Introduction

This study examines the ability of vegetation to act as biomonitors for plutonium (Pu) in a contaminated environment: the Nevada National Security Site (N2S2). After 1951, the N2S2 was the primary location in the continental United States for testing nuclear devices. This area was contaminated by radionuclides, including Pu from a series of atmospheric testing (1951-1958), followed by underground testing (1961-1992).

The behavior of Pu and other contaminant metals in the environment is a function of many physical and biogeochemical processes, which may confound characterization of site exposure risk and transport potential. Due to its low solubility and high particle reactivity, Pu is classically thought to be largely immobile in the environment, persisting in the top few centimeters of regolith upon deposition.[1] Yet, Pu research has demonstrated considerable Pu mobility in the subsurface environment. Colloids rich in aluminum (Al) silicates, organic carbon (C), or iron (Fe) can facilitate the transport Pu over substantial distances from source areas. Plutonium can also migrate downward in soils, even in arid regions.[2]

There is evidence that the migration of Pu into the soil profile over time increases the bioavailability of the contaminant via exposure to plant root systems and microorganisms.[3] Soil sampling furnishes only total deposition of an area contaminant and research is limited in the fundamental understanding of Pu *in situ* speciation as a factor in Pu behavior.[4] Vegetation is an important biomonitor; plants represent a key mode of Pu transport from the soil to biota, through root uptake and foliar interception of resuspended Pu particles.[5] Thus, the use of biomonitors can assist in the assessment of ecological and human health exposure risk from biologically available contaminants.

There are numerous processes of ion uptake from the rhizosphere; each imparts selectivity for needed ions so a plant can function in a given soil environment.[6] Plant-available Fe and manganese (Mn) may be limited due to the low solubility of these elements in the high pH, calcareous soils endemic to the N2S2. The release of root exudates by plant roots during growth, can increase access to such nutrients. Organic acids like citrate, malate and phenolates are typical complexants that plants use for mobilizing Fe, Mn, and phosphate in the rhizopshere. Iron and Mn oxides and oxyhydroxides are known to be highly reactive to contaminant metals in the environment.[7] The subsequent chelation of Fe oxide Fe(III) may impact the chemically and structurally similar Pu oxide Pu(IV), increasing the mobility and bioavailability of each in the soil.[8] As an active uptake process, the transport of Fe across the root plasma membrane occurs following plant enhanced reduction, via a Fe(II) transporter (IRT1). This transporter might also facilitate the transport of heavy-metal cations.[9] Plants can also obtain Fe through foliar uptake. The cuticle can exchange cations due to the negatively-charged nature of its pectic and nonesterified polymeric components. This behavior also promotes the absorption of contaminants. Without having to determine the geochemical form of Pu (i.e., sorbed, oxide, etc.) in the soil or as suspended particulates in these areas, biomonitors offer a direct assessment of the bioavailability of Pu.

As discussed, Fe and Mn mineral acquisition can strongly influence the aqueous mobility of contaminants like Pu. It can also impact other less toxic metals, like the rare earth element (REE) cerium (Ce).[10,11,12,13] Cerium is considered to be an inactive chemical analogue of Pu in the geological sciences due to its similarities to Pu under certain conditions.[14] The ionic radius and chemical properties connected to the 4f electrons of Ce are very close to those observed in Pu.[15] In the geochemical environment, the most stable form of Pu is generally considered to be the sparingly soluble $Pu(+IV)O_2$ or oxide species.[12] Unlike most REEs which are trivalent in the environment, Ce(+III) can be oxidized to the less soluble Ce(+IV) species by oxidizing surfaces (like Mn and Fe oxides), and it may precipitate as $Ce(IV)O_2$.[7,16] The primary oxide forms of Pu and Ce [i.e., $Pu(IV)O_2$ and $Ce(IV)O_2$] are structurally equivalent. The ions of Ce(+III) and Pu(+III) and the ions of Ce(+IV) and Pu(+IV) are of similar respective sizes and the solubility behavior of +III and +IV ions are also similar. However, given these similarities, few studies have examined and compared the uptake of these two analogue elements (in addition to other elements like Fe and Mn) by a variety of plants in Pu-contaminated surface soils.

Two objectives were central to this study. The first was the characterization of Pu accumulation in plant species at the N2S2, under the presumption that the phylogenic growth strategies of differential species which allow plants to function under Fe-limiting conditions at N2S2 may be related to an ability to accumulate Pu. As a second objective, this study examined plant accumulation of Fe, Al, Mn, magnesium (Mg), calcium (Ca), and the REE [Ce, and samarium (Sm)] as they correlate with Pu accumulation. Identified correlations in accumulation could provide mechanisms for predicting Pu bioavailability in uncontaminated environments.

Materials and Methods

The N2S2 occupies 350,000 hectares of desert and rangeland terrain in south-central Nevada (Fig. 1). Average annual precipitation ranges between 13 and 33 cm. For 6 to 8 months per year, the soil moisture potential is below -30 bars and often drops below -90 bars in the summer.[17] Monthly average temperatures range from 7˚C to 32˚C.[17]

Vegetation and soil samples were collected in four N2S2 locations: Frenchman Flat, Sedan and Palanquin and Test Cell C (Fig. 1). The Frenchman Flat, Sedan and Palanquin locations were subject to surface or near-surface nuclear testing. As a result, the soils of these sites are contaminated with fission and activation products as well as by transuranic radionuclides. The Test Cell C site was used to develop nuclear rocket technology and nuclear fuels for rocket engines. Test Cell C is contaminated with a mixture of fission products.[18]

Most soils of the N2S2 developed on alluvial deposits containing unconsolidated sedimentary and volcanic parent materials. They developed under conditions of high temperature and low rainfall, and are characteristically coarse textured, rich in carbonates (calcareous) and low in organic matter. The soils collected for this study have a mean pH of 8.3 (7.9 to 9.1).

Vegetation was collected in May and August 2008. Samples taken at each location were based on species availability. The species and number of samples collected by location are described in Table 1. Three to 4 liters of vegetation was sampled, consisting of upper stem and leaf tissues clipped from actively growing plants. Lichen and moss were collected on a whole portion basis. Vegetation density in this ecosystem is low. As this was a preliminary study, used to identify species as accumulators, replication was kept low to limit ecological impact. Due to the likelihood that wind deposition would be a prominent mechanism of accumulation by the plants, samples were not rinsed with water or organic solvents after collection.[19] All vegetation samples were dried to a constant weight and ground to a particle size of 1 mm for analysis. Composite soil samples (500 ml) were taken at each location using a standard soil corer at a root zone depth range of 0 to 5 cm. All soil samples were mixed by site, dried to a constant weight, and milled to a uniform particle size (< 1 mm) for analysis.

Radiochemical and stable element analyses were done by GEL Laboratories LLC (Charleston, SC). Soil pH was determined by electrometric measurement, using the Environmental Protection Agency analytical protocol established in SW846 9045C/9045D. Concentrations of ^{238}Pu and $^{239+240}$Pu were determined by alpha spectrometry applicable to method DOE RP 800 1997. Soil and vegetation samples were aliquoted and digested; elements were then separated through ion exchange resins, coprecipitated with neodymium fluoride (NdF_3) and ^{242}Pu tracer, filtered, mounted on a stainless steel disk and measured by alpha spectrometry for a four hour count time. All activity data for these isotopes are presented in Bq kg^{-1} dry weight. The typical method detection limit is 37 Bq kg^{-1}. The ^{239}Pu and ^{240}Pu peaks are reported as a single value due to their similar energies.[20] Average errors associated with samples were 33% for ^{238}Pu and 17% for $^{239+240}$Pu. This was due to the activities of ^{238}Pu being relatively closer to the minimum detection level (MDL).

The metal analysis for Pu and other metals was performed on a Perkin Elmer ELAN 6100E inductively coupled plasma mass spectrometer (ICP-MS). Internal standards of scandium, germanium, indium, tantalum, and/or lutetium were utilized for calibration. Values for metals are expressed in mg kg^{-1} dw. Measurements are accurate within a 10% error range.

Concentration ratios (CR) will be defined here as the Pu activity in the dw plant tissue in Bq kg^{-1} divided by the Pu activity in the associated dw soil in Bq kg^{-1}. The soil data used to calculate CR values are from composite samples specific to a site location. Some vegetation samples were determined to be below our analytical detection limit for ^{238}Pu or $^{239+240}$Pu. In those instances, the data below the MDL was censored.

A Pearson Correlation Matrix was used to describe the relationship between plant concentrations of Pu and stable elements using SYSTAT 12 statistical software.[21] A Bonferroni test was conducted to determine the significance of the correlations.

Results

Radionuclide and Elemental Levels in Surface Soils

Soil concentrations of Pu in N2S2 soils vary by several orders of magnitude (Table 2). Plutonium levels at the Test Cell C site were low and generally not detectable by our methods. Soil concentrations of Pu from Frenchman Flat were low but detectable. The Sedan site concentrations were approximately 15 fold greater than values from Frenchman Flat (6.03 Bq kg^{-1} ^{238}Pu, 55.13 Bq kg^{-1} $^{239+240}$Pu). The Palanquin soils were substantially more contaminated, averaging ^{238}Pu and $^{239+240}$Pu concentrations 39 and 20 fold higher, respectively, than the Sedan site. A great deal of variation was noted between the two Palanquin soil composite samples. The first possessed values of 25.4 Bq kg^{-1} ^{238}Pu and 477.7 Bq kq^{-1} $^{239+240}$Pu, as compared to values from the second sample of 65.5 Bq kq^{-1} and 2171.9 Bq kq^{-1} respectively. Such variation is not unexpected and highlights a base difficulty in characterizing a site for human and ecological exposure risks solely from soil monitoring. The levels of other elements (Ce, Sm, Fe, Al, Mn, Ca and Mg) in the soils were within the typical ranges for soils throughout the world.[22] The highest soil concentrations of Ce, Sm and Fe concentrations were in the Palanquin soil.

Radionuclide and Elemental Levels in Vegetation

Onion moss (24.27 Bq kg^{-1} ^{238}Pu, 52.78 bq kg^{-1} $^{239+240}$Pu) and lichen (8.18 Bq $kg^{-1}$and 18.41 Bq kg^{-1} respectively) possessed the highest concentrations of Pu (Table 3). These species are known to accumulate radionuclides and non-radioactive heavy metals.[23,24,25,26,27,28,29] Among the rooted plants, brome and desert globemallow species tended to accumulate higher Pu concentrations than the slower growing creosote bush, fourwing saltbush and sagebrush. Species are listed by location in Table 4 to account for site specific Pu concentrations. Despite Palanquin being the most Pu contaminated site in this study, sage brush Pu concentrations were relatively low. For Sedan, brome and desert globemallow concentrations were relatively high, while creosote bush and fourwing saltbush were approximately 10 times lower for $^{239+240}$Pu and below the MDL of ^{238}Pu.

The Ce and Sm concentrations in brome, lichen and moss samples in our study exceed the previously reported levels by 10 fold based.[22] The Al levels observed in N2S2 vegetation were considerably higher than those reported in the literature as well, whereas the levels of Fe and Mn were within normal limits for most terrestrial vegetation.

Plants in this study displayed sensitivity to soil concentrations of elements. As previously mentioned, the highest concentrations of Fe, Sm and Ce were sampled from the Palanquin site. Concentrations were similarly elevated for these elements in the brome, desert globemallow and sage brush species sampled at the Palanquin site as compared to those sampled elsewhere (Table 3).

Concentration Ratios

The highest CR values were found in brome (0.1 for ^{238}Pu and 0.8 for $^{239+240}$Pu) and desert globemallow (0.06 for ^{238}Pu, 0.16 for $^{239+240}$Pu) as shown in (Table 5). This study provided limited replication in areas of heterogeneous Pu distribution, but the CR values for most of the N2S2 vegetation were comparable to other wild terrestrial vegetation from Pu contaminated areas. In the literature, CR values as high as 0.042 and 0.66 for ^{238}Pu were reported in crested wheatgrass and Russian thistle respectively. For $^{239+240}$Pu, species of crested wheatgrass, Russian thistle, sweet pea, lichen, sedge, moss, blackberry, blueberry and fescue have CR values as high as 0.12, 1.6, 0.13, 0.28, 0.14, 0.18, 0.33, 0.17 and 0.57 respectively.[30,31,32,33] However, in most cases, CR values for wild plant species were reported as <0.1, regardless of Pu isotope(s) measured.

Less variability of Al, Ca, Ce, Fe, Mg, Mn, and Sm concentrations was noted in soils sampled at N2S2, diminishing the importance of location as a variable in comparison of CR values between species. A pattern of plant species accumulation is evident with the REEs (Ce and Sm) as well as with Fe and Al. For each element, CR rankings in decreasing order are the same: onion moss, lichen, followed by brome. Creosote bush and fourwing saltbush were ranked lowest in CR values. These two plant species also possessed very low Pu concentrations (<MDL for ^{238}Pu).

Elemental Correlations

Total plant concentrations of Al, Ca, Ce, Fe, Mn, Mg, and Sm were correlated with Pu isotopes to determine similarities in accumulation patterns of these elements in plants. These correlations are shown in Figure 2 and Table 6. Based on limited sample size, the plant biomass concentrations of ^{238}Pu and $^{239+240}$Pu in the N2S2 vegetation were significantly, strongly correlated with REEs and metals in this study. Using the Bonferroni test of significance, both Pu isotopes exhibit significant positive correlations ($p<0.05$) with the elements tested except Ca and Mg. Correlations observed between Fe and Al with Pu were amongst the strongest.

The relative strength of these relationships in the case of ^{238}Pu correlated in the following order: Fe > Al > Sm > Ce > Mn. The ranked correlations for $^{239+240}$Pu were the same, but the correlation strengths were reduced. Despite being considered an analogue to Pu, Ce concentrations were not as strongly correlated with Pu as were Fe and Al. Ce and Sm were very strongly correlated to each other, likely due to soil processes that make these REE similarly less available to plants.[34] Conversely, the newly introduced Pu may be more bioavailable, thus accounting for the weaker correlations with REE.

Discussion

The vegetation sampled on the N2S2 comprised a diverse group of species and the Pu concentrations observed reflect as such. While a highly replicated study would provide required statistics from which to draw conclusions, it was not warranted in this preliminary study; observations did reveal trends to be utilized in future investigations. Of the eight species studied, four (onion moss, lichen, brome and desert globemallow) displayed an ability to accumulate and therefore act as biomonitors for Pu contamination at N2S2. The concentrations of ^{238}Pu and $^{239+240}$Pu in onion moss and lichen are clearly higher than those of the other species. As these non-vascular plants utilize osmosis and diffusion to accumulate minerals, one could conclude that leaf interception of eolian Pu contamination is an important mode of biota contamination at the N2S2. A previous study performed at the Rocky Flat found a correlation between soil and lichen Pu concentrations reflecting wind-borne transport patterns.[35] These results support the use of biota to assist in the monitoring of contaminant transport.

Plant species of various growth rate patterns were included in this sampling. The slow-growing creosote bush, which is considered one of the oldest living organisms on earth was compared to brome, a C3 photosynthetic plant growing for only a year as an annual plant. Brome forms extensive root hairs, enhancing mycorrhizal inoculation.

Brome is also member of the Poaceae family, which includes barley and wheat, which have been identified as capable of Fe accumulation.[36] The evaluation of these species allows for consideration of whether dynamic accumulation outweighs the duration of exposure in species-specific accumulation of Pu. Brome and desert globemallow distinguished themselves from other rooted plants as Pu accumulators. Desert globemallow is similar to brome in that it is small in size, has a shallow root system, and is a short-lived, rapidly growing perennial. Following this growth rate trend, it would be expected that the hoary aster would also accumulate Pu, yet our samples concentrations were relatively low. This could be attributable to a tap-root morphology that would potentially extend beyond contamination in the soil profile. In this study, rapidly growing plants accumulated higher concentrations of Pu than the long lived, slow growing creosote sage brush and fourwing saltbush species. These results support the idea that species specific elemental accumulation strategies will have a greater impact on Pu concentrations in plants than will the variable of exposure duration. This is of concern, as brome is an invasive species that creates wildfire fuel and proliferates following wildfires threatening a sudden Pu atmospheric release and globemallow is considered forage vegetation for bighorn and domestic sheep. In these species, transport and bioavailability potentials are enhanced.

A matrix of factors exist that may impact plant ion uptake, including soil properties, contaminant concentrations and competing ions which influence plant saturation and active uptake mechanisms. These are not parameters that this study is attempting to define; instead, the cumulative effect is used to characterize the bioavailability of a contaminant. The CR values for Pu in plants were highly influenced by the heterogeneity of Pu distribution among sites. Results from the naturally occurring elements of concern were more evenly distributed between sample sites. This allowed for the development of a pattern of plant species that accumulated Ce, Sm, Fe and Al. For each of these elements, the same ranked order of highest CR values was: onion moss, lichen, and brome. As mentioned, these species also possessed the highest concentrations of ^{238}Pu and $^{239+240}$Pu. The lowest CR values for these elements were observed in the creosote bush and fourwing saltbush.

In general, plant concentrations of Pu were strongly correlated with concentrations of Fe, Al, Sm, Ce and Mn. Plant concentrations of Ca and Mg were uncorrelated with Pu, suggesting alternative uptake mechanisms for these elements. These results support the inferred identification of Pu accumulating plants through the evaluation of Fe, Al, Sm, Ce and Mn uptake potentials. This would provide a means for evaluating a site for ecological and human health exposure risks, even if Pu concentrations are currently at low background levels. This information also has future applications in the identification of field phytoremediators for areas with low concentrations of Pu.

Acknowledgements

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Fig. 1. Map of the Nevada National Security Site with sample areas represented.

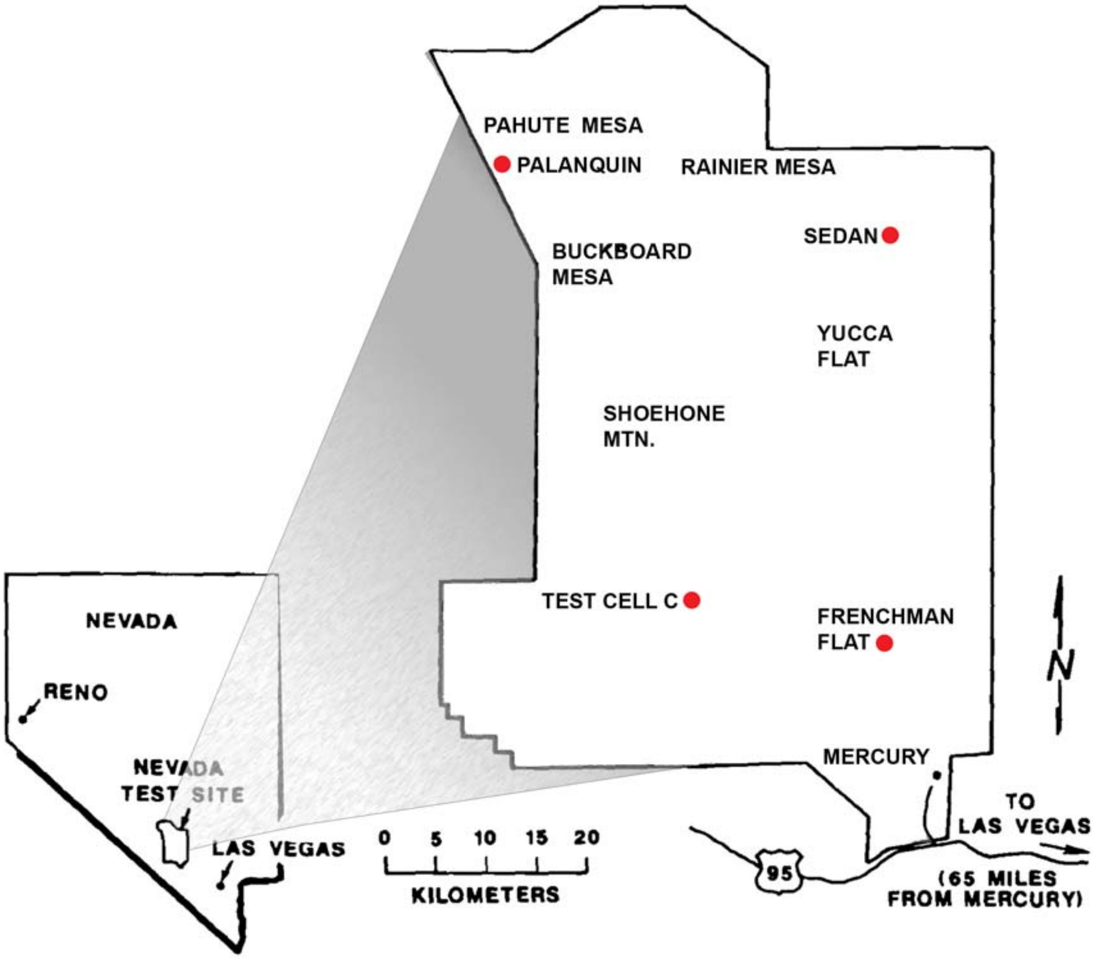

Table 1. The number of N2S2 samples collected, designated by species and location.

Species	**Common Name**	**Sample Location**				
		Test Cell C	**Frenchman Flat**	**Sedan**	**Palanquin**	***Total***
Rhizoplaca melanophthalma	Rimmed navel lichen	0	0	0	2	***2***
Bromus tinctorem	Cheatgrass brome	1	1	1	1	***4***
Larrea tridentata	Creosote bush	2	0	2	0	***4***
Sphaeralcea ambigua	Desert globemallow	1	0	3	1	***5***
Atriplex canescens	Fourwing saltbush	0	2	2	0	***4***
Machaeranthera canescens	Hoary-aster	0	0	3	0	***3***
Pterygoneurum ovatum	Onion moss	0	0	0	2	***2***
Artemisia spp.	Sage brush	0	0	0	3	***3***

Table 2. The mean ^{238}Pu and $^{239+240}$Pu (Bq kg^{-1} dw) and stable element (mg kg^{-1} dw) values in soil samples from N2S2 sample sites. The standard deviation of values within a sample set is represented in parenthesis (*stdev*) when the sample number is greater than 1.

site *sample(n)*	**Test Cell C** (3)	**Frenchman Flat** (1)	**Sedan** (1)	**Palanquin** (2)
^{238}Pu	<MDL	0.34	6.03	236.8
(stdev)				*(298.6)*
$^{239+240}$Pu	3.43	3.56	55.13	1117.00
(stdev)				*(1489.00)*
Al	7990	18300	15300	18400
(stdev)	*(1013)*			*(3677)*
Ca	3337	76900	23600	4800
(stdev)	*(816)*			*(947)*
Ce	32.6	41.0	47.6	64.3
(stdev)	*(1.9)*			*(33.8)*
Fe	5567	1330	9300	14750
(stdev)	*(581)*			*(2333)*
Mg	2637	19800	9000	4715
(stdev)	*(455)*			*(460)*
Mn	174	425	388	527
(stdev)	*(45)*			*(64)*
Sm	2.36	2.99	3.25	4.08
(stdev)	*(0.09)*			*(1.62)*
pH	7.99	8.66	9.14	8.29
(stdev)	*(0.09)*			*(0.11)*

Table 3. The mean ^{238}Pu and $^{239+240}$Pu (Bq kg^{-1} dw) and stable element (mg kg^{-1} dw) values in vegetation collected from N2S2 sample sites. The value in subscripted parenthesis, preceding the mean, represents the number of samples above the MDL, if different from the number of plants sampled. The standard deviation of values within a sample set are represented in parenthesis (*stdev*) when the sample number is greater than 1.

$_{(n)}$ **Species**	$_{(4)}$ **Brome**	$_{(4)}$ **Creosote bush**	$_{(5)}$ **Desert globemallow**	$_{(4)}$ **Fourwing saltbush**	$_{(3)}$ **Hoary-aster**	$_{(2)}$ **Lichen**	$_{(2)}$ **Onion moss**	$_{(3)}$ **Sage brush**
^{238}Pu	$_{(2)}$ 1.88	<MDL	$_{(4)}$ 0.60	<MDL	0.32	8.18	24.27	0.70
(stdev)	*(1.04)*		*(0.23)*		*(0.11)*	*(8.53)*	*(6.59)*	*(0.21)*
$^{239+240}$Pu	$_{(2)}$ 6.85	$_{(2)}$ 1.05	$_{(4)}$ 9.36	$_{(2)}$ 1.61	3.15	18.41	52.78	2.33
(stdev)	*(3.08)*	*(0.15)*	*(11.99)*	*(0.86)*	*(1.73)*	*(8.82)*	*(42.05)*	*(0.72)*
Al	705	110	316	177	309	2260	10800	441
(stdev)	*(515)*	*(27.5)*	*(118)*	*(31.8)*	*(292.8)*	*(127)*	*(141)*	*(62.8)*
Ca	4810	1373	20960	17500	8600	38000	6245	6533
(stdev)	*(611)*	*(364)*	*(6367)*	*(4157)*	*(2241)*	*(11030)*	*(728)*	*(1395)*
Ce	2.96	0.27	0.93	0.63	1.15	17.85	43.71	1.58
(stdev)	*(3.01)*	*(0.09)*	*(0.35)*	*(0.28)*	*(0.98)*	*(0.07)*	*(9.70)*	*(0.26)*
Fe	595	183	371	245	297	2020	8645	389
(stdev)	*(437)*	*(32)*	*(68)*	*(29)*	*(237)*	*(71)*	*(205)*	*(33)*
Mg	1703	1543	3426	7242	3073	852	3400	1507
(stdev)	*(329)*	*(243)*	*(442)*	*(2593)*	*(456)*	*(29)*	*(254)*	*(264)*
Mn	98.0	40.7	59.1	60.9	49.6	60.8	261.0	68.4
(stdev)	*(39.3)*	*(10.5)*	*(14.4)*	*(6.2)*	*(6.4)*	*(22.2)*	*(14.1)*	*(14.4)*
Sm	$_{(3)}$ 0.26	<MDL	$_{(4)}$ 0.09	$_{(2)}$ 0.07	$_{(1)}$ 0.16	1.06	2.71	0.10
(stdev)	*(0.18)*		*(0.01)*	*(0.02)*		*(0.98)*	*(0.50)*	*(0.18)*

Table 4. The mean ^{238}Pu and $^{239+240}$Pu (Bq kg^{-1} dw) values in vegetation separated by site location and plant species. The standard deviation of values within a sample set is represented in parenthesis (*stdev*) when the sample number is greater than 1.

Species	***n***	**Location**	**^{238}Pu**	**$^{239+240}$Pu**
Brome	1	Frenchman Flat	<MDL	<MDL
Fourwing saltbush	2	Frenchman Flat	<MDL	<MDL
Brome	1	Palanquin	2.62	4.66
Desert globemallow	1	Palanquin	0.92	3.09
Lichen *(stdev)*	2	Palanquin	8.18 *(8.53)*	18.4 *(8.81)*
Onion moss *(stdev)*	2	Palanquin	24.27 *(6.59)*	52.78 *(42.04)*
Sage brush *(stdev)*	3	Palanquin	0.70 *(0.21)*	2.33 *(0.72)*
Brome	1	Sedan	1.14	9.03
Creosote bush *(stdev)*	2	Sedan	<MDL	1.052 *(0.150)*
Desert globemallow *(stdev)*	3	Sedan	0.50 *(0.11)*	11.45 *(13.77)*
Fourwing saltbush *(stdev)*	2	Sedan	<MDL	1.61 *(0.850)*
Hoary-aster *(stdev)*	3	Sedan	0.32 *(0.115)*	3.15 *(1.730)*
Brome	1	Test Cell C	<MDL	<MDL
Creosote bush	2	Test Cell C	<MDL	<MDL

Table 5. Mean CR values for Pu and elements of interests separated by plant species. The standard deviation of values within a sample set is represented in parenthesis (*stdev*) when the sample number is greater than 1.

Species	**Brome**	**Creosote**	**Desert globemallow**	**Fourwing saltbush**	**Hoary-aster**	**Lichen**	**Onion moss**	**Sage brush**
^{238}Pu *CR*	0.10	<MDL	0.06	<MDL	0.05	0.04	0.10	0.003
(stdev)	*(0.13)*		*(0.04)*		*(0.02)*	*(0.04)*	*(0.03)*	*(0.01)*
$^{239+240}$Pu *CR*	0.08	0.02	0.16	0.03	0.06	0.02	0.05	0.002
(stdev)	*(0.11)*	*(0.01)*	*(0.23)*	*(0.02)*	*(0.03)*	*(0.01)*	*(0.04)*	*(0.01)*
Al CR	0.04	0.01	0.02	0.01	0.02	0.12	0.59	0.02
(stdev)	*(0.03)*	*(0.01)*	*(0.01)*	*(0.01)*	*(0.02)*	*(0.01)*	*(0.01)*	*(0.01)*
Ca *CR*	0.64	2.40	2.62	0.49	0.36	7.92	1.30	1.36
(stdev)	*(0.58)*	*(2.26)*	*(2.48)*	*(0.36)*	*(0.09)*	*(2.30)*	*(0.15)*	*(0.29)*
Ce *CR*	0.06	0.01	0.02	0.01	0.02	0.28	0.68	0.03
(stdev)	*(0.04)*	*(0.01)*	*(0.01)*	*(0.01)*	*(0.02)*	*(0.01)*	*(0.15)*	*(0.01)*
Fe *CR*	0.12	0.03	0.04	0.11	0.03	0.14	0.59	0.03
(stdev)	*(0.12)*	*(0.01)*	*(0.01)*	*(0.10)*	*(0.03)*	*(0.01)*	*(0.01)*	*(0.01)*
Mg *CR*	0.29	0.38	0.67	0.63	0.34	0.18	0.72	0.32
(stdev)	*(0.17)*	*(0.24)*	*(0.53)*	*(0.45)*	*(0.05)*	*(0.01)*	*(0.05)*	*(0.06)*
Mn *CR*	0.28	0.17	0.19	0.15	0.13	0.12	0.50	0.13
(stdev)	*(0.10)*	*(0.09)*	*(0.13)*	*(0.02)*	*(0.02)*	*(0.04)*	*(0.03)*	*(0.03)*
Sm *CR*	0.07	<MDL	0.03	0.02	0.05	0.26	0.67	0.02
(stdev)	*(0.04)*		*(0.01)*	*(0.01)*		*(0.02)*	*(0.12)*	*(0.01)*

Figure 2. Distribution of correlation values for Pu as it relates to elements of interest using a Pearson correlation.

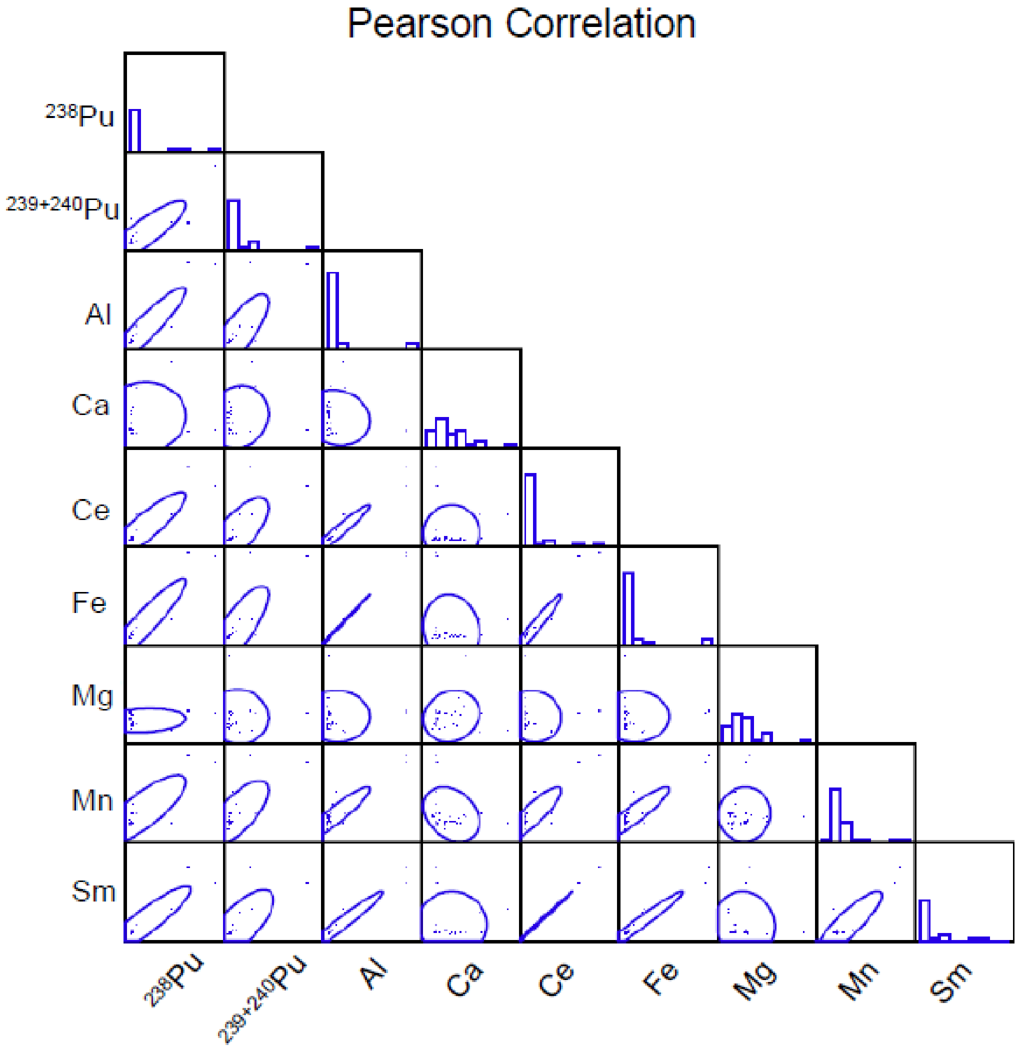

Table 6. Correlation values from the Pearson correlation. Values that are not significant at the 0.05 level are represented as *ns*.

	^{238}Pu	**$^{239+240}$Pu**	**Al**	**Ca**	**Ce**	**Fe**	**Mg**	**Mn**	**Sm**
^{238}Pu	1								
$^{239+240}$Pu	0.875	1							
Al	0.931	0.789	1						
Ca	*ns*	*ns*	*ns*	1					
Ce	0.896	0.698	0.969	*ns*	1				
Fe	0.935	0.788	0.999	*ns*	0.973	1			
Mg	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	1		
Mn	0.804	0.697	0.923	*ns*	0.872	0.919	*ns*	1	
Sm	0.908	0.699	0.973	*ns*	0.999	0.978	*ns*	0.874	1

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Abstract

Eight species of desert vegetation and associated soils were collected from the Nevada National Security Site (N2S2) and analyzed for 238Pu and 239+240Pu concentrations. Amongst the plant species sampled were: atmospheric elemental accumulators (moss and lichen), the very slow growing, long-lived creosote bush and the rapidly growing, short-lived cheatgrass brome. The diversity of growth strategies provided insight into the geochemical behavior and bio-availability of Pu at the N2S2. The highest concentrations of Pu were measured in the onion moss (24.27 Bq kg-1 238Pu and 52.78 Bq kg-1 239+240Pu) followed by the rimmed navel lichen (8.18 Bq kg-1 and 18.4 Bq kg-1 respectively), pointing to the importance of eolian transport of Pu. Brome and desert globemallow accumulated between 3 and 9 times higher concentrations of Pu than creosote and sage brush species. These results support the importance of species specific elemental accumulation strategies rather than exposure duration as the dominant variable influencing Pu concentrations in these plants. Total vegetation elemental concentrations of Ce, Fe, Al, Sm and others were also analyzed. Strong correlations were observed between Fe and Pu. This supports the conclusion that Pu was accumulated as a consequence of the active accumulation of Fe and other plant required nutrients. Cerium and Pu are considered to be chemical analogs. Strong correlations observed in plants support the conclusion that these elements displayed similar geochemical behavior in the environment as it related to the biochemical uptake process of vegetation. Soils were also sampled in association with vegetation samples. This allowed for the calculation of a concentration ratio (CR). The CR values for Pu in plants were highly influenced by the heterogeneity of Pu distribution among sites. Results from the naturally occurring elements of concern were more evenly distributed between sample sites. This allowed for the development of a pattern of plant species that accumulated Ce, Sm, Fe and Al. The highest accumulators of these elements were onion moss, lichen flowed by brome. The lowest accumulators were creosote bush and fourwing saltbush. This ranked order corresponds to plant accumulations of Pu.