2.0, respectively) is believed to reflect the fact that most kangaroo rats at those study sites did not live in the more highly contaminated areas.

The GM carcass-over-pelt ^{239}Pu ratio for kangaroo rats at Clean Slate 2 was statistically greater than the GMs

Table 2. Tissue-over-tissue ^{239}Pu concentration ratios for kangaroo rats (*Dipodomys* spp.) and grazing beef cattle at Area 13, NS201 and Clean Slate 2.

	Area 13 Beef Cattle†	Area 13 Dipodomys microps	NS201 Dipodomys spp.	Clean Slate 2 Dipodomys microps
Carcass/GI				*
n***	13	12	59	14
GM	0.00073	0.021	0.012	0.017
GSE**	1.6	2.0	1.2	1.8
Carcass/Pelt				
n	14	12	59	14
GM	0.0015	0.026	0.025	0.17
GSE	2.0	1.8	1.2	1.4
GI/Pelt				
n	15	13	59	15
GM	2.8	1.1	2.0	9.4
GSE	1.7	1.6	1.3	1.8

* A line over two or more data sets indicates no statistical differences ($p > 0.05$) between the geometric-mean ratios for

for kangaroo rats at Area 13 and NS201 (Table 2). The reason for this difference is the same as just discussed for the GM GI-over-pelt ratios. The GM carcass-over-pelt ratio for cattle was statistically smaller than the GMs for kangaroo rats. This result is consistent with the smaller carcass-over-GI ratio for cattle and the similar GM GI-over-pelt ratios for cattle and kangaroo rats.

Tissue-over-vegetation and tissue-over-soil ratios for kangaroo rats and cattle

Carcass-over-vegetation. In Fig. 7, the GM carcass-over-vegetation ^{239}Pu ratio for kangaroo rats was 0.024 at Area 13, 0.042 at Clean Slate 2 and 0.026 at NS201 (not statistically different). The similarity of these GM ratios is expected since carcass/veg = (carcass/GI) × (GI/veg) and the GM GI-over-vegetation ratios (Fig. 7) and and (3) the GM carcass-over-GI ratios were very similar at the three sites (Table 2).

The GM GI(rumen)-over-soil ratio for Area 13 cattle was 0.20, which was statistically greater than the GM GI-over-soil ratio for kangaroo rats at Area 13 (0.047) (Fig. 7). This result was unexpected since the GM GI-over-vegetation ratios for cattle and kangaroo rats at Area 13 were not statistically different (Fig. 7), although the GM for cattle was about 40% larger than for kangaroo rats. One possible explanation is that the soil concentrations to which cattle were exposed may have been larger than used here in computing the GI-over-soil ratio for cattle. Recall from the Methods and Data section that we used the median soil concentration for the enclosure to compute the ratio for each cow in the enclosure. If we had instead used the mean concentration for the enclosure, the GM GI-over-soil ratio would have decreased to about

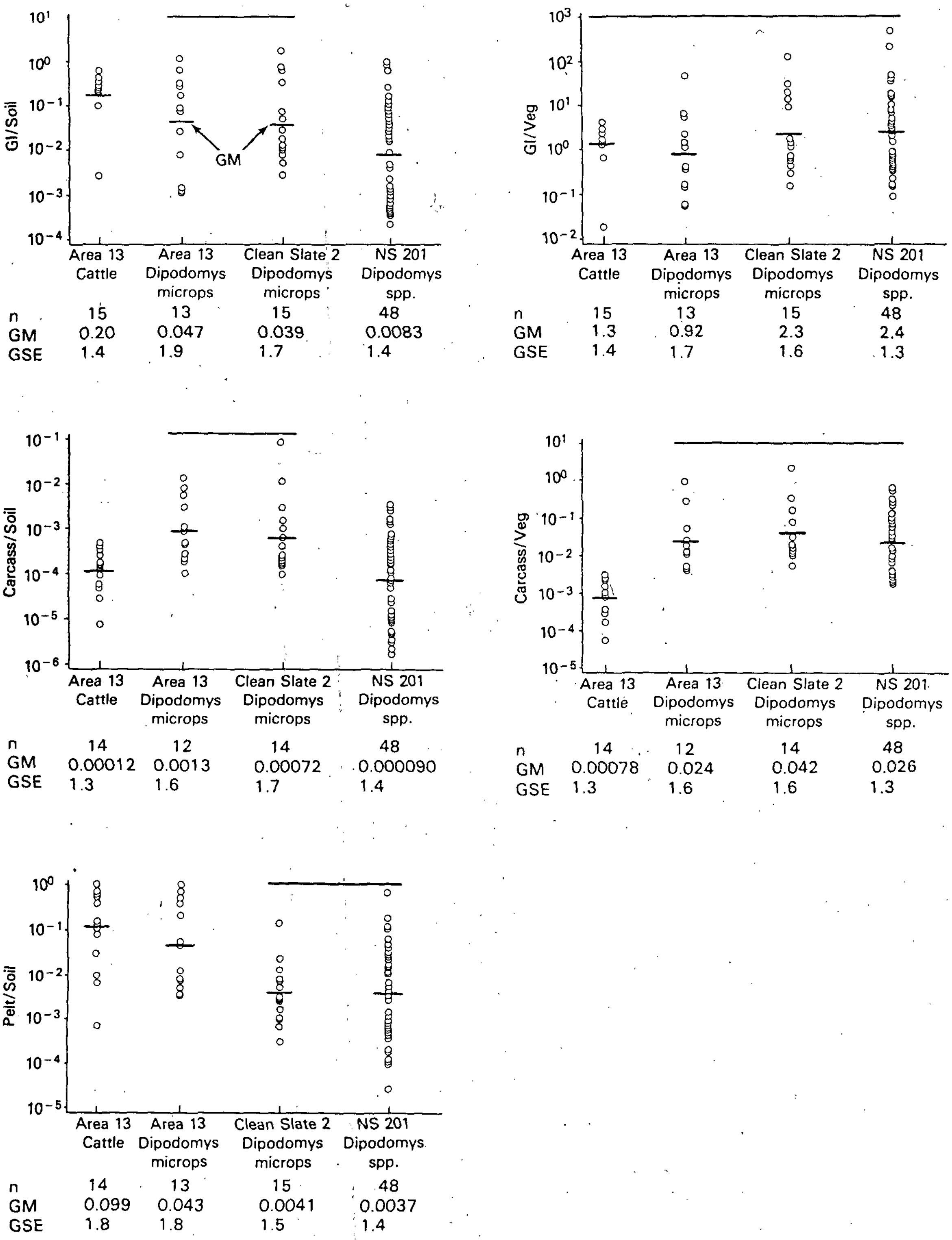


Fig. 7. Tissue-over-soil and tissue-over-vegetation ^{239}Pu concentration ratios for cattle at Area 13 and for kangaroo rats (*Dipodomys* spp.) at Area 13, Clean Slate 2 and NS201. A line drawn over two or more data sets indicates no statistical difference ($p > 0.05$) between the geometric-mean ratios for those data sets. The comparisons were made using Bonferroni t tests (Miller 1966) conducted on the logarithms of the ratios.

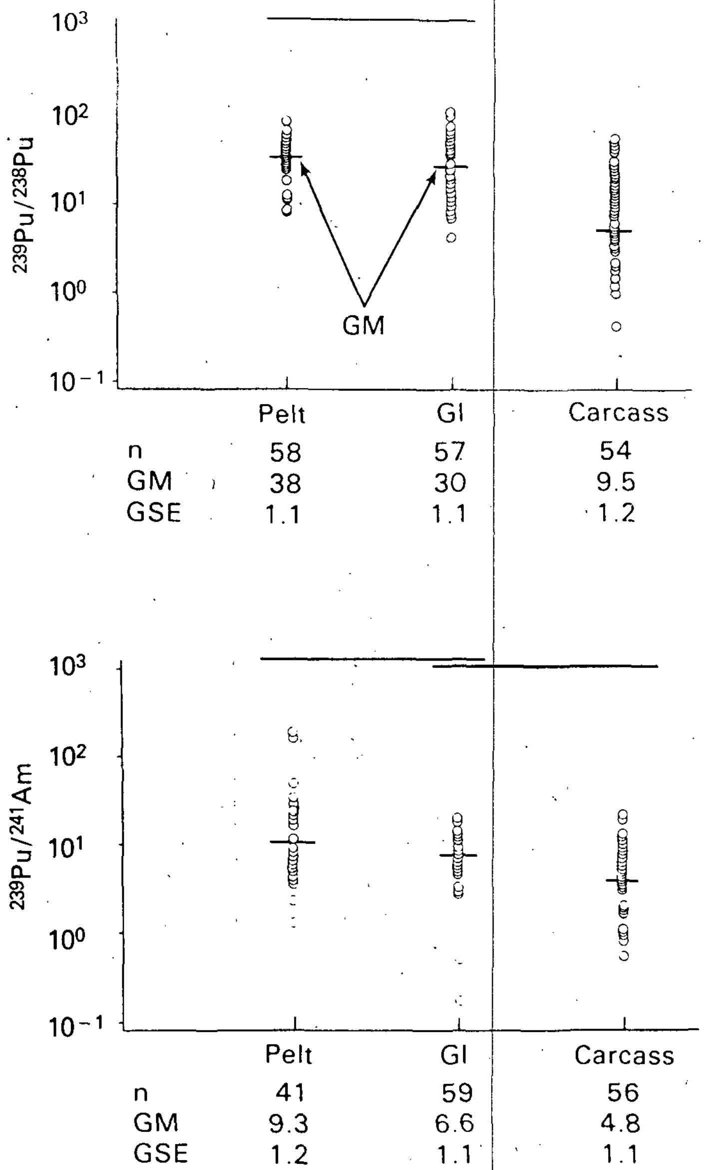


Fig. 8. Plutonium-239-over-^{238}Pu and ^{239}Pu-over-^{241}Am concentration ratios for the pelt, GI and carcass of kangaroo rats (*Dipodomys* spp.) at NS201. A line drawn over two data sets indicates no statistical difference ($p > 0.05$) between the geometric-mean ratios for those data sets. These comparisons were made using Bonferroni *t* tests (Miller 1966) conducted on the logarithms of the ratios. All tests were based on only those animals that had ratios for all three tissues; $n = 51$ for ^{239}Pu-over-^{238}Pu ratios; $n = 40$ for ^{239}Pu-over-^{241}Am ratios.

CONCLUSIONS

This paper synthesizes radionuclide concentrations at nuclear and nonnuclear testing areas on the NTS and adjacent areas to provide information for the continuing development of radionuclide transport and dose-to-man models for these areas. The data indicate that the transuranic radionuclide contamination in soil at the nonnuclear Area 13 site may be transferred more readily to plants and animals than the transuranic radionuclide soil contamination at NS201 and NS219. Compared to these nuclear sites, Area 13 has orders-of-magnitude higher resuspension factors; a higher percentage of radioactivity in smaller soil particle-size fractions; a larger percentage of resuspendable and respirable soil and GM carcass-over-soil, GI-over-soil, and pelt-over-soil ^{239}Pu ratios that are ten times larger than at NS201. Also, the vegetation-over-soil ratios of ^{239}Pu concentrations (an indirect measure of resuspension factors) at Area 13 tend to exceed those at NS201. The data also show that NS201 and NS219 have potential for increased resuspension if the desert pavement is disturbed, if wildfires destroy native vegetation or if the fragile silicate glass material (at NS219) containing ^{239}Pu is ever broken down into resuspendable particles by the forces of nature or the activities of man.

The vegetation-over-soil concentration ratios at all sites and for all radionuclides tend to be larger in areas of lower soil concentrations. Equations are fit to data to relate the vegetation-over-soil ratio to the soil concentration in the denominator of this ratio and to hypothesize a possible relationship between resuspension processes (the enhancement factor) and the vegetation-over-soil and air-over-vegetation radionuclide concentration ratios. These results indicate that realistic radionuclide transport and dose-prediction models for regions surrounding point sources of radioactivity originating from explosions may require that concentration ratios be allowed to vary depending on direction and distance from the point source.

The estimated GM carcass-over-GI ^{239}Pu concentration ratios at Area 13 indicate there may have been a greater transfer of ^{239}Pu from the GI to the carcass of kangaroo rats than from the GI to carcass of grazing cattle at that study site. However, there is considerable uncertainty in this estimate, since cattle carcass concentrations had to be calculated using an approximate formula. Nevertheless, our discussion here of the diets of kangaroo rats and grazing cattle, of the concentrations of radionuclides in their digestive tracts (GI and rumen) and of the transfer of radionuclides to their tissues may help address the question of whether rodent diets and radionuclide transfers can be used to approximate such transfers of radionuclides to cattle. It is of interest in this regard that the average (GM) concentration of ^{239}Pu for the GI of Area 13 kangaroo rats was very similar to the GM for the rumen contents of grazing beef cattle at that study site (400 vs. 440 Bq kg^{-1}, respectively).

At NS201 there is evidence for a four-fold enhanced bioavailability of ^{238}Pu to the carcass of kangaroo rats relative to ^{239}Pu and a two-fold enhanced bioavailability of ^{241}Am to the carcass relative to ^{239}Pu. Also, the bioavailability of ^{90}Sr to kangaroo-rat carcass (as measured by the GM carcass-over-GI ratio) appears to have been about 60 times larger than for ^{239}Pu or ^{241}Am, about 30 times larger than for ^{238}Pu and about six times larger than for ^{137}Cs. Hence, the data indicate that the order of bioavailability of radionuclides to the carcass of the kangaroo rat was ^{90}Sr > ^{137}Cs > ^{238}Pu > ^{241}Am > ^{239}Pu. Evidence for a greater transfer of ^{238}Pu than of ^{239}Pu to cattle tissues of Area 13 grazing cattle was reported by Smith (1979), but he found no evidence of enhanced uptake of ^{241}Am relative to ^{239}Pu. These results emphasize the importance of developing radionuclide transport and dose models that take into account differences in bioavailability of different radionuclides.

Acknowledgments—The authors wish to extend their sincere thanks to Dr. Lynn R. Anspaugh for his guidance in developing the theme and direction for this paper, to David W. Engel for his excellent computer-graphics and data-analysis support, to the reviewers for their very helpful questions and comments and to Susan Cammann and Cindy Ruecker for typing assistance. This research was funded by the Nevada Applied Ecology Group, U.S. Department of Energy, Nevada Operations Office, Las Vegas, NV.

REFERENCES

Arthur, W. J.; Markham, O. D.; Groves, C. R.; Keller, B. L. Radionuclide export by deer mice at a solid radioactive waste disposal area in southeastern Idaho. Health Phys. 52:45–53; 1987.

Barnes, M.; Delfiner, P.; Gilbert, R. O. A new statistical tool, kriging, and some applications to Area 13 data. In: Transuranics in desert ecosystems, Las Vegas, NV: U.S. Department of Energy; NVO-181; 1977:431–445.

Black, S. C.; Smith, D. D. Nevada Test Site experimental farm: summary report 1963–1981. Las Vegas, NV: U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory; EPA-600/4-84-066, DOE/DP/0539-052; 1984.

Blincoe, C.; Bohman, V. R.; Smith, D. D. The ingestion of plutonium and americium by range cattle. Health Phys. 41:285–291; 1981.

Bradley, W. G.; Mauer, R. A. Reproduction and food habits of Merriam's kangaroo rat, *Dipodomys merriami*. J. Mammal. 52:497–507; 1971.

Bradley, W. G.; Moor, K. S. Ecological studies of small vertebrates in Pu-contaminated study areas of NTS and TTR. In: The radioecology of plutonium and other transuranics in desert environments, Las Vegas, NV: U.S. Department of Energy; NVO-153; 1975:151–185.

Burt, W. H. The mammals of southern Nevada. Trans. San Diego Soc. Nat. Hist. 7:377–427, 1934.

Chilton, B. D.; Cox, T. L. Nevada Applied Ecology Group Publications. Oak Ridge, TN: Oak Ridge National Laboratory; ORNL-6011 (NVO-AEIC-264); 1988.

Delfiner, P.; Gilbert, R. O. Combining two types of survey data for estimating geographical distribution of plutonium in Area 13. In: Selected environmental research reports of the NAEG. Las Vegas, NV: U.S. Department of Energy; NVO-192, Vol. 2; 1978:361–404.

Eisele, G. R.; Chertok, R. J. The metabolism of americium-241 in swine. In: The dynamics of transuranics and other radionuclides in natural environments. Las Vegas, NV: U.S. Department of Energy; NVO-272; 1987:345–372.

Eisenberg, J. F. The behavior of heteromyid rodents. Univ. Calif. Publ. Zool. 69:1–114; 1963.

Essington, E. H. Soil radioactivity distribution studies for the Nevada Applied Ecology Group. In: Selected environmental plutonium research reports of the NAEG. Las Vegas, NV: U.S. Department of Energy; NVO-192, Vol. 1; 1978:177–244.

Essington, E. H. Progress of soil radionuclide distribution studies for the Nevada Applied Ecology Group. In: The radioecology of transuranics and other radionuclides in desert ecosystems. Las Vegas, NV: U.S. Department of Energy; NVO-224; 1982: 145–184.

Essington, E. H. Soil radionuclide distribution studies for the Nevada Applied Ecology Group—1981. In: The dynamics of transuranics and other radionuclides in natural environments. Las Vegas, NV: U.S. Department of Energy; NVO-272; 1987a:123–195.

Essington, E. H. Soil investigations for the Nevada Applied Ecology Group: A historical review and current status. In: of radionuclides at nuclear sites 201, 219 and 221. In: The dynamics of transuranics and other radionuclides in natural environments. Las Vegas, NV: U.S. Department of Energy; NVO-272; 1987:381–429.

Gilbert, R. O.; Engel, D. W.; Smith, D. D.; Shinn, J. H.; An-

and 20. Las Vegas, NV: U.S. Department of Energy; DOE/NV/10384-22; 1988.

McLendon, H. R.; Stewart, O. M.; Boni, A. L.; Corey, J. C.; McLeod, K. W.; Pinder, J. E. Relationships among plutonium contents of soil, vegetation and animals collected on and adjacent to an integrated nuclear complex in the humid southeastern United States of America. In: Transuranium nuclides in the environment. Proceedings Series; Vienna: International Atomic Energy Agency; IAEA-SM-199/85; 1976:347–363.

Miller, R. G. Simultaneous statistical inference. First edition. New York: McGraw Hill; 1966.

Moor, K. E.; Bradley, W. G. Ecological studies of vertebrates in plutonium-contaminated areas of the Nevada Test Site. In: The dynamics of plutonium in desert environments. Las Vegas, NV: U.S. Department of Energy; NVO-142; 1974:187–212.

Moor, K. S.; Bradley, W. G. Radioecology of small animal populations inhabiting a nuclear event site at the Nevada Test Site. In: The dynamics of transuranics and other radionuclides in natural environments. Las Vegas, NV: U.S. Department of Energy; NVO-272; 1987:321–344.

Moor, K. S.; Bradley, W. G.; Miller, J. S.; Naegle, S. R. Standard NAEG procedures for collection of small vertebrates from intensive study areas. In: Nevada Applied Ecology Group procedures handbook for environmental transuranics. Las Vegas, NV: U.S. Department of Energy; NVO-166, Vol. 1; 1976a:139–146.

Moor, K. S.; Bradley, W. G.; Miller, J. S.; Naegle, S. R. Standard NAEG procedures for preparation of small vertebrates from NAEG intensive study areas for radioanalysis and histopathological examination. In: Nevada Applied Ecology Group procedures handbook for environmental transuranics. Las Vegas, NV: U.S. Department of Energy; NVO-166, Vol. 1; 1976b:147–153.

Moor, K. S.; Naegle, S. R.; Bradley, W. G. ^{239}Pu and ^{241}Am contamination of small vertebrates in NAEG study areas of NTS and TTR. In: Environmental plutonium on the Nevada Test Site and environs. Las Vegas, NV: U.S. Department of Energy; NVO-171; 1977:193–217.

O'Farrell, T. P.; Sauls, M. L. Small mammals inhabiting nuclear-event sites: population characteristics and radionuclide body burden. In: The dynamics of transuranics and other radionuclides in natural environments. Las Vegas, NV: U.S. Department of Energy; NVO-272; 1987:279–304.

Patzer, R. G.; Sutton, W. W.; Potter, G. D. Passage of sand particles through the gastrointestinal tract of dairy cows. In: Environmental plutonium of the Nevada Test Site and environs. Las Vegas, NV: U.S. Department of Energy; NVO-171; 1977:151–165.

Reichman, O. J. Relation of desert rodent diets to available resources. J. Mammal. 56:731–751; 1975.

Rhoads, W. A.; Platt, R. B. Beta radiation damage to vegetation from close-in fallout from two nuclear detonations. Bioscience 21:1121–1125; 1971.

Romney, E. M.; Wallace, A.; Gilbert, R. O.; Bamberg, S. A.; Childress, J. D.; Kinnear, J. E.; Ackerman, T. L. Some ecological attributes and plutonium contents of perennial vegetation in Area 13. In: The dynamics of plutonium in desert environments. Las Vegas, NV: U.S. Department of Energy; NVO-142; 1974:91–106.

Romney, E. M.; Wallace, A.; Gilbert, R. O.; Kinnear, J. E. $^{239-240}$Pu and ^{241}Am contamination of vegetation in aged plutonium fallout areas. In: The radioecology of plutonium and other transuranics in desert environments. Las Vegas, NV: U.S. Department of Energy; NVO-153; 1975:43–88.

Romney, E. M.; Hunter, R. B.; Wallace, A. Distribution of $^{239-240}$Pu, ^{241}Am, ^{137}Cs and ^{90}Sr on vegetation at nuclear event sites 201, 219, and 221. In: The dynamics of transuranics and other radionuclides in natural environments. Las Vegas, NV: U.S. Department of Energy; NVO-272; 1987a:69–78.

Romney, E. M.; Essington, E. H.; Fowler, E. B.; Tamura, T.; Gilbert, R. O. Plutonium in the desert environment of the Nevada Test Site and the Tonopah Test Range. In: Environmental research on actinide elements. Proceedings of a symposium held at Hilton Head, South Carolina, 7–11 November 1983. Springfield, VA: NTIS, U.S. Department of Energy; CONF-841142; 1987b:121–130.

Shinn, J. H.; Homan, D. N. Plutonium-aerosol emission rates and human pulmonary deposition calculations for Nuclear Site 201, Nevada Test Site. Livermore, CA: Lawrence Livermore National Laboratory; UCRL-53301; 1982.

Shinn, J. H.; Homan, D. N.; Hofmann, C. B. A summary of plutonium aerosol studies: resuspension at the Nevada Test Site. Livermore, CA: Lawrence Livermore National Laboratory; UCRL-90746; 1986.

Smith, D. D. Summary report of the grazing studies conducted on a plutonium-contaminated range in Area 13 of the Nevada Test Site. Las Vegas, NV: U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory; EMSL-LV-0539-24; 1979.

Smith, D. D.; Black, S. C. Animal investigation program for the Nevada Test Site: 1957–1981. Las Vegas, NV: U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory; EPA 600/6-84-020, DOE/DP/0539-050; 1984.

Snedecor, G. W.; Cochran, W. G. Statistical methods. Ames: The Iowa State University Press; 1980.

Soholt, L. F. Consumption of primary production by a population of kangaroo rats (*Dipodomys merriami*) in the Mojave desert. Ecolog. Monog. 43:357–376; 1973.

Tamura, T. Distribution and characterization of plutonium in soil from Nevada Test Site. J. Environ. Qual. 4:350–354; 1975.

Tamura, T. Plutonium in surface soils of Area 13: a progress report. In: Studies of environmental plutonium and other transuranics in desert ecosystems. Las Vegas, NV: U.S. Department of Energy; NVO-159; 1976:5–16.

Tamura, T. Plutonium association in soils. In: Transuranics in natural environments. Las Vegas, NV: U.S. Department of Energy; NVO-178; 1977:97–114.

Tamura, T. Plutonium-soil association: a summary. In: Selected environmental plutonium research reports of the NAEG. Las Vegas, NV: U.S. Department of Energy; NVO-192, Vol. 2; 1978:245–252.

Tinney, J. F. Calibration of an X-ray sensitive plutonium detector. In: Hazards control progress report No. 31. Livermore, CA: Lawrence Livermore National Laboratory; TID-4500; 1968:24–31.

Wessman, R. A.; Leventhal, L. Historical review of transuranic analytical methodology. In: Transuranics in natural environments. Las Vegas, NV: U.S. Department of Energy; NVO-178; 1977:545–574.

Wessman, R. A.; Benz, M.; Hemighaus, G. Analysis of Pu, Am, and Sr radioisotopes in samples from aged nuclear test sites. In: The radioecology of transuranics and other radionuclides in desert ecosystems. Las Vegas, NV: U.S. Department of Energy; NVO-224; 1982:341–356.