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Assessment of Chronic Low-Dose Elemental and Radiological Exposures of Biota at the Kanab North Uranium Mine Site in the Grand Canyon Watershed

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ABSTRACT

High-grade U ore deposits are in various stages of exploitation across the Grand Canyon watershed, yet the effects of U mining on ecological and cultural resources are largely unknown. We characterized the concentrations of Al, As, Bi, Cd, Co, Cu, Fe, Pb, Hg, Mo, Ni, Se, Ag, Tl, Th, U, and Zn, gross alpha and beta activities, and U and Th radioisotopes in soil, vegetation (*Hesperostipa comata*, *Artemisia tridentata, Tamarix chinensis*), and rodents (*Peromyscus maniculatus*, *P. boylii*) to waste material at the Kanab North mine, a mine with decades-long surficial contamination, and compared the concentrations ($P < 0.01$) to those at a premining site (Canyon Mine). Rodent tissues were also analyzed for radium-226 and microscopic lesions. Radioactivities and some elemental concentrations (e.g., Co, Pb, U) were greater in the Kanab North mine biological samples than in Canyon Mine biota, indicating a mining-related elemental signature. Mean rodent Ra-226 (111 Bq/kg dry weight [dry wt]) was 3 times greater than expected, indicating radioactive disequilibrium. Multiple soil sample U concentrations exceeded a screening benchmark, growth inhibition thresholds for sensitive plants, and an EC_{20} for a soil arthropod. Lesions associated with metals exposure were also observed more frequently in rodents at Kanab North than those at Canyon Mine but could not be definitively attributed to U mining. Our results indicate that Kanab North biota have taken up U mining-related elements owing to chronic exposure to surficial contamination. However, no literature-based effects thresholds for small rodents were exceeded, and only a few soil and vegetation thresholds for sensitive species were exceeded; therefore, adverse effects to biota from U mining-related elements at Kanab North are unlikely despite chronic exposure. *Integr Environ Assess Manag* 2019;15:112–125. Published 2018. This article is a US Government work and is in the public domain in the USA.

Keywords: Breccia pipe uranium mining   Body burdens   Chronic exposure assessment   Arizona   Colorado River

INTRODUCTION

The Grand Canyon watershed contains the largest U deposit in the United States, from which more than 150 000 metric tons of ore have been produced to date (Otton and Van Gosen 2010; Energy Fuels Inc. 2014). The relatively high-grade U-bearing ore is hosted in solution-collapse breccia pipes and intergrown with co-occurring sulfide and oxide minerals, which are often enriched in Cu, Pb, Mo, Tl, Co, As, and other elements (Alpine 2010). Uncertainty about the potential effects of U mining on environmental and cultural resources led to mineral extraction being limited on federal lands in the Grand Canyon watershed in 2012 (USDOI 2012). Although the primary concern associated with U mining is often focused on radiation, chemical exposure to U and its co-occurring ore body elements may be of greater concern. Toxicity varies among elements, exposure pathways, and biological receptors (Hinck et al. 2013, 2014). However, elemental concentrations in tissues, a fundamental requirement for determination of toxicity and risk to biota, have not been reported for historical or active U mines in the region.

Surficial concentrations of elements and radioisotopes in soil can increase during U ore production compared to preproduction; therefore, the mining process can create contaminant exposure pathways that need to be considered under risk management scenarios. Previous studies at reclaimed mines in the region have documented elevated concentrations of breccia pipe–related elements in onsite soils (Otton et al. 2010) that may represent a risk to wildlife (Hinck et al. 2013). The Kanab North breccia pipe mine (36° 68′73.26″ N, 112°64′37.26″ W), located north of the Grand Canyon, provided an opportunity to evaluate chronic exposure of biological receptors to these elements and radioisotopes. The Kanab North mine produced U ore (approximately 237 000 metric tons; 1260 metric tons as uranium oxide) from 1988 until 1991 and was placed on

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standby in 1992 (Otton and Van Gosen 2010; Ross and Moreton 2012). Reclamation of the site began in 2014, but large piles of mine waste rock were documented on the site surface until spring 2015. The weathering of exposed waste rock can enhance the environmental mobility of elements and radioisotopes (Attendorn and Bowen 1997; Lottermoser et al. 2005). Aeolian transport of soil, dust, and weathered rock is also an important vector for the movement of mining-related constituents off site and into the surrounding landscapes (Pozolotina et al. 2000). We collected vegetation and small rodents for chemical and radiological exposure characterization from the Kanab North mine, which was considered a chronic exposure site because of its decades-long postmining, unreclaimed status. Our hypothesis was that exposure and effects of elements and radioisotopes would be greater at the Kanab North mine than at the Canyon Mine, a breccia pipe mine where ore has not yet been extracted. We also examined the translocation of elements and radioisotopes in roots and above-ground vegetation (AGV) collected from the former mine yard as indicators of tolerance and potential for trophic transfer to herbivores. Our aim was to identify potential plant species that sequester elements in the soil and roots, rather than translocating them to the AGV, as a method of disrupting an exposure pathway for browsers and grazers using the area post reclamation. However, it is important to note that this study was intended as an exposure assessment and not an ecological risk assessment.

MATERIALS AND METHODS

Study area

The Kanab North mine site is located in Mohave County, Arizona, USA, approximately 32 km south of Fredonia, Arizona, and 0.8 km west of Kanab Creek, a tributary of the Colorado River and the Grand Canyon. All ore was shipped to a mill near Blanding, Utah, during active operations from 1988 to 1991; no milling was performed at the mine site (Alpine 2010). Site reclamation began in 2014. However, as previously mentioned, large piles of mine waste rock were observed on the surface in spring 2015. Further reclamation progress in summer 2015 included the removal of the perimeter fence and a reduction in surface material. Elevated elemental concentrations in soils at the mine were reported by Otton et al. (2010). Little vegetation was present in the mine yard because of scraping and grading activities related to mining and initial reclamation activities.

Sample collection

Vegetation and soil were collected within the Kanab North mine yard in 2013, and small rodents were collected outside the former mine yard perimeter in 2015. All rodents were collected within 200 meters of the mine yard. The site was in reclamation during our 2015 sampling, but site remediation was not complete until late 2017 or early 2018, as previously described. In this way, we were unable to directly link element concentrations in vegetation with those in rodents, but the site still represented a chronic exposure pathway for rodents to mining-related elements. Rodent species presumed to have small home ranges and high site fidelity to the mine area were targeted (Wood et al. 2010; Hinck et al. 2014, 2017). Deer mice (*Peromyscus maniculatus*, n = 9) and brush mice (*P. boylii*, n = 10) were trapped with live traps (Sherman Traps, Tallahassee, Florida). Animals were euthanized (carbon dioxide), and the livers and kidneys were harvested. The left kidneys and livers were immediately preserved in 10% neutral buffered formalin for histopathological examination. The carcass remainders (hereafter referred to as whole bodies; for example, soft tissues, fur, bones, teeth, gastrointestinal tracts) and right kidneys were frozen separately for chemical analyses. All collection, handling, and euthanasia procedures followed animal care and use guidelines approved by the US Geological Survey and the Northern Arizona University Institutional Animal Care and Use Committees and allowed under Arizona Game and Fish Department's Scientific Collecting Permit (No. SP616013 and SP7115011).

Needle and thread (a grass; *Hesperostipa comata*), sagebrush (*Artemisia tridentata*), and saltcedar (*Tamarix chinensis*) were growing within the mine yard where elevated elemental concentrations in soil had been previously documented (Otton et al. 2010) and may improve our understanding of species tolerant of elevated concentrations of U and other co-occurring elements. To determine if these species translocate contaminants from soil and roots into the AGV, nonrandom samples (n = 3 per species) were split into AGV and root portions for chemical analysis. The soil surrounding each root ball was also collected for separate chemical analysis. Sampling was not intended as an extensive, nonbiased spatial investigation. Saltcedar occurred only near the detention pond; sagebrush and 2 needle and thread samples were collected downwind of the mine, and 1 needle and thread sample was collected near the waste rock pile. A basic site orientation map is provided in the Supplemental Data, Figure S1, to indicate these locations. All chemical and radiological samples were shipped and stored frozen prior to processing and analysis. Data from Canyon Mine, as a premining reference, are included for comparisons with Kanab North. Canyon Mine (35°52′59.3″ N, 112°05′46. 1″ W) data are described elsewhere (Hinck et al. 2017).

Chemical analyses

Samples were processed for elemental and radiological analyses by lyophilization and homogenization (see Supplemental Data Section 1). The rodents were not depurated, and furs were not washed prior to processing for analyses. This approach was used to reflect rodent exposure pathways; in addition to inhalation, ingestion, and dermal contact and fur adherence during burrowing and foraging, incidental soil ingestion during grooming and feeding is an important exposure pathway (French et al. 1965; Beyer et al. 1994). Root tissues were washed with deionized water prior to processing to remove as much surficial soil as possible; AGV tissues were processed unwashed to reflect the dietary uptake of the rodents and other animals.

Inductively coupled plasma mass spectrometry (ICP-MS; PerkinElmer Elan DRC-e) following microwave-assisted acid digestion (MARS 6 Xpress) was used to quantify total recoverable Ag, Al, As, Bi, Cd, Co, Cu, Fe, Mo, Ni, Pb, Th, Tl, U, and Zn in the samples (similar to USEPA 2014). The microwave digestion approaches (similar to USEPA 1996) were intended to solubilize metals that could become biologically or environmentally available; additional information about the digestion matrices is given in Supplemental Data Section 1. Mercury was measured with a direct mercury analyzer (Milestone DMA-80; similar to USEPA 1998), and Se concentrations were determined with flow injection–hydride generation–atomic absorption spectrophotometry (FI-HG-AAS, PerkinElmer AAnalyst 400 with FIAS-400; similar to USEPA 1994). Kidney sample weights were insufficient for Hg and FI-HG-AAS Se analyses. Although Se is typically accessible by ICP-MS, at the time of analyses, the sensitivity of the laboratory ICP-MS was insufficient to accurately measure low-level Se, and the Se concentrations for Kanab North kidneys were too low for the laboratory to have confidence in the results. Therefore, kidney Se concentrations are not reported. All elemental concentrations are reported on a dry weight basis (mg/kg dry wt). The estimated method quantification limits (MQLs) are given in Supplemental Data Table S1. Quality control (QC) sample analyses indicated that the analyses were generally in control; a summary of the QC results for elemental analyses is given in Supplemental Data Section 2.

Radiochemical analyses

Radiochemistry measurements were intended to evaluate radioactive species for which the radiation doses to biota may be associated with health risks. Portions of the lyophilized rodent whole bodies, AGV, roots, and soil were screened for gross alpha and beta activities by gas flow proportional counting (USEPA 1986). Samples that screened high for gross alpha and beta activities ($n = 2$ for rodents; $n = 9$ for soils; $n = 16$ for plants) were analyzed by alpha spectroscopy for isotopic U (U-234, U-235, U-238; US DOE 1997), isotopic Th (Th-228, Th-230, Th-232; US DOE 1997), and Ra-226 (rodents only; Maxwell and Culligan 2012) to assess exposure of the biota to naturally occurring U and Th radioisotopes. Results for U-234 and U-235 were provided as U-233/234 and U-235/236, but U-233 and U-236 are not naturally occurring and were therefore considered not present in our samples. Reporting limits (RLs) and QC information for these analyses are given in Supplemental Data Section 2.

Histopathological analyses

Formalin-fixed liver and kidney samples were dehydrated, embedded in paraffin, sectioned at 5 μm, stained (hematoxylin and eosin), and examined with a light microscope (Luna 1968) for lesions (i.e., hepatic vacuolation, periportal inflammation, hepatic mineralization, hepatic degeneration or necrosis, granulomas, parasite presence, extramedullary hematopoiesis, biliary hyperplasia, kidney inflammation, kidney regeneration, and kidney karyomegaly) potentially associated with toxicosis (e.g., Thoolen et al. 2010). Lesions were qualitatively scored as absent, mild, moderate, or severe.

Statistical analyses

All computations and statistical analyses were performed with Version 9.4 of the Statistical Analysis System (SAS Institute, Cary, North Carolina). Elemental and radiochemical concentrations were statistically analyzed as dry wt values and were log10 transformed to mitigate the effect of a few large values and make the comparisons very conservative. Differences in concentrations were evaluated with analysis of variance (ANOVA) by SAS PROC GLM. Least-squares means, which are adjusted for all factors in the ANOVA models, were evaluated as Fisher's unrestricted least significant difference (Saville 1990). A conservative alpha level of 0.01 was used for these comparisons to protect against experiment-wise error (as suggested by Saville [1990]). A value of one-half the MQL was substituted for censored values in all statistical analyses. If all samples were less than the MQL for a given matrix, that matrix was excluded from the statistical analyses. As previously mentioned, vegetation concentrations were not used to evaluate dietary uptake in rodents because rodent and vegetation samples were not spatially or temporally colocated. Statistical comparisons among the 3 vegetation species at Kanab North were not made because of the nonrandomized collection approach but were made for soil, root ball, and AGV within each species to evaluate element translocation. All element concentrations (mg/kg dry wt) are reported as arithmetic means and standard errors (SE); radioactivities are reported as arithmetic means and SE in Bq/kg dry wt. Isotopic Th and U data were not collected for Canyon Mine, with the exception of U-238 by gamma spectrometry; therefore, comparison for radioisotope results between mines could not be made. Concentrations were compared with available literature-based effect thresholds (multiple types; e.g., LOAECs, reproductive effects, inhibition of germination, etc.) to assess rodent and vegetation exposures (Hinck et al. 2014). Concentrations of As and Hg in deer mice whole bodies could not be statistically compared between sites because neither element was detected in Canyon Mine samples (Hinck et al. 2017).

RESULTS

Radiochemistry

Soil and vegetation. Gross alpha and beta activities were greatest in soil and least in AGV for all Kanab North vegetation species; these differences were significant for gross alpha in saltcedar (Table 1). Gross alpha and beta activities were significantly greater in needle and thread and sagebrush AGV at Kanab North than in mixed grasses and shrubs AGV at Canyon Mine, respectively (Table 1). Concentrations of Th-228 in needle and thread soil were significantly greater than Th-228 in AGV. In saltcedar, Th-230 soil concentrations were significantly greater than those

Table 1. Mean radioactivities (±standard error; Bq/kg dry weight) for rodent whole bodies,[1] soil, root, and AGV from Kanab North, compared with mixed-species AGV grasses and shrubs from Canyon Mine (Hinck et al. 2017)

	Gross activities			Isotopes							
Matrix	n	Gross α	Gross β	n	Th-228	Th-230	Th-232	U-234	U-235	U-238	Ra-226
Mammal											
Brush mouse	6	100 ± 17 a	410 ± 48 a	0	nm	nm	nm	nm	nm	nm	nm
Deer mouse	8	140 ± 33 a	460 ± 52 a	2	<37 nd	<37 nd	<37 nd	38 ± 20 nd	<37 nd	37 ± 18 nd	120 ± 48 nd
Deer mouse (CM)	10	<150 a	440 ± 130 a	10	nm	nm	nm	nm	nm	<2600 nd[2]	nm
Needle and thread											
Soil	3	7800 ± 2700 a	3300 ± 1100 a	3	160 ± 13 b	1400 ± 570 a	<37 nd	680 ± 280 a	39 ± 20 a	730 ± 300 a	nm
Roots	1 [3]	3600 nd	2000 nd	1	<37 nd	440 nd	<37 nd	420 nd	<37 nd	450 nd	nm
AGV	3	730 ± 430 aB	790 ± 280 aB	3	<37 a	110 ± 44 a	<37 nd	81 ± 31 a	<37 a	78 ± 19 a	nm
AGV grass (CM)	8	<150 A	360 ± 41 A	8	nm	nm	nm	nm	nm	<1700 nd [2]	nm
Sagebrush											
Soil	3	21000 ± 17000 a	4800 ± 3300 a	3	59 ± 40 a	2100 ± 1700 a	<37 nd	960 ± 780 a	64 ± 46 a	960 ± 740 a	nm
Roots	3	6800 ± 6200 a	3800 ± 3400 a	3	<37 a	59 ± 30 a	<37 nd	730 ± 490 a	61 ± 27 a	750 ± 530 a	nm
AGV	3	690 ± 170 aB	1000 ± 110 aB	3	<37 a	97 ± 53 a	<37 nd	41 ± 22 a	<37 a	45 ± 6 a	nm
AGV shrub (CM)	8	<150 A	530 ± 55 A	8	nm	nm	nm	nm	nm	<1700 nd [2]	nm
Saltcedar											
Soil	3	33000 ± 11000 c	8800± 3500 a	3	49 ± 31 a	5300 ± 2900 b	37 ± 19 a	2900 ± 1600 b	150 ± 77 a	2800 ± 1400 a	nm
Roots	3	3800 ± 1600 b	2400 ± 1000 a	3	<37 a	55 ± 21 a	<37 a	3700 ± 3400 b	220 ± 200 a	3900 ± 3700 a	nm
AGV	3	350 ± 270 a	460 ± 200 a	3	<37 a	<37 a	<37 a	<37 a	<37 a	<37a	nm

Means followed by a different letter are significantly different at $P < 0.01$ (see text for details). Lower case, comparisons within each Kanab vegetation species. Upper case, comparisons between Kanab North and Canyon AGV. Needle and thread roots not compared to AGV or soil because n = 1 (see footnote 3 below).
Reporting limits of 150 Bq/kg for gross alpha activity, 370 Bq/kg for gross beta activity, 37 Bq/kg for isotopic U and Th, and 18.5 Bq/kg Ra-226 applied to means.
AGV = above-ground vegetation; CM = Canyon Mine; nm = not measured;
nd = statistical differences not determined because measured concentrations were below the MQL of the data set being compared, or n = 1.
[1]Whole bodies include all tissues except livers and kidneys, which were removed for separate analyses (see text for details). Rodent furs were not washed prior to processing and may include elemental contributions from soil and dust. Animals were not depurated; digestive tracts may include vegetation (dietary) and soil contributions.
[2]U-238 in CM rodent and vegetation samples was determined by gamma spectrometry; no samples had positive detections. Reporting limits for gamma spectrometry were not assigned; values above are maximum value of "minimum detectable concentration" for the matrix.
[3]The total available dry weight of each root sample replicate for needle and thread was very low; therefore, priority was assigned to elemental analyses. Two replicates were fully consumed for elemental analyses, and only one replicate was available for radiochemistry.

in roots and AGV, while differences in U-234 soil and root concentrations were not significant. The U-234 concentrations were significantly less in AGV compared to soil and roots. However, measured activities generally had wide error ranges (Table 1).

Small rodents. Gross alpha activities were below the RL (150 Bq/kg dry wt) in all deer and brush mice whole bodies at Kanab North and Canyon Mine; gross beta activities were low (410–460 Bq/kg dry wt; Table 1). All Th isotopes and U-235 were below the RL (<37 Bq/kg dry wt); U-234 and U-238 were also low (37–38 Bq/kg). Mean Ra-226 activity in the deer mice at Kanab North (mean 120 Bq/kg dry wt) was approximately 3 times that of U isotopes (Table 1).

Elemental concentrations

Vegetation and soil. Elemental concentrations differed among vegetation types and sampling location (Table 2); Hg was detected in few samples ($n = 2$ AGV; $n = 2$ soil; Supplemental Data Table S1). Mean concentrations of As, Co, Cu, Pb, Ni, Se, Ag, and Tl in AGV needle and thread at Kanab North were not significantly different from those in AGV of mixed grass species at Canyon Mine. Likewise, mean concentrations of Al, Bi, Cd, Co, Cu, Fe, Pb, Se, Th, and Zn in AGV shrubs were not significantly different between mine sites (Table 2); concentrations of Bi, Cd, Ag, and Tl in AGV grass at both sites were generally low and at or near the MQL. Canyon Mine mixed grass species AGV had 5 to 12.5 times greater mean concentrations of Al, Bi, Cd, Fe, and Th than needle and thread at Kanab North (Table 2), although mean Bi and Cd AGV grass concentrations were at or near the MQL at both sites. Mean concentrations of As, Mo, Ni, Ag, Tl, and U were 2 to 165 times greater in Kanab North sagebrush than in Canyon Mine mixed shrub species; Mo, U, and Zn were also 2 to 68 times greater in needle and thread AGV at Kanab North than in mixed grasses at Canyon Mine (Table 2).

Mean concentrations were greater in soil, followed by roots and then AGV tissue for the following elements within these Kanab North vegetation species: Al (needle and thread, sagebrush, saltcedar); As (needle and thread, saltcedar); Cd (saltcedar); Co (needle and thread, saltcedar); Cu (needle and thread); Fe (needle and thread); Pb (needle and thread, saltcedar); and Ni (needle and thread, saltcedar) (Table 2). Concentrations of Bi, Hg, and Ag (AGV and roots: needle and thread, sagebrush, saltcedar) were generally low and at or near the MQL. Soil concentrations of As, Fe, and Ni surrounding sagebrush root balls were greatest (compared to roots and AGV), but root and AGV concentrations were not significantly different. Similarly, saltcedar Cu, Fe, Tl, Th, and Zn concentrations were greatest in soil but were not statistically different in roots and AGV. Differences in concentrations of Cd, Co, Cd, Mo, Se, Ag, Tl, Th, and U in sagebrush soil, roots, and AGV were not significant; likewise, differences in concentrations of Mo (needle and thread, saltcedar), Se (needle and thread, saltcedar), Th (needle and thread), U (needle and thread), and Zn (needle and thread) were not significantly different in soil, roots, and AGV (Table 2). Concentrations of Cd (needle and thread), Tl (needle and thread), and U (saltcedar) were not statistically different for the roots and soil but were greater than AGV concentrations. Sagebrush Zn concentrations were not statistically different for soil and AGV or for roots and AGV; sagebrush Pb concentrations in AGV were greater than in the roots (Table 2).

Small rodent whole bodies. Mean concentrations of Al, Th, and Zn in whole-body samples were not statistically different in brush mice and deer mice at Kanab North and in deer mice at Canyon Mine (Table 3). The Fe concentrations in deer and brush mice at Kanab North were not statistically different, but the mean concentration of Fe in Kanab North deer mice was 2.7 times greater than in Canyon Mine deer mice. Concentrations of Bi, Cd, Ag, and Tl in whole bodies were typically at or below the MQL (Supplemental Data Table S1) for brush mice at Kanab North and deer mice at both Kanab North and Canyon Mine. Statistical comparisons for As and Hg concentrations could not be made between Kanab North and Canyon Mine, but mean concentrations were of similar magnitude for brush and deer mice at Kanab North. Mean concentrations of Se were not significantly different in brush mice and deer mice at Kanab North, but Canyon Mine deer mice had up to 1.8 times greater whole-body Se concentrations than the Kanab North brush and deer mice. Whole-body concentrations of Co, Mo, Ni, and U were not statistically different between brush and deer mice at Kanab North but were 1.6 to 56 times greater in deer mice from Kanab North than in deer mice from Canyon Mine (Table 3). Copper concentrations in deer mice were not statistically different at Kanab North and Canyon Mine, but means were 1.3 to 1.5 times greater than concentrations in Kanab North brush mice. Mean whole-body concentrations of Pb were greatest in Kanab North deer mice (1.67 mg/kg dry wt), followed by Kanab North brush mice (0.66 mg/kg dry wt), and Canyon Mine deer mice (0.37 mg/kg dry wt; Table 3).

Small rodent kidneys. Differences between mean concentrations of Cd, Cu, Mo, Tl, and Zn in kidneys were not significant for brush mice and deer mice at Kanab North, nor for deer mice at Kanab North and Canyon Mine (Table 3). Mean kidney Al, As, Bi, Co, and Ag concentrations were at or near the MQL at Kanab North (deer and brush mice); of these elements, only kidney Al was statistically different at Kanab North (4 mg/kg dry wt) compared to Canyon Mine (9 mg/kg dry wt; Table 3). Lead was greater in Kanab North deer mice kidneys (mean 0.65 mg/kg dry wt) than in brush mice kidneys (mean 0.06 mg/kg dry wt), but kidney Pb in Canyon Mine deer mice and Kanab North brush and deer mice were not statistically different. The mean kidney Fe concentration was greatest in brush mice at Kanab North, but results for brush and deer mice at Kanab North were not statistically different, as were results for deer mice at Kanab North and Canyon Mine.

Differences in the Ni kidney concentrations for brush and deer mice at Kanab North, and for deer mice at Kanab North and Canyon Mine, were not significant; however, the mean Ni

Table 2. Mean concentrations (±standard error; mg/kg dry weight) of elements in soil, washed roots, and unwashed AGV species at Kanab North, and comparisons with AGV mixed-species grasses and shrubs from Canyon Mine (Hinck et al. 2017)

	Kanab North, needle and thread grass			Canyon Mine, mixed grasses	Kanab North, sagebrush			Canyon Mine, mixed shrubs	Kanab North, saltcedar		
Element[1]	Soil (n = 3)	Roots (n = 3)	AGV (n = 3)	AGV (n = 24)	Soil (n = 3)	Roots (n = 3)	AGV (n = 3)	AGV (n = 24)	Soil (n = 3)	Roots (n = 3)	AGV (n = 3)
Al	11000 ± 1100 c	3300 ± 1600 b	160 ± 3 aA	2000 ± 280 B	13000 ± 480 b	730 ± 300 a	1100 ± 550 aA	1500 ± 240 A	6900 ± 494 c	190 ± 34 b	59 ± 4 a
As	17.8 ± 5.4 c	4.59 ± 0.67 b	0.84 ± 0.15 aA	0.58 ± 0.12 A	30.7 ± 13.7 b	2.32 ± 0.80 a	1.95 ± 0.27 aB	0.68 ± 0.04 A	95.9 ± 25.6 c	2.33 ± 0.46 b	0.91 ± 0.08 a
Bi	0.12 ± 0.01 a	0.07 ± 0.02 a	0.01 ± 0.00 aA	0.08 ± 0.03 B	0.10 ± 0.00 a	0.03 ± 0.02 a	0.07 ± 0.03 aA	0.08 ± 0.03 A	0.10 ± 0.00 a	0.02 ± 0.00 a	0.02 ± 0.00 a
Cd	0.29 ± 0.07 b	0.21 ± 0.03 b	0.02 ± 0.01 aA	0.08 ± 0.01 B	0.46 ± 0.18 a	0.39 ± 0.09 a	0.16 ± 0.02 aA	0.28 ± 0.03 A	0.91 ± 0.28 c	0.11 ± 0.03 b	0.07 ± 0.02 a
Co	11.3 ± 3.4 c	4.4 ± 0.3 b	0.40 ± 0.08 aA	0.78 ± 0.12 A	18.6 ± 10.8 a	1.8 ± 0.8 a	1.15 ± 0.23 aA	0.57 ± 0.08 A	41.3 ± 8.2 c	4.2 ± 2.2 b	0.36 ± 0.05 a
Cu	68.4 ± 41.8 c	12.7 ± 0.8 b	3.8 ± 0.3 aA	4.9 ± 0.2 A	31.1 ± 15.1 a	14.4 ± 1.1 a	14.3 ± 2.2 aA	9.6 ± 0.5 A	59.1 ± 1.1 b	12.9 ± 4.0 a	7.4 ± 1.0 a
Fe	10000 ± 600 c	3100 ± 1300 b	190 ± 17 aA	1400 ± 220 B	13000 ± 67 b	540 ± 220 a	920 ± 430 aA	710 ± 93 A	11000 ± 630 b	280 ± 41 a	190 ± 36 a
Pb	23.2 ± 8.0 c	4.96 ± 0.95 b	0.70 ± 0.21 aA	1.1 ± 0.1 A	22.6 ± 10.8 c	1.01 ± 0.42 a	1.90 ± 0.57 bA	1.0 ± 0.1 A	40.3 ± 7.9 c	0.95 ± 0.28 b	0.20 ± 0.05 a
Hg	<0.06 a	<0.06 a	<0.06 aA	0.02 ± 0.00 A	<0.06 a	<0.06 a	0.04 ± 0.01 aB	0.02 ± 0.00 A	0.05 ± 0.01 a	<0.06 a	0.04 ± 0.01a
Mo	7.9 ± 6.2 a	24.3 ± 13.2 a	37.8 ± 25.4 aB	1.56 ± 0.11 A	7.8 ± 6.4 a	11.7 ± 3.5 a	11.8 ± 1.5 aB	0.74 ± 0.08 A	57.9 ± 16.9a	28.7 ± 7.8 a	23.0 ± 2.7 a
Ni	19.9 ± 3.7 c	10.8 ± 1.1 b	1.7 ± 0.1 aA	2.0 ± 0.2 A	30.4 ± 14.4 b	3.3 ± 0.8 a	4.3 ± 0.8 aB	1.8 ± 0.2 A	59.3 ± 7.2 c	12.4 ± 5.3 b	1.6 ± 0.1 a
Se	0.51 ± 0.17 a	0.31 ± 0.04 a	0.20 ± 0.05 aA	0.17 ± 0.01 A	0.66 ± 0.27 a	0.21 ± 0.02 a	0.24 ± 0.03 aA	0.17 ± 0.02 A	1.28 ± 0.07 a	0.92 ± 0.23 a	1.34 ± 0.24 a
Ag	0.23 ± 0.13 a	0.07 ± 0.02 a	0.01 ± 0.00 aA	0.01 ± 0.00 A	0.29 ± 0.22 a	0.02 ± 0.01 a	0.03 ± 0.01 aB	<0.02 A	0.96 ± 0.26 c	0.09 ± 0.03 b	0.01 ± 0.00 a
Tl	0.54 ± 0.23 b	0.20 ± 0.04 b	0.03 ± 0.00 aA	0.04 ± 0.01 A	0.83 ± 0.53 a	0.15 ± 0.01 a	0.07 ± 0.02 aB	0.03 ± 0.01 A	1.97 ± 0.15 b	0.68 ± 0.08 a	0.77 ± 0.07 a
Th	3.79 ± 0.34 a	0.96 ± 0.39 a	0.09 ± 0.08 aA	0.49 ± 0.07 B	4.05 ± 0.26 a	0.10 ± 0.06 a	0.28 ± 0.14 aA	0.21 ± 0.02 A	2.81 ± 0.15 b	0.07 ± 0.05 a	<0.003 a
U	54.1 ± 21.9 a	70.0 ± 50.1 a	3.39 ± 1.51 aB	0.05 ± 0.01 A	82.4 ± 63.9 a	35.5 ± 23.0 a	8.24 ± 1.73 aB	0.05 ± 0.01 A	223 ± 94 b	77.2 ± 21.6 b	1.99 ± 0.42 a
Zn	79 ± 22 a	99 ± 36 a	51 ± 24 aB	23 ± 1 A	99 ± 50 b	27 ± 0 a	57 ± 1 abA	35 ± 2 A	263 ± 83 b	29 ± 4 a	26 ± 3 a

Means followed by a different letter are significantly different at $P < 0.01$ (see text for details). Lower case, comparisons of soil, roots, and AGV within each Kanab North species. Upper case, comparisons between Kanab North AGV and Canyon Mine AGV. AGV portions are unwashed and likely contained different amounts of surficial dust. Root portions are washed but likely contain residual amounts of soil.

AGV = above-ground vegetation.

[1]Regional median soil concentrations (Van Gosen et al. 2016) are 4.9 wt% Al, <10 mg/kg As, <0.5 mg/kg Bi, <0.5 mg/kg Cd, 10 mg/kg Co, 22 mg/kg Cu, 2.3 wt% Fe, 13 mg/kg Pb, <0.05 mg/kg Hg, <2 mg/kg Mo, 25 mg/kg Ni, <1 mg/kg Se, 0.08 mg/kg Ag, <0.5 mg/kg Tl, 10.1 mg/kg Th, 3.5 mg/kg U, and 57 mg/kg Zn. Different digestion and analytical methods were used to obtain regional values, compared to methods used for soils from Kanab North; refractory and other elements may be underrepresented at Kanab North on direct comparison (wt% = weight percent).

Table 3. Mean concentrations (±standard error; mg/kg dry weight) of elements in small rodents[1] from Kanab North. Premining concentrations from Canyon Mine deer mice (Hinck et al. 2017) are also presented

Element	Brush mouse, Kanab North (n = 10)	Deer mouse, Kanab North (n = 9)	Deer mouse, Canyon (n = 10)
Al			
Whole body	424 ± 141 a	889 ± 309 a	329 ± 48 a
Kidney	4 ± 1 a	4 ± 1 a	9.3 ± 2.0 b
As			
Whole body	0.79 ± 0.05 nd	0.85 ± 0.10 nd	<1.20 nd
Kidney	0.25 ± 0.05 a	0.15 ± 0.03 a	0.11 ± 0.02 a
Bi			
Whole body	<0.03 a	0.02 ± 0.002 a	<0.04 a
Kidney	0.021 ± 0.011 a	<0.02 a	<0.01 a
Cd			
Whole body	0.03 ± 0.004 a	0.04 ± 0.01 a	0.08 ± 0.02 b
Kidney	0.60 ± 0.27 a	1.06 ± 0.38 a	0.89 ± 0.45 a
Co			
Whole body	0.43 ± 0.05 b	0.54 ± 0.11 b	0.18 ± 0.02 a
Kidney	0.16 ± 0.06 a	0.15 ± 0.02 a	0.13 ± 0.01 a
Cu			
Whole body	6.89 ± 0.25 a	8.80 ± 0.33 b	10.4 ± 0.75 b
Kidney	15.21 ± 0.72 a	16.30 ± 0.57 a	17.56 ± 0.75 a
Fe			
Whole body	731 ± 133 ab	1068 ± 284 b	402 ± 54 a
Kidney	437 ± 40 b	380 ± 45 ab	251 ± 30 a
Pb			
Whole body	0.66 ± 0.06 b	1.67 ± 0.37 c	0.37 ± 0.10 a
Kidney	0.06 ± 0.02 a	0.65 ± 0.20 b	0.15 ± 0.04 ab
Hg			
Whole body	<0.15 nd	<0.15 nd	0.03 ± 0.01 nd
Mo			
Whole body	0.99 ± 0.10 b	1.14 ± 0.10 b	0.70 ± 0.04 a
Kidney	1.56 ± 0.44 a	2.27 ± 0.29 a	2.41 ± 0.11 a
Ni			
Whole body	1.86 ± 0.14 b	2.07 ± 0.27 b	0.60 ± 0.10 a
Kidney	0.40 ± 0.14 b	0.28 ± 0.12 ab	0.05 ± 0.001 a
Se			
Whole body	0.86 ± 0.04 a	0.98 ± 0.05 a	1.51 ± 0.22 b
Ag			
Whole body	<0.03 nd	<0.03 nd	<0.02 nd
Kidney	<0.02 nd	<0.02 nd	<0.01 nd

(*Continued*)

Table 3. (*Continued*)

Element	Brush mouse, Kanab North (n = 10)	Deer mouse, Kanab North (n = 9)	Deer mouse, Canyon (n = 10)
Tl			
Whole body	0.008 ± 0.002 a	0.028 ± 0.009 a	0.011 ± 0.002 a
Kidney	0.064 ± 0.018 a	0.101 ± 0.037 a	0.028 ± 0.004 a
Th			
Whole body	0.10 ± 0.04 a	0.10 ± 0.04 a	0.19 ± 0.05 a
Kidney	0.07 ± 0.02 a	0.07 ± 0.02 a	0.08 ± 0.03 b
U			
Whole body	0.73 ± 0.13 b	1.11 ± 0.26 b	0.02 ± 0.01 a
Kidney	0.10 ± 0.03 b	0.43 ± 0.23 b	<0.004 a
Zn			
Whole body	130 ± 11 a	221 ± 70 a	131 ± 17 a
Kidney	76 ± 3 a	79 ± 1 a	72 ± 4 a

Means followed by a different letter are significantly different at $P < 0.01$ (see text for details) for species among sites. Measurements of Hg in kidneys were not performed because of the small sample size, and Se concentration results were too low to be reliable by ICP-MS. These are not shown in this table; see text for details.
nd = statistical differences not determined because measured concentrations were below the MQL of the data set being compared.
[1]Whole bodies include all tissues except livers and kidneys, which were removed for separate analyses. Rodent furs were not washed prior to processing and may include elemental contributions from soil and dust. Animals were not depurated; digestive tracts may include vegetation (dietary) and soil contributions.

concentration in Kanab North deer mice kidney was 5 times greater than the mean Ni concentration for Canyon Mine deer mice kidneys (Table 3). Kidney Th concentrations were not statistically different in brush and deer mice at Kanab North but were greater in Canyon Mine deer mice kidneys. Differences in kidney U concentrations for brush and deer mice at Kanab North were not significant; means were 25 to 108 times greater in Kanab North kidneys (brush and deer mice) than in deer mice kidneys at Canyon Mine.

Histopathology

Lesions (Table 4) having positive detections in the kidney and liver tissues were hepatocellular vacuolation by glycogen (V-G) and lipid (V-L), hepatic inflammatory cell infiltration (PPI), renal inflammatory cell infiltration (INF), hepatic and renal mineralization (LMIN and KMIN, respectively), hepatocellular degeneration or necrosis (DEG), hepatic granulomas (GR), liver parasites (metazoan and protozoan; PS), hepatic extramedullary hematopoiesis (EMH), hepatic biliary hyperplasia (BH), renal tubular regeneration (KREG), and renal tubular epithelial karyomegaly (KARY). Conditions not detected in any sample were hepatic hemorrhage, hepatic hemosiderosis, and renal EMH. The most common lesion, glycogen vacuolation in the liver (V-G; Table 4) was observed in a majority of the mice from both Canyon Mine (deer mice, 83%) and Kanab North (brush and deer mice, 84%). One deer mouse from Canyon Mine and 2 brush mice from Kanab North also had mild discrete hepatocellular vacuolation consistent with lipid accumulation (V-L). Prevalence of hepatic EMH was also similar at Kanab North (37%) and Canyon Mine (42%).

Inflammatory cell infiltrates in the liver (PPI), typically characterized by portal infiltrates of mononuclear cells, were more common in mice from Kanab North, with 11 of 19 animals (58%) showing mild to moderate inflammation, compared to mild inflammation in only 1 of 12 (8%) animals at Canyon Mine (Table 4). Similarly, liver granulomas (GR) were more common in mice from Kanab North (9 of 19, 47%) than in those from Canyon Mine (0 of 12, 0%). Five of 19 mice at Kanab North were observed to have mild hepatic mineralization (LMIN), but this lesion was absent in Canyon Mine mice (Table 4). Kidney inflammation (INF) and tubular regeneration (KREG) lesions were also more prevalent in Kanab North mice than in Canyon Mine mice. Kidney inflammation was characterized by interstitial accumulation of mononuclear cells and ranged from mild to moderate in 4 of 19 (21%) Kanab North mice, compared with 0 of 10 Canyon Mine mice. Tubular regeneration was present in 6 of 19 (32%) Kanab North mice compared with 1 of 10 Canyon Mine mice (10%). Prevalence of hepatocellular degeneration or necrosis (DEG), hepatic extramedullary hematopoiesis (EMH), liver BH, KMIN, and renal tubular karyomegaly (KARY) were similar for mice at Kanab North and Canyon Mine.

DISCUSSION

Radiochemistry

Soil and vegetation. Although the statistical significance of observed differences could not be evaluated among species because of the nonrandom sampling approach at Kanab North, we used literature values (Supplemental Data Table S2) and mean results from Canyon Mine soils (n = 8; Katie Walton-Day, USGS, personal communication) to place our radiochemistry

Table 4. Summary of histopathological findings in Kanab North brush mice and deer mice kidneys and livers compared with Canyon Mine tissues

Lesion	Brush mouse, Kanab North n = # animals affected (% animals collected)				Deer mouse, Kanab North n = # animals affected (% animals collected)				Deer mouse, Canyon Mine n = # animals affected (% animals collected)			
	Absent	Mild	Moderate	Marked	Absent	Mild	Moderate	Marked	Absent	Mild	Moderate	Marked
Liver												
V-G	2 (20)	1 (10)	3 (30)	4 (40)	1 (11)	3 (33)	3 (33)	2 (22)	2 (17)	3 (25)	5 (41)	2 (17)
V-L	8 (80)	2 (20)	0 (0)	0 (0)	9 (100)	0 (0)	0 (0)	0 (0)	11 (92)	1 (8)	0 (0)	0 (0)
PPI	4 (40)	5 (50)	1 (10)	0 (0)	4 (44)	3 (33)	2 (22)	0 (0)	11 (92)	1 (8)	0 (0)	0 (0)
LMIN	7 (70)	3 (30)	0 (0)	0 (0)	7 (78)	2 (22)	0 (0)	0 (0)	12 (100)	0 (0)	0 (0)	0 (0)
DEG	9 (90)	1 (10)	0 (0)	0 (0)	8 (89)	0 (0)	1 (11)	0 (0)	9 (75)	3 (25)	0 (0)	0 (0)
GR	6 (60)	2 (20)	2 (20)	0 (0)	4 (44)	4 (44)	1 (11)	0 (0)	12 (100)	0 (0)	0 (0)	0 (0)
PS	9 (90)	1 (10)	0 (0)	0 (0)	7 (78)	2 (22)	0 (0)	0 (0)	12 (100)	0 (0)	0 (0)	0 (0)
EMH	5 (50)	5 (50)	0 (0)	0 (0)	7 (78)	2 (22)	0 (0)	0 (0)	7 (58)	3 (25)	2 (17)	0 (0)
BH	10 (100)	0 (0)	0 (0)	0 (0)	8 (89)	1 (11)	0 (0)	0 (0)	10 (83)	2 (17)	0 (0)	0 (0)
Kidney												
INF	8 (80)	2 (20)	0 (0)	0 (0)	7 (78)	1 (11)	1 (11)	0 (0)	10 (100)	0 (0)	0 (0)	0 (0)
KMIN	10 (100)	0 (0)	0 (0)	0 (0)	8 (89)	1 (11)	0 (0)	0 (0)	10 (100)	0 (0)	0 (0)	0 (0)
KREG	5 (50)	5 (50)	0 (0)	0 (0)	8 (89)	0 (0)	1 (11)	0 (0)	9 (90)	1 (10)	0 (0)	0 (0)
KARY	9 (90)	0 (0)	1 (10)	0 (0)	8 (89)	1 (11)	0 (0)	0 (0)	9 (90)	1 (10)	0 (0)	0 (0)

Hepatic hemorrhage, hepatic hemosiderosis, and renal EMH were not detected.
BH = biliary hyperplasia; DEG = degeneration or necrosis; EMH = extramedullary hematopoiesis; GR = granulomas; INF = inflammation; KARY = kidney karyomegaly; KMIN = kidney mineralization; KREG = kidney regeneration; LMIN = liver mineralization; PPI = periportal inflammation; PS = parasite; V-G = vacuolation by glycogen; V-L = vacuolation by lipid.

results in context. The range of mean gross alpha activity in soil at Kanab North was greater than results from baseline and U exploration and exploitation areas (Supplemental Data Table S2) and from Canyon Mine (480-1040 Bq/kg). Similarly, gross beta activity, Th-230, U-234, U-235, and U-238 in Kanab North soils were greater than literature values (Supplemental Data Table S2) and Canyon Mine results (gross beta, 700–1600 Bq/kg; Th-230, 33–124 Bq/kg; U-234, <110 Bq/kg; U-235, <10 Bq/kg; U-238, 20–104 Bq/kg; Katie Walton-Day, USGS, personal communication) values. Results for Th-228 (49–160 Bq/kg) and Th-232 (<37 Bq/kg) in Kanab North soils were indicative of background (Supplemental Data Table S2). Differences between literature and Canyon Mine values are likely related to differences in the natural mineralization (Naftz and Walton-Day 2016) of Canyon Mine compared with the literature locations; the mining activities at Kanab North contributed additional radioactivity to the baseline mineralized Canyon Mine levels. There also appeared to be a trend in Kanab North soil toward radioactive disequilibrium and enrichment of mean Th-230 relative to U-238; the lack of unity may indicate that breccia pipe mining at Kanab North opened the chemical system for surface weathering and fractional crystallization processes in soils (Scott 1968; Santos and Marques 2007). However, this interpretation is subjective because some practitioners consider ratios from unity to 2 to be in equilibrium.

Gross alpha activities in Kanab North AGV were similar to literature and Canyon Mine values, but AGV gross beta activity was more indicative of background. The U-238 activity in Kanab North was greater than a literature value for crops grown on a field treated with U-containing fertilizer (Supplemental Data Table S2). Interestingly, the ratio of Th-230 to U-238 in saltcedar roots indicated a potential radioactive disequilibrium, but with an excess of U-238 as opposed to the excess of Th-230 in soil. Our results may reflect contributions from the following sources: (1) plant tissue U has been shown to be dependent on soil U, but plant tissue Th is not dependent on soil Th (Sheppard et al. 1989); (2) saltcedar has unique physiological processes compared with the other plant species, including a greater water uptake rate and evapotranspiration (Di Tomaso 1998); (3) the preferable binding of U to the root cell walls by saltcedar (Rodriguez-Freire et al. 2018); and (4) the close proximity of these plants to the former detention pond.

Considering the radiochemistry results, mining-related activities have increased the presence of naturally occurring U on the surface at Kanab North. Radiological evaluations for weathering processes and the presence of efflorescent salts within the soils may be usefully included during active mining and remediation of mines on high-value lands like the Grand Canyon watershed, since these processes may increase the bioavailability of U and other cooccurring elements (Attendorn and Bowen 1997; Meza-Figueroa et al. 2009); however, these analyses were confounded for Kanab North by the large SE ranges, and further work was beyond the scope of this assessment. Land managers might also usefully consider radiochemical data for phytoremediation of breccia pipe sites (Pulford and Watson 2003). Replanting with species that can sequester radioisotopes below the surface and/or provide sufficient ground cover to reduce aeolian transport of dust would help minimize radiation exposure risks to surrounding environs. For example, while considered invasive, saltcedar appears to have sequestered U-234 in the roots, but AGV activities were below the RL.

Small rodents. The 3-fold increase in Ra-226 compared with U isotopes in deer mice (not determined for brush mice) indicates a radioactive disequilibrium, and the potential for Ra, as a bone-seeking carcinogen, to be a greater concern for biota health than U and Th at breccia pipe mine sites (Tim Jannik, Savannah River National Laboratory, personal communication). Cloutier et al. (1985) showed transfer of Ra-226 from soil and vegetation into the gut, skin, and bones of meadow voles (*Microtus pennsylvanicus*) living near U mine tailings. However, dose calculations (e.g., USDOE 2002) will be required to evaluate biological effects and toxicity drivers of mining-related radiation on the small rodents; these calculations are beyond the scope of this assessment.

Elemental concentrations

Soil. Generally, Canyon Mine soil elemental concentration ranges were similar (Katie Walton-Day, USGS, personal communication) to regional soil values (Van Gosen 2016). Soil elemental concentrations at Kanab North were also in line with Canyon Mine values, except for Co, As, Mo, and U. The soils surrounding the root balls of the saltcedar samples had mean Co, As, and Mo concentrations that were 1.4 to 5.3 times greater than the maximum regional concentration (Van Gosen 2016), and soil U for all 3 Kanab North plant species were 6 to 25 times greater than the regional maximum. Kanab North soil concentrations of Co, Ni, and U were similar to those in overburden at a partially remediated U mine (Supplemental Data Table S2). Soils associated with the saltcedar samples more frequently contained greater metal loads, potentially due to phytoexcretion (Kadukova et al. 2008) and to the proximity of these plants to the former detention pond. The mine yard was graded such that all surficial runoff, historically including runoff from ore and waste rock piles, would flow into the detention pond. Over time, this may have led to greater concentrations in and around the detention pond; Otton et al. (2010) noted substantial amounts of mine waste rock around the mine yard and that sediment had accumulated in the detention pond.

Elemental loads at Kanab North were also evaluated with literature-based toxicity thresholds, where available. All Kanab North soil U concentrations ($n = 11$) exceeded the soil-screening benchmark of 5 mg/kg (Efroymson et al. 1997). Some soil U concentrations ($n = 5$) also exceeded the phytotoxic soil concentration of 100 mg/kg for growth of Scots pine seedlings (*Pinus sylvestris*; Sheppard et al. 1985), thresholds for the growth inhibition of swiss chard (*Beta vulgaris*; 10 mg/kg; Sheppard et al. 1983), biomass increase of prairie grasses (50 mg/kg; *Aristida purpurea, Buchloe dactyloides, Schizachyrium scoparium*; Meyer et al. 1998), and an EC_{20} (85–150 mg/kg) for a soil arthropod, *Folsomia candida* (Sheppard and Stephenson 2012). Concentrations of Se in some Kanab North soils ($n = 6$) exceeded avian reproduction effect concentrations (0.9 to 3 mg/kg dry wt; USDOI 1998).

Soil As concentrations ($n = 11$) were greater than a gastric intubation dose range (>1 mg/kg As), which showed decreased locomotor activity in rats (Pryor et al. 1983), and a soil plant toxicity level (15 mg/kg; $n = 10$) based on total metal concentrations and growth (Khalid and Tinsley 1980; Munshower 1994; Mulvey and Elliott 2000; Kataba-Pendias and Pendias 2001). The Kanab North soil Ag concentrations were greater than effect thresholds for viability of heterotrophic bacteria in culture media (>0.01 mg/L; Albright et al. 1972), which may impede restoration efforts with biocrusts or other sensitive species; however, soil leaching studies would likely be required to assess the exact level of impact (i.e., solubility of As species). Soil Tl concentrations at Kanab North ($n = 6$) exceeded a threshold that indicates an anthropogenic source (>1.0 mg/kg; Kataba-Pendias and Pendias 2001; Wierzbicka et al. 2004). Additional literature-based comparison values and literature-based thresholds that were not exceeded are given in Supplemental Data Tables S2 and S3, respectively.

Vegetation. Concentrations of Cu, Zn, As, Ag, and Cd (Table 2) in Kanab North AGV were within literature-based "normal" plant concentration ranges (Supplemental Data Table S2), but AGV concentrations of Ni (sagebrush, $n = 3$ of 3), Tl (saltcedar, $n = 3$ of 3), and U (needle and thread, sagebrush, saltcedar; $n = 9$ of 9) were greater than "normal" (Supplemental Data Table S2). Indeed, Kanab North AGV U concentrations were also greater than those measured in grasses grown on U tailings (Supplemental Data Table S2). This is in contrast to mean AGV concentrations of Ni and Tl in mixed grass and shrub species at Canyon Mine, which were within "normal" plant ranges. It should be noted that mean U in Canyon Mine AGV (0.05 mg/kg dry wt) was slightly greater than the upper "normal" concentration of 0.015 mg/kg U (Supplemental Data Table S2), although this was expected because of the natural mineralization of breccia pipe sites (Van Gosen 2016; Naftz and Walton-Day 2016).

There is limited threshold information specific to the plant species occurring at Kanab North; many vegetation thresholds are for sensitive agricultural crops and forage species (Supplemental Data Table S2). Mean As in Kanab North sagebrush AGV was within the low end of the 1–20 mg/kg As phytotoxicity range (yield depression); however, this concentration range also overlaps the "normal" As plant concentration range (1–22 mg/kg). The abundance of sagebrush at breccia pipe sites across the Grand Canyon watershed suggests that As is well tolerated by this species, but this threshold should be considered during species selection for remedial planting. The mean Se AGV concentration (1.34 mg/kg) for saltcedar was close to a sublethal effects dietary threshold for rats (lifetime exposure, 1.4 mg/kg); $n = 2$ of 3 saltcedar AGV exceeded this threshold (Supplemental Data Table S3).

As previously described, mean AGV concentrations of Al, Bi, Cd, Fe, and Th in mixed Canyon Mine grass species were significantly greater than those in needle and thread AGV at Kanab North. Plant species-specific physical and physiological differences (Brekken and Steinnes 2004) likely contributed to the observed differences. For example, external plant structures may have permitted some Canyon Mine grass species to accumulate and retain greater loads of depositional soil and aeolian-transported dust (Alfani et al. 1996). The effect of removable surficial soil and dust on elemental concentration results was previously demonstrated at Canyon Mine (Hinck et al. 2017). Conversely, AGV concentrations of As (sagebrush), Mo (needle and thread), Ni (sagebrush), Ag (sagebrush), Tl (sagebrush), U (needle and thread, sagebrush), and Zn (needle and thread) were significantly greater at Kanab North than in mixed-species AGV at Canyon Mine. This was not surprising given the known cooccurrence of these elements with uranium ores in breccia pipes. Mining activities, coupled with plant physiological differences, potentially contributed to these results. For example, sagebrush AGV was likely able to retain greater loads of depositional soil and dust via trichomes (Kelsey 1984), which would increase soil-associated elements measured in the sagebrush.

Translocation of elements from soil to roots and AGV is an additional consideration for these results; root and AGV elemental uptake may be driven by active accumulation of plant-required nutrients (Caldwell et al. 2011). Statistical analyses indicated that needle and thread and saltcedar sequestered in the roots or transferred from the roots to the AGV significantly less Al, As, Cd, Co, Ni, and Pb; similar results were observed for Cu and Tl in needle and thread and Ag and U in saltcedar. However, root uptake and translocation occurred for some species and elements. Our results are consistent with previous findings that indicated that sagebrush (*A. tridentata* Nutt.) can translocate Mo from the soil to the leaves (Rickard and Van Scoyoc 1984). Most notably, AGV Pb concentrations for sagebrush were significantly greater than root Pb concentrations. While Pourrut et al. (2011) indicated that most of the Pb taken up by the roots of many plant species is not readily translocated into the AGV, sagebrush may be an exception. Some degree of translocation cannot be completely ruled out for all elements. Therefore, translocation (including hyperaccumulation), surficial dust loading capability, and soil stabilization should be considered during selection of vegetation species to be replanted during remediation to minimize the dietary uptake and bioaccumulation of mining-related elements by animals consuming vegetation at the former mine sites (e.g., Sorensen et al. 2009). For example, ruminants have a higher exposure risk from Co ingestion than monogastric animals (Gál et al. 2008); species differences should be considered for remediated lands that will be open to ruminant grazing. Information on elemental sequestration may also be important for plants used for medicinal or cultural purposes (e.g., Saenboonruang et al. 2018).

Small rodents. Our rodent results document that residual contamination left onsite at Kanab North (particularly Co, Pb, Mo, Ni, and U) has entered the food web, resulting in uptake by small rodents. However, in terms of the abundance of animals collected and histopathological findings, the effects appear limited despite this chronic exposure. Mining inputs, rodent species differences, dietary preferences, and soil element concentrations likely contributed to the Kanab North rodent results. Uptake mechanisms likely included dietary exposure to translocated elements, direct soil exposure by dermal contact and accumulation in the fur, ingestion of soil-covered AGV and other foodstuffs, burrowing, and grooming. Elemental variations between brush mice and deer mice at Kanab North (whole body, Cu and Pb; kidney, Pb) likely reflect differences in dietary preferences, life history strategies (e.g., foraging, caching), and habitat preferences (e.g., AGV cover, burrowing) between the 2 species (Hanson and Miera 1978; Vander Wall et al. 2001; Gottesman et al. 2004). Similarly, dietary preferences or alterations in food choices and availability at Kanab North may have contributed to differences in element loads in rodents at Kanab North compared with Canyon Mine (Everett et al. 1978).

Few literature-based whole-body and kidney reference, mining, and threshold values were available (Supplemental Data Tables S2 and S3) for context. Arsenic and Se concentrations in Kanab North rodents (Table 3) were within "normal" range, and Se did not exceed a mammalian reproductive depression threshold (>10 mg/kg; Supplemental Data Table S3). However, the Kanab North whole-body As concentration range overlapped a range given for As in wood mice and bank voles collected from a moderately contaminated As site (Supplemental Data Table S2); the Kanab North whole-body U concentration range overlapped ranges of U measured in voles and deer mice collected from U tailings, milling, and nuclear testing and disposal sites (Supplemental Data Table S2). Kanab North kidney concentrations of Cu, As, Mo, Cd, and Tl were generally within "normal" range (Supplemental Data Table S2), and the kidney U concentration only exceeded the minimum U lowest observed effect concentration value for renal damage in rats (1 mg/kg, Supplemental Data Table S3) in a single deer mouse. Cooke (2011) reported that insectivores may be exposed to and accumulate more Cd than the omnivorous species we studied. It should be noted that we were unable to study the aquatic pathway at Kanab North, which may have posed As and Se hazards similar to or greater than those previously noted at Canyon Mine for spadefoot tadpoles

(*Spea multiplicata*; Hinck et al. 2017). Therefore, land managers might consider species-specific traits (e.g., dietary and habitat preferences, life stages and metamorphic processes, incidental soil ingestion) to reduce biota exposure to elements during active mining through reclamation.

Histopathology

Liver and kidney lesions generally occurred more frequently in mice at Kanab North than at Canyon Mine, with the exception of hepatocellular vacuolation (consistent with glycogen accumulation) and hepatic EMH, which occurred with similar frequency at both sites. However, many of these lesions are not specific to U mining and typically considered normal when mild. For example, mild hepatocellular vacuolation is a common lesion that is heavily dependent on the fed or fasted state of the animal and is therefore unlikely to be related to chronic element or radiation exposure. Additional lesions thought unlikely to be associated with U mining are described in Supplemental Data Section 4. Periportal inflammation and liver granulomas are typically considered nonspecific findings with a variety of potential causes (e.g., immune system activation, infectious agents, xenobiotics) but may be related to radiation exposure at Kanab North (Thoolen et al. 2010; Morley 2012). For example, Silverman et al. (1969) noted that mice chronically exposed to gamma radiation were more susceptible to tularemia infection, and the organs of these mice had more extensive pathological changes than those of nonradiated mice. Similarly, prevalence of ectoparasite infection was higher in animals having close contact with radionuclide-contaminated soil (e.g., voles, shews) than in animals from noncontaminated areas (Maslov et al. 1967). Kidney inflammation and tubular regeneration were also more prevalent in Kanab North mice than in Canyon Mine mice (Table 4). Tubular degeneration and other tubular epithelial cell changes have been noted in rats exposed to U compared to control animals (Kennedy et al. 1995, Donnadieu-Claraz et al. 2007). Others have observed various immune responses, renal tubular dysfunction, cell damage, and other tubular histopathologies due to Cd and Ni (Dunnick and Fowler 1988; Sunderman 1988 and references therein; Cooke 2011). Each of these elements (U, Cd, Ni) were significantly greater in Kanab North rodent whole bodies than in Canyon Mine whole bodies; U was also greater in kidney tissues.

CONCLUSIONS

The results presented here indicate that small rodents and vegetation have been exposed to mining-related elements and radioisotopes at the Kanab North site. Although uptake has occurred, no effect thresholds for small rodents were exceeded, and only a few soil and vegetation thresholds for sensitive species were exceeded. Therefore, overall risk of adverse effects from U mining-related constituents in biota appears low. However, the availability of literature-based thresholds for both vegetation and small rodents is limited for many of our target elements. Studies at additional breccia pipe mining sites are planned to assess elemental and radioisotope exposures across the entire U mining life cycle (i.e., premining, active mining, postactive, and preremediation). In particular, aquatic pathways may provide an important route for trophic transfer and bioaccumulation of mining-related elements at these sites. Seasonal changes in element and radioisotope bioavailability, effects of precipitation and wind, soil conditions and leaching, plant uptake and bioconcentration, and animal foraging and caching behaviors may be worth further consideration (e.g., Alfani et al. 1996; Erry et al. 1999; Meza-Figueroa et al. 2009; Bidar et al. 2009). While we believe that these aspects are unlikely to alter the overall low-risk profile at Kanab North, they may have greater effects at active mines. Deer mice lung histopathology and particulate analyses, as a surrogate for human inhalation, may warrant investigation for protection of mine workers and site visitors (Williams et al. 2010). Ultimately, these results may assist land managers in making resource decisions about relative U mining risks, approaches to site remediation, and resource protection.

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SUPPLEMENTAL DATA

Section 1. Sample processing.
Section 2. Quality control.
Section 3. Literature-based comparison values.
Section 4. Histopathological changes not likely associated with mining.
Figure S1. An overview map of the Kanab North site in 2013, showing the general orientation of the former detention pond, waste pile, and downwind locations for vegetation collection.
Table S1. Estimated method quantification limits (mg/kg dry weight) for elements in sample types from Kanab North mine.
Table S2. Literature-based soil and rodent tissue concentrations (dry weight basis) from impacted and reference areas.

Table S3. Literature-based thresholds that were not exceeded at Kanab North.

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