Arch Environ Contam Toxicol (2013) 65:332–344
DOI 10.1007/s00244-013-9893-5

Derivation of Soil-Screening Thresholds to Protect the Chisel-Toothed Kangaroo Rat from Uranium Mine Waste in Northern Arizona

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Received: 5 November 2012 / Accepted: 3 March 2013 / Published online: 19 April 2013

Abstract. Chemical data from soil and weathered waste material samples collected from five uranium mines north of the Grand Canyon (three reclaimed, one mined but not reclaimed, and one never mined) were used in a screening-level risk analysis for the Arizona chisel-toothed kangaroo rat (*Dipodomys microps leucotis*); risks from radiation exposure were not evaluated. Dietary toxicity reference values were used to estimate soil-screening thresholds presenting risk to kangaroo rats. Sensitivity analyses indicated that body weight critically affected outcomes of exposed-dose calculations; juvenile kangaroo rats were more sensitive to the inorganic constituent toxicities than adult kangaroo rats. Species-specific soil-screening thresholds were derived for arsenic (137 mg/kg), cadmium (16 mg/kg), copper (1,461 mg/kg), lead (1,143 mg/kg), nickel (771 mg/kg), thallium (1.3 mg/kg), uranium (1,513 mg/kg), and zinc (731 mg/kg) using toxicity reference values that incorporate expected chronic field exposures. Inorganic contaminants in soils within and near the mine areas generally posed minimal risk to kangaroo rats. Most exceedances of soil thresholds were for arsenic and thallium and were associated with weathered mine wastes.

High-grade uranium ore was discovered in geologic features called "breccia pipes" in the Grand Canyon region during the late 1940s and became the subject of intense exploration during the 1970s. Uranium was mined from 7 breccia pipes north of the Grand Canyon during the 1980s and early 1990s. Uranium mining persists in the Grand Canyon area despite decreasing market values in the early 1980s because of the greater ore grades found in these deposits (Otton and Van Gosen 2010). Uranium price increases from 2005 to 2007 renewed interest in mining, which led to thousands of new mining claims in the Grand Canyon region. Growing public concern that uranium-mining activities could have adverse environmental, cultural, and social impacts prompted the withdrawal of approximately 1 million acres (404,686 ha) of federal lands from future mineral extraction to study the potential effects of uranium mining (Alpine 2010) and to prepare an environmental impact statement (Bureau of Land Management 2011). These federal parcels were subsequently withdrawn from mineral extraction for 20 years in early 2012 partially based on uncertainty associated with toxicological risks to wildlife and humans (Hinck et al. 2010; Department of Interior 2012). However, uranium mining during the next 20 years could increase in the region because existing valid claims were not affected by the federal land withdrawal; as many as 11 mines could proceed under the current restrictions.

Gaps in the scientific data related to evaluating the ecotoxicological risks of uranium mining in the Grand Canyon region have been identified (Hinck et al. 2010). Uranium mines are sources of radiation from uranium and its daughter products as well as chemical contaminants from uranium and other cooccurring inorganic constituents in the ore (e.g., arsenic, cadmium, copper, nickel, lead, selenium, and zinc). These other inorganic constituents may not pose radiation

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Electronic supplementary material The online version of this article (doi:10.1007/s00244-013-9893-5) contains supplementary material, which is available to authorized users.

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hazards in field exposures, but some of these elements are potentially as toxic, if not more toxic, to biota than uranium. Chemical analyses of biota for uranium and other contaminants commonly found in breccia pipes have not been performed, nor are these data readily available for regional species from other studies. Exposure pathways including ingestion, inhalation, absorption, and bioaccumulation, have been identified (Hinck et al. 2010) but not prioritized in terms of risk. Many species in the region have specialized life-history strategies that allow them to survive in the arid environment but may also increase their exposure to contaminants. For example, some reptiles, amphibians, birds, and mammals spend significant amounts of time in burrows, where they may inhale, ingest, or dermally absorb uranium and other contaminants while digging, eating, preening, and hibernating. As such, existing toxicity effect thresholds developed using common laboratory test organisms may have limited applicability in assessing risk given the physiology and behaviors of wild species compared with the standard laboratory model species.

Surface soils, weathered waste material, and sediments were collected in and around several reclaimed or inactive breccia-pipe uranium mines in 2009 to characterize inorganic concentrations (Otton et al. 2010). In the absence of inorganic concentration data from biota inhabiting these locations, our objective was to use inorganic concentrations in soil and weathered mine waste material (Otton et al. 2010) to conduct a screening-level risk analysis for the herbivorous Arizona chisel-toothed kangaroo rat (*Dipodomys microps leucotis*; hereafter, kangaroo rat). This endemic species found north of the Grand Canyon drinks essentially no water and has unique life-history strategies (e.g., seed caching, bathing in dust, using subterranean burrows; Hayssen 1991; Schmidt-Nielsen and Schmidt-Nielsen 1952; Schmidt-Nielsen 1964) that are important to consider when evaluating chemical exposure and subsequent risk. The limited population size of this subspecies places it at risk for extinction, which has led it to be designated as a “sensitive species” by the United States Forest Service and Bureau of Land Management (2011). We derived species-specific soil-screening thresholds for inorganic constituents to determine if they could be useful in beginning to establish remediation and restoration goals that would be protective of the kangaroo rat for nonradiation exposure. We also compared inorganic constituent concentrations in soils and weathered waste material among site types (never mined, reclaimed, and mined but not reclaimed) to determine if historical reclamation efforts decreased exposure and therefore risks from inorganic constituents. We did not evaluate the radiation risk because empirical radiation data are not available for the sites. Risk from radiation toxicity would need additional consideration to fully evaluate risk to biota at these mines and their adjacent habitats in northern Arizona (e.g., Beaugelin-Seiller et al. 2009).

Methods

Study Area

All sites are located north of the Grand Canyon in northern Arizona and represent a variety of lithostratigraphic units and topographic settings (Fig. 1 map; Otton et al. 2010). This arid area has sparse vegetation that is predominantly sagebrush and grasslands. One site had never been mined (Kanab South Pipe); one site was mined but not reclaimed (Kanab North Mine); and three sites were mined and reclaimed (Pigeon Mine, Hermit Mine, Hack Canyon mine complex). Exploratory drilling was performed at the Kanab South Pipe (36°40′39.81″ N latitude and 112°38′48.47″ W longitude), but ore grade and tonnage were insufficient to support mine development. The Kanab North Mine (36°41′14.42″ N latitude and 112°38′36.98″ W longitude) was mined from 1988 to 1990 and went on standby in 1992. Reclamation planning is currently underway for the Kanab North Mine. The Pigeon Mine (36°43′27.35″ N latitude and 112°31′40.80″ W longitude) was explored then mined from 1984 to 1989, and reclamation was completed by 1989 (mining took place in <1 year). Hermit Mine (36°41′24.81″ N latitude and 112°45′06.57″ W longitude) was mined in 1989, and reclamation was completed in 1990. Breccia pipes along Hack Canyon (near the confluence with Robinson Canyon; ~36°35′3.23″ N latitude and 112°48′34.31″ W longitude) were mined from 1981 to 1987; reclamation was completed in 1988. All ore was shipped to mills in Utah to be processed. However, the uranium and associated inorganic constituents remain at the mine sites in weathered waste material piles, stockpiled lower-grade ore, dust-contaminated soils, and reclaimed soil areas, each of which may be sources of exposure.

In general, reclamation of mine sites includes the restoration of the surface topography, vegetation, and drainage concomitant with mining activities and after mining ceased (Bureau of Land Management 2011). Reclamation of Hack Canyon, Hermit, and Pigeon mines included removal of surface stock piles, equipment, and structures; backfilling mine openings with waste rock and low-grade ore; sealing the mine shaft; recontouring the site using premining local topsoil or alluvium; covering remaining waste rock exposed at the surface with clean soil or alluvium; and revegetation of the mine site and haul roads to promote soil stabilization. Mine areas are vegetated to varying degrees and evidence of animal activity (e.g., sightings, scat, tracks) within the mine sites has been observed (Hinck, personal observation).

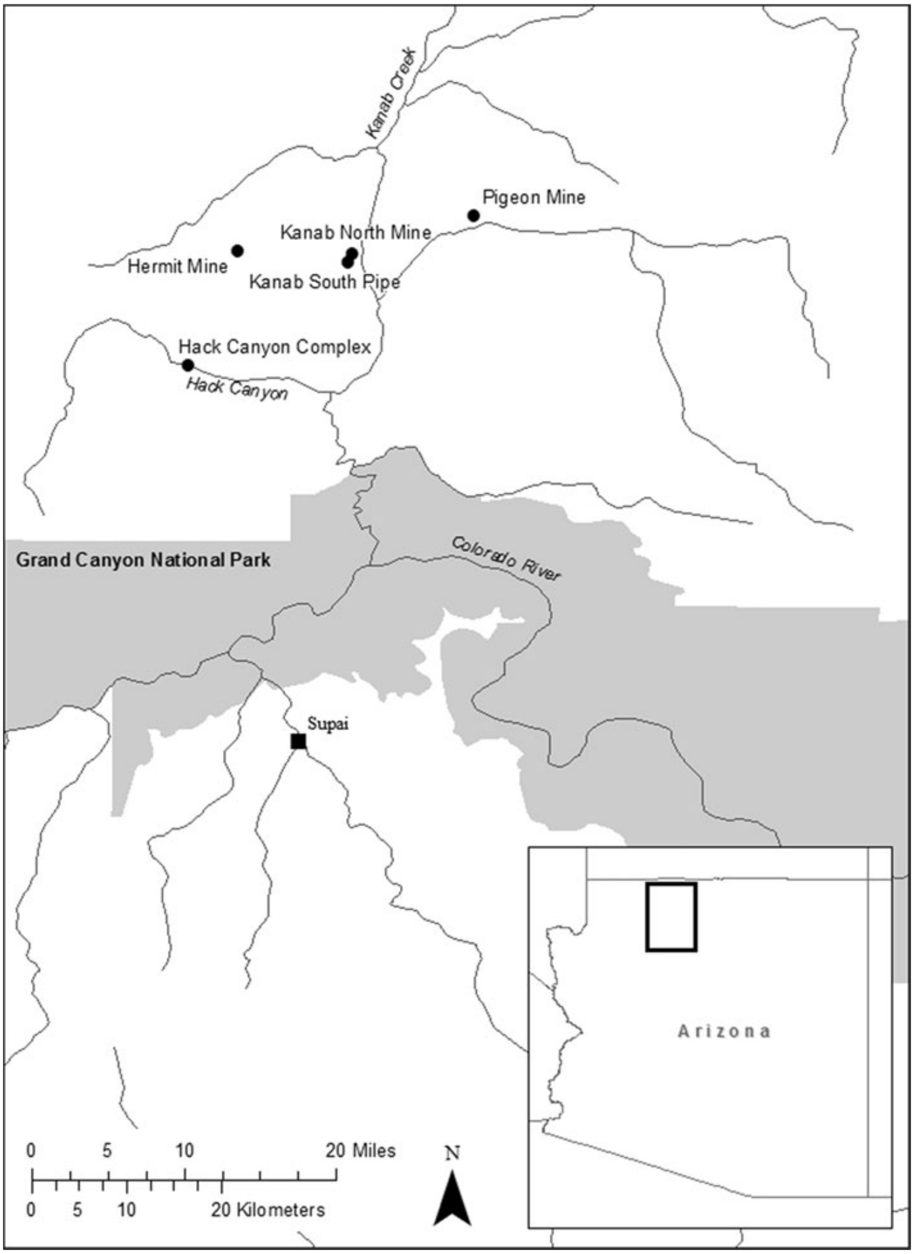

Fig. 1 Uranium mine sampling sites in northern Arizona, USA

Sampling and Geochemical Analysis

Collection of soil and weathered waste material samples from the mine sites has been previously described (Otton et al. 2010). Nonrandomized sample locations selected before arrival at each site were based on aerial images and designed to represent the anticipated range of chemical contamination. Sampling locations were chosen to characterize contaminant concentrations in surface soils (0–5 cm) outside and inside the mine area (Pigeon, Kanab North, and Hermit mines), weathered mine waste material left behind on the ground surface or in stream channels (Pigeon, Kanab North, and Hack Canyon mines), and unmined surface rocks. Soils outside the mine area were considered to be representative of local background conditions for our risk analysis. Surface litter of organic matter (leaves, needles, or twigs) or of pebbles or cobbles larger than ~2.5-cm diameter were removed. Soil was excavated using a stainless steel trowel at a 0- to 5-cm depth interval and passed through a sieve until 1–2 kg of sample was collected in a plastic 1-gallon bucket. Composite samples ($n \geq 5$ subsamples) of near-surface (0–5 cm depth) materials from a weathered mined waste-rock pile at the Kanab North Mine were also collected but not sieved.

Samples from each mine site included in this study are described here. Pigeon Mine samples included soil from within and outside of the reclaimed mine area and weathered waste material. Samples collected at the Hermit Mine include soil within and outside of the reclaimed area. Samples collected at the Kanab North Mine (mined but not reclaimed) included soil from within and outside the fenced perimeter and weathered waste material from a large ore pile and a small ore pile. Samples at the drilled but unmined Kanab South Pipe included soil around the perimeter of the site; one surface rock sample outside the pipe was collected. At Hack Canyon Mine, samples included weathered ore/waste material caught up in flash flood events and deposited along a stream channel.

Samples were prepared for chemical analysis according to previously described procedures (Otton et al. 2010). Chemical analysis of soil and rock samples included inductively coupled plasma–atomic emission spectrometry (ICP-AES) and ICP–mass spectrometry (ICP-MS) after acid digestion. Individual samples were digested using a mixture of hydrochloric, nitric, perchloric, and hydrofluoric acids, heated to dryness, and redissolved in nitric acid. This complete digestion is considered a total extraction and may result in greater concentrations than would be bioavailable to biota under natural conditions. Sample aliquots were aspirated into the ICP-AES and the ICP-MS spectrometers. Measured concentrations were within ±15 % of five times the lower limits of determination, and the calculated relative SD of duplicate samples was <15 %. Of the 42 elements previously reported (Otton et al. 2010), we present data only for arsenic, cadmium, chromium, copper, lead, nickel, and zinc because toxicological effects of these constituents to biological receptors has been well-documented in the scientific literature. Uranium and thallium were also included because they occur in high concentrations within breccia-pipe deposits. All inorganic concentrations were reported as dry weight (mg/kg).

Screening-Level Risk Analysis

The Arizona chisel-toothed kangaroo rat has a limited population size in shrub-dominated communities of northern Arizona; hence, its listing as a “sensitive species” by the United States Forest Service and BLM (Bureau of Land Management 2011). This species, which is active above ground throughout the year, avoids temperature fluctuations by constructing burrows at least 25 cm in depth and plugging burrow entrances daily. Studies with other species of kangaroo rats in Arizona deserts (Merriam’s kangaroo rat; *Dipodomys merriami*) provides insight into potential exposures in near-surface burrows and feeding behaviors during crepuscular and nocturnal foraging periods (Tracy and Walsberg 2002), wherein temperature and humidity regimes likely do not motivate preferences for occupancy of burrows at depths for extended times. Earlier synthesis publications similarly identified the range of general burrowing behaviors for kangaroo rats and clearly noted that soil attributes, including the depths attained to their burrow systems (e.g., Reichman and Smith, 1990), strongly influenced such behaviors. Seed foraging by raking through surficial sand/dirt, transporting seeds by way of pouches to caches in burrows, grooming (licking of forepaws before wiping fur and cleaning dirt off toes and forepaws with the mouth), dust bathing, and burrow construction and maintenance could increase contaminant exposure through inhalation and incidental ingestion.

Risk to kangaroo rats was evaluated based on dietary exposure doses used to derive protective soil-threshold concentrations. Dietary exposure doses (mg/kg/d) were calculated as the according to the following equation (Eq. 1):

$$\frac{\left(\left(\mathrm{IR}_{\mathrm{soil}} \times C_{\mathrm{soil}}\right) + \left(\mathrm{IR}_{\mathrm{vegetation}} \times C_{\mathrm{vegetation}}\right)\right) \times \mathrm{AF} \times \mathrm{EF}}{\mathrm{BW}}, \tag{1}$$

where IR represents ingestion rate (kg/day) and C represents chemical concentration (mg/kg). The exposure frequency was set at 100 % given that the home range for chisel-toothed kangaroo rats reported by Hayssen (<2 acres; 1991) was less than the area of individual mine sites ($\sim$20 acres). The absorption factor was assumed to be 100 % to provide conservative risk estimates. Preliminary sensitivity analysis indicated that body weight (BW) critically affected outcomes of exposed-dose calculations; therefore, BW or attributes linked to BW (e.g., age) predominately affected risk estimates. BW values were based on the mean values for juvenile (0.021 kg; Hayssen 1991) and adult chisel-toothed kangaroo rats from Arizona (0.0675 kg; Morton et al. 1980). Food IR (0.005 $\mathrm{kg}_{\mathrm{dry\ weight}}$/d) was derived from the metabolic rate for chisel-toothed kangaroo rats (Nagy et al. 1999). Given the available algorithms and empirical data underlying the application of allometric extrapolations and the range of algorithms advanced by experts in the field (e.g., Nagy et al. 1999; Sample and Arenal 1999; White 2003), the food IR was held equal for both juvenile and adult kangaroo rats to calculate a conservative estimate for dietary intake of chemical-enriched foods. Such conservativeness accounts for a positive bias in our estimation of dietary intake, which reflects the presumed role of juvenile kangaroo rats in preserving long-term maintenance of sustainable populations of this sensitive species. Within the context of uncertainty, we opted for such a conservative, empirical data-based approach in deriving our estimates of exposed dose given the indeterminate and continuing debates in the literature regarding derivation of toxicity reference values (TRVs), the application of uncertainty factors, and other risk-management practices (e.g., Allard et al. 2009; Barron and Wharton 2005; Chapman et al. 1998; Duke and Taggart 2000; Mayfield and Fairbrother 2012; Tannenbaum 2005). Empirical incidental soil ingestion data were not available for kangaroo rats but were assumed to be 3 % of total diet (0.00015 kg/d) based on data from other small mammal species (Beyer et al. 1994). The concentration from food was estimated by multiplying C_{soil} by the constituent specific plant-to-soil transfer factor. Given the absence of site-specific empirical data available for northern Arizona, median soil-to-vegetation transfer factors for arsenic, cadmium, copper, lead, nickel, and zinc based on foliage and stems (from Bechtel Jacobs 1998) were used for the screening-level risk analyses (Table 1); median values were selected as an unbiased descriptor of central tendency and a conservative estimate given the variation of the transfer factors presented (Bechtel Jacobs 1998). Soil-to-vegetation transfer factors for uranium and thallium were generally lacking and not readily available in existing compilations (e.g., Bechtel Jacobs 1998). Therefore, a transfer factor for uranium (median of 0.05) was computed using aboveground forb, grass, and shrub data available for field studies from the Colorado Plateau (G. Linder, unpublished data), which is consistent with estimates for uranium derived by other investigators (Vandenhove et al. 2009). A soil-to-vegetation transfer factor of 2 for thallium was computed using seed data from vegetation grown in 5 mg thallium/kg soil (Vanek et al. 2010), a thallium concentration less than that observed in soil samples from the Arizona uranium mines. Simple ratio estimators for soil-to-vegetation transfer factors from Bechtel Jacobs (1998), or derived specifically for this study (uranium and thallium), were based on constituent concentrations in soils and vegetation. Given the variation in data available to characterize soil-to-vegetation transfer factors, simple ratio estimators provided consistent empirically derived inputs that decreased model uncertainty in estimating exposed dose calculated for each constituent. Alternative derivations of soil-to-vegetation transfer factors, such as regression-based methods, were not used but may be used for updating risk estimates once colocated empirical data collections of soils and vegetation become available for uranium mines in the United States.

Dietary-based TRVs based on no observed adverse–effect levels (NOAELs) to laboratory rats from the scientific literature were used to estimate soil-screening thresholds representing risk to kangaroo rats (Table 1); ecotoxicity studies specific to kangaroo rats were not found in our literature review. Existing mammal TRVs used in deriving ecological soil-screening levels (EcoSSLs) by the United States Environmental Protection Agency (USEPA) (2005a), which included various exposure pathways, were initially examined in our risk analysis. The mammal TRVs for individual contaminants in soil were derived through a multistakeholder workgroup and were designed to be protective of ecological receptors that commonly come into contact with soil or ingest biota that live in or on soil. The mammal TRVs for chromium, zinc, cadmium, and lead included NOAELs from oral gavage and drinking water exposure studies. Oral gavage and drinking water exposure studies compiled during the TRV derivation process do not accurately represent exposure pathways of the kangaroo rat given that it does not drink water (Schmidt-Nielsen and Schmidt-Nielsen 1952; Schmidt-Nielsen 1964). Routine behaviors, such as dust bathing, burrowing, and seed caching, of kangaroo rats would be more representative of chronic than acute exposures to chemical contaminants in the soil given their relatively small home range (Hayssen 1991). Therefore, we reviewed the literature to find studies that would replicate kangaroo rat exposure to the greatest extent possible. Specifically, chronic dietary exposure (no drinking water exposure) studies of laboratory rats at multiple doses were preferred but generally limited to a few studies for each chemical (Supplemental Table 1). For our analysis, the study with the lowest NOAEL was used to calculate a conservative

Table 1 Soil-to-vegetation transfer factors and dietary-based TRVs (mg/kg/d) based on NOAELS used in the risk analysis for kangaroo rats

Contaminant	Transfer factor		Kangaroo rat TRV		Mammal TRV	
	Value	Reference	Value	Reference	Value	Reference
Arsenic	0.0472	Bechtel Jacobs (1998)	2.5	Byron et al. (1967)	1.04	USEPA (2005b)
Cadmium	0.833	Bechtel Jacobs (1998)	8	Waalkes and Rehm (1992)	0.77	USEPA (2005c)
Copper	0.2	Bechtel Jacobs (1998)	80	Aburto et al. (2001)	5.6	USEPA (2007a)
Lead	0.117	Bechtel Jacobs (1998)	40	Azar et al. (1973)	4.7	USEPA (2005d)
Nickel	0.0136	Bechtel Jacobs (1998)	8	Whanger (1973)	1.7	USEPA (2007b)
Thallium	2	Vanek et al. (2010)	0.62	Downs et al. (1960)	NA	NA
Uranium	0.05	G. Linder, unpublished data	28.8[a]	Maynard and Hodge (1949)	NA	NA
Zinc	0.43	Bechtel Jacobs (1998)	80	Sutton and Nelson (1937)	75.4	USEPA (2007c)

NA not applicable

The kangaroo rat TRV included chronic dietary exposure (no drinking water exposure) studies of laboratory rats at multiple doses, and mammal TRVs were mammalian values reported by the USEPA

[a] LOAEL because a no observed adverse–effects level was not available

estimate of food-only exposure risk for the kangaroo rat (krat TRV; Table 1). The krat TRV (mg/kg/d) was computed according to the following equation (Eq. 2):

$$\mathrm{TRV}\ (\mathrm{mg/kg/d}) = \frac{\mathrm{Dose}\ (\mathrm{mg\ chemical/kg\ food}) \times \mathrm{food\ ingestion\ rate}\ (\mathrm{kg\ food/d})}{\mathrm{Body\ weight}\ (\mathrm{kg})} \qquad (2)$$

We used a standard food IR (28 g/d) and BW (0.35 kg) for laboratory rats (USEPA 1988) because most studies did not report specific values; only Maita et al. (1981) reported a food IR for rats. Subsequent estimates for threshold effects levels linked to soil concentrations were derived by algebraic rearrangement of the traditional hazard quotient, wherein the soil concentration that resulted in a hazard quotient >1 was determined to be the soil-screening threshold protective of juvenile and adult kangaroo rats (Linder and Joermann 2001; Linder et al. 2003).

Initial evaluation of soils data (Otton et al. 2010) included exploratory data analysis, rank-correlation analysis using Spearman's method, and reconnaissance-level analysis of variance (ANOVA) using parametric or nonparametric procedures. Original and log-transformed data displayed departures from statistical assumption of normality and variance homogeneity; therefore, nonparametric methods were used to test for differences among sample types (soil outside mine perimeter, soil inside mine perimeter, weathered waste material) and specific sites (Kanab South Pipe, Hack Canyon Mine, Hermit Mine, Pigeon Mine, Kanab North Mine). Arithmetic means and SEs were calculated for inorganic constituent concentrations by sample type and site, and differences were evaluated using Kruskal–Wallis test. Unmined surface rock concentrations are presented to provide concentration data in natural formations, but they were not included in the risk analysis, which focused on soils and vegetation more likely dominating dietary exposure. However, unmined surface rock could be significant in terms of radiation exposure. Statistical analyses were performed using version 9.2 of the Statistical Analysis System (SAS Institute, Cary, NC).

Results

Uranium and Trace-Element Concentrations in Surface Materials

Mean concentrations of uranium and trace elements in surface soils (outside and within the mine perimeter) were generally greater in samples collected from mining areas than in samples from mineralized breccia pipes with no history of mining (Kanab South Pipe; Table 2). Concentrations of arsenic, cadmium, and uranium were significantly greater in surface soils outside the mine perimeter of Pigeon Mine and Kanab North Mine than those from Kanab South Pipe or Hermit Mine. At Pigeon mine, naturally occurring low-grade mineralization occurs in rocks and overlying soils outside the perimeter of the mine site (Otton et al. 2010). Significant differences in the concentrations of chromium, copper, lead, nickel, thallium, and zinc in soils outside the mine perimeter were not consistently associated with any one site.

Concentrations of arsenic, cadmium, copper, lead, nickel, thallium, uranium, and zinc in surface soils inside the mine perimeter were similar to surface soils outside the mine perimeter at Hermit and Pigeon mines, which are reclaimed sites. However, concentrations were approximately 10-fold greater in mine soils than in soils outside the mine perimeter at Kanab North Mine (not reclaimed). Concentrations of arsenic, cadmium, copper, lead, nickel, thallium, uranium, and zinc were significantly greater in soils within the mine perimeter at Kanab North Mine than in those from the reclaimed Hermit Mine, Pigeon Mine, or both.

Concentrations of arsenic, cadmium, copper, lead, nickel, thallium, uranium, and zinc were significantly greater in weathered waste material than in surface soil (Table 2). However, concentrations in samples of weathered waste material from Hack Canyon, Pigeon, and Kanab North mines did not differ significantly among sites (Table 2).

Concentrations of arsenic, cadmium, copper, lead, nickel, thallium, uranium, and zinc were included in the risk analysis because concentrations in soils inside the mine perimeter and weathered waste material were significantly greater than those outside the mine perimeter (considered to be representative of local background conditions). Concentrations of chromium did not differ consistently among sample types; therefore, risk of exposure linked to dietary sources of chromium among sites was not considered in the risk analysis.

Risk Analysis for Chemical Stressors

Soil threshold concentrations to protect kangaroo rats were lower for juvenile than adult kangaroo rats (Table 3).

Table 2 Inorganic constituent concentrations (mg/kg; mean ± SE) in surface soil, surface rock, and weathered mine waste material from breccia-pipe uranium mines in northern Arizona (Otton et al. 2010)

Site and sample type	*n*	Arsenic	Cadmium	Chromium	Copper	Lead	Nickel	Thallium	Uranium	Zinc
Kanab south pipe (not mined)										
Surface soil outside mine	6	9.50 ± 3.30^{AB}	$<0.2 \pm 0^{A}$	26.8 ± 1.7^{A}	13.9 ± 1.4^{A}	14.1 ± 1.2^{A}	10.9 ± 0.7^{A}	0.3 ± 0.03^{A}	2.0 ± 0.2^{A}	41 ± 2^{A}
Surface soil within mine	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Surface rock**	1	896	0.9	20	1,010	415	365	0.8	54.9	1,720
Weathered waste material	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hack Canyon (reclaimed)***										
Surface soil outside mine	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Surface soil within mine	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Surface rock	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Weathered waste material	5	$4,855 \pm 2,115^{A}$	16.5 ± 10.0^{A}	9.4 ± 1.3^{A}	$2,425 \pm 1291^{A}$	378 ± 144^{A}	397 ± 244^{A}	98 ± 67^{A}	$4,467 \pm 1928^{A}$	$3,254 \pm 1,943^{A}$
Hermit (reclaimed)										
Surface soil outside mine	6	4.83 ± 0.17^{Aa}	0.18 ± 0.02^{Ab}	27.8 ± 1.3^{Ab}	30.1 ± 2.3^{Bb}	14.2 ± 0.8^{Ab}	14.4 ± 0.7^{Ba}	0.5 ± 0.02^{Ba}	2.0 ± 0.2^{Aa}	55 ± 3^{Ba}
Surface soil within mine	22	7.45 ± 1.14^{Ab}	0.12 ± 0.01^{Aa}	22.9 ± 0.8^{Aa}	19.9 ± 1.1^{Aa}	12.1 ± 0.4^{Aa}	14.6 ± 0.5^{Aa}	0.4 ± 0.01^{Aa}	4.6 ± 0.9^{Ab}	50 ± 3^{Aa}
Surface rock	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Weathered waste material	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pigeon (reclaimed)										
Surface soil outside mine	16	50 ± 23^{Ca}	0.39 ± 0.05^{Ca}	32.3 ± 3.2^{Cab}	20.4 ± 3.2^{Aa}	12.8 ± 1.2^{Aa}	24.2 ± 7.5^{ABa}	0.6 ± 0.2^{ABa}	9.5 ± 2.3^{Bab}	57 ± 14^{ABa}
Surface soil within mine	26	68 ± 19^{Bb}	0.25 ± 0.06^{Bb}	34.3 ± 1.6^{Bb}	24.4 ± 2.9^{Aa}	13.5 ± 3.0^{Bb}	23 ± 4.8^{Ba}	1.3 ± 0.4^{Bb}	9.6 ± 3.7^{Aa}	63 ± 11^{Aa}
Surface rock	4	479 ± 384^{abc}	2.3 ± 2.2^{abc}	18.5 ± 6.8^{a}	119 ± 42^{ab}	134 ± 75^{abc}	234 ± 139^{ab}	53 ± 33^{abc}	165 ± 117^{bc}	378 ± 361^{ab}
Weathered waste material	3	$2,399 \pm 1431^{Ac}$	11.9 ± 5.4^{Ac}	26.7 ± 9.4^{Aab}	$3,090 \pm 2,970^{Ab}$	607 ± 280^{Ac}	81 ± 13^{Ad}	14 ± 10^{Ac}	$1,090 \pm 495^{Ac}$	$2,144 \pm 975^{Ab}$
Kanab North (not reclaimed)										
Surface soil outside mine	22	12.2 ± 1.5^{Ba}	0.26 ± 0.02^{Ba}	21.7 ± 0.6^{Ba}	17.9 ± 1.3^{Aa}	14.5 ± 1.0^{Aa}	14.1 ± 1.0^{ABa}	0.4 ± 0.03^{Ba}	28 ± 5^{Ca}	55 ± 4^{ABa}
Surface soil within mine	8	169 ± 45^{Bb}	2.5 ± 0.7^{Cb}	22.8 ± 1.6^{Aa}	136 ± 30^{Bb}	110 ± 28^{Cb}	70 ± 15^{Cb}	4.2 ± 1.4^{Cb}	$1,060 \pm 363^{Bb}$	514 ± 145^{Bb}
Surface rock	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Weathered waste material	2	$1,130 \pm 850^{Ab}$	6.5 ± 4.0^{A}	26.0 ± 12.0^{Aa}	140 ± 33^{Ab}	972 ± 818^{Ab}	119 ± 4^{Ac}	21 ± 9^{Ac}	584 ± 96^{Ab}	929 ± 471^{Ab}

NA not applicable

Chemical concentrations for a sample type followed by the same upper-case letter were not significantly different among sites, and C values for a site followed by the same lower-case letter were not significantly different among sample types ($P > 0.05$, Kruskal–Wallis test)

** Statistical analysis not performed because $n = 1$

*** No among sample type analysis

Threshold concentrations derived from mammal TRVs were 2–14 times lower than those derived from krat TRVs for most inorganic constituents; however, the krat TRV and mammal TRV for zinc were comparable. Models using juvenile kangaroo rat and mammal TRVs resulted in greater risk estimates from individual contaminants compared with those using adult kangaroo rat and krat TRVs. Most of the soil threshold exceedances were for arsenic and thallium and were associated with weathered mine waste material; few exceedances occurred for cadmium, copper, lead, nickel, uranium, and zinc using krat TRVs (Fig. 2).

Inorganic concentrations in soils outside the mine perimeter at Kanab South Pipe, Hermit Mine, Pigeon Mine, and Kanab North Mine were generally less than soil thresholds to protect kangaroo rats; exceptions included concentrations of arsenic ($n = 3$; 62–393 mg/kg) and thallium ($n = 1$; 3.9 mg/kg) from Pigeon Mine (Fig. 2). Overall, inorganic contaminants in soil samples from outside the reclaimed mine areas generally posed little, if any, risk to kangaroo rats.

Concentrations of inorganic contaminants in soils within the mine perimeter at the reclaimed Hermit and Pigeon mines rarely exceeded soil thresholds for juvenile or adult kangaroo rats (Fig. 2). Arsenic concentrations exceeded protective thresholds based on krat and mammal TRVs in six samples from Pigeon Mine (63–407 mg/kg), and thallium concentration exceeded krat TRVs in five samples from Pigeon Mine (1.5–11.5 mg/kg; Fig. 2).

Concentrations of arsenic, cadmium, copper, lead, thallium, uranium, and zinc in mine soils from the unreclaimed Kanab North Mine exceeded one or more protective thresholds for juvenile and adult kangaroo rats (Fig. 2); most exceedances were for thresholds based on mammal TRVs and not krat TRVs. Concentrations of arsenic ($n = 5$; 145–388 mg/kg), thallium ($n = 6$; 2.7–10.7 mg/kg), and uranium ($n = 4$; 1,050–2,840 mg/kg) in mine soil samples

Table 3 Soil threshold concentrations (mg/kg) resulting in dietary exposure dose for juvenile and adult kangaroo rats exceeding protective TRVs

Chemical constituent	Kangaroo rat TRV		Mammal TRV	
	Soil threshold (mg/kg)	Exceedances ($n = 121$)	Soil threshold (mg/kg)	Exceedances ($n = 121$)
Arsenic				
Juvenile	137	21	57	28
Adult	438	10	182	18
Cadmium				
Juvenile	20	2	3.8	9
Adult	63	0	12	4
Copper				
Juvenile	1,461	4	103	19
Adult	4,697	2	330	6
Lead				
Juvenile	1,143	0	134	15
Adult	3,674	0	432	4
Nickel				
Juvenile	771	1	164	5
Adult	2,478	0	527	3
Thallium				
Juvenile	1.3	24	NA	NA
Adult	4.2	12	NA	NA
Uranium				
Juvenile	1,513	6	NA	NA
Adult	4,861	2	NA	NA
Zinc				
Juvenile	731	9	689	9
Adult	2,348	4	2,213	4

Kangaroo rat TRVs were used to derive soil thresholds on the left, and the mammal TRVs were used to derive soil thresholds on the right. Kangaroo rat TRVs were chosen to replicate exposure pathways of the kangaroo rat (see Methods section). Mammal TRVs were mammalian values reported by the USEPA (see Table 1). The number of soil samples from 2009 ($n = 121$; Otton et al. 2010) exceeding a soil threshold concentration is also presented from Kanab North Mine exceeded the threshold to protect juvenile kangaroo rats based on krat TRVs (Fig. 2). Mean concentrations of arsenic (169 mg/kg) and copper (136 mg/kg) exceeded thresholds to protect juvenile kangaroo rats based on mammal TRVs in mine soils from Kanab North Mine (Fig. 2; Table 2).

Inorganic concentrations in weathered mine waste samples exposed at Hack Canyon, Pigeon, and Kanab North mines consistently exceeded one or more soil thresholds to protect juvenile and adult kangaroo rats (Fig. 2). Arsenic concentrations in all mine waste samples (158 to > 10,000 mg/kg) exceeded one or more soil thresholds based on krat and mammal TRVs. Few mine waste samples exceeded thresholds for cadmium, lead, nickel, and zinc to protect juvenile and adult kangaroo rats based on krat TRVs. Mean concentrations of copper exceeded thresholds to protect juvenile kangaroo rats in samples from Hack Canyon Mine complex (2,425 mg/kg) and Pigeon Mine (3,090 mg/kg) based on krat TRVs (Fig. 2; Table 2). For thallium, all 10 mine waste samples (1.7–349 mg/kg) exceeded protective thresholds for juvenile kangaroo rats, and mean concentrations in samples from Hack Canyon Mine complex (98 mg/kg), Pigeon Mine (14 mg/kg), and Kanab North Mine (21 mg/kg) also exceeded protective thresholds for juvenile kangaroo rats (Fig. 2; Table 2). For uranium, 4 of 10 mine waste samples exceeded protective thresholds for juvenile kangaroo rats (1,870 to >10,000 mg/kg), and 2 of 10 samples exceeded soil thresholds for adult kangaroo rats (7,760 to >10,000 mg/kg; Fig. 2). The mean concentration of uranium in mine waste samples from Hack Canyon (4,467 mg/kg) exceeded the soil threshold for juvenile kangaroo rats (Fig. 2; Table 2).

Discussion

Risk to wildlife posed by inorganic constituents was not eliminated regardless of the reclamation status of the formerly mined areas. However, sampling sites represent a variety of lithostratigraphic units and topographic settings, which may have differing background inorganic constituent concentrations; therefore, comparisons of concentrations among sample types at a site are preferred to comparisons among sites. Concentrations of arsenic, cadmium, copper, lead, nickel, thallium, uranium, and zinc were increased in weathered mine wastes compared with surface soils inside and outside reclaimed and unreclaimed mine sites.

Concentrations of inorganic contaminants in mine waste samples from reclaimed mines (Hack Canyon and Pigeon mines) were the greatest of all samples measured and consistently exceeded soil-screening thresholds to protect juvenile and adult kangaroo rats. We acknowledge some uncertainty and conservatism in our risk analysis. The concentrations of inorganic constituents are likely greater than concentrations that are bioavailable to kangaroo rats under natural conditions given the chemical extraction method used and for certain types of media analyzed (e.g., weathered mine waste material). However, all waste rock material collected had been exposed to surface environmental (or weather) conditions, including episodic wetting events since reclamation (late 1980s to early 1990s). Geochemical analysis indicated that uranium, arsenic, and molybdenum were readily leachable in some weathered waste samples, and a greater percentage of uranium was leached from weathered waste material than unweathered high-grade ore samples (Otton et al. 2010). Therefore, chemical constituents may have greater bioavailability in weathered waste material than those in unweathered samples.

Our measurements can be useful in developing a conservative risk-screening analysis given that one species of kangaroo rat in northern Arizona has been designated at risk for extinction by several federal agencies. If further remediation is not planned for these sites, then management of the potential source area, including monitoring of contaminant releases over time, is warranted. Future exposure may occur as cover over waste materials weathers over time at any particular mining site. During these processes, inorganic contaminants and radionuclides may become more bioavailable to burrowing animals such as kangaroo rats, which means that exposure pathways will change.

Greater risk to inorganic constituents was associated with juvenile compared with adult kangaroo rats based on our models. Therefore, management actions to establish soil thresholds to protect kangaroo rats could be directed at juveniles unless species-specific empirical data (for both adults and juveniles)—including food ingestion, soil ingestion, metabolic rate, and site use—become available and indicate otherwise. Our screening-level risk analysis indicates that arsenic and thallium may pose greater risk than other inorganic constituents to kangaroo rats at historical uranium mine sites in northern Arizona. In part, thallium remained a concern because of a relatively high soil-to-vegetation transfer factor and a relatively low krat TRV from the limited scientific literature available for this constituent. Accordingly, additional evaluation of the chemical toxicities of arsenic and thallium specifically to kangaroo rats is warranted. Concentrations of inorganic constituents were correlated in our samples, meaning that the same samples consistently had the greatest concentrations for most, if not all, inorganic constituents. Establishing management goals to protect kangaroo rats from arsenic and/or thallium may also protect them from the individual chemical toxicities of other inorganic constituents found in breccia pipe deposits, but these would not

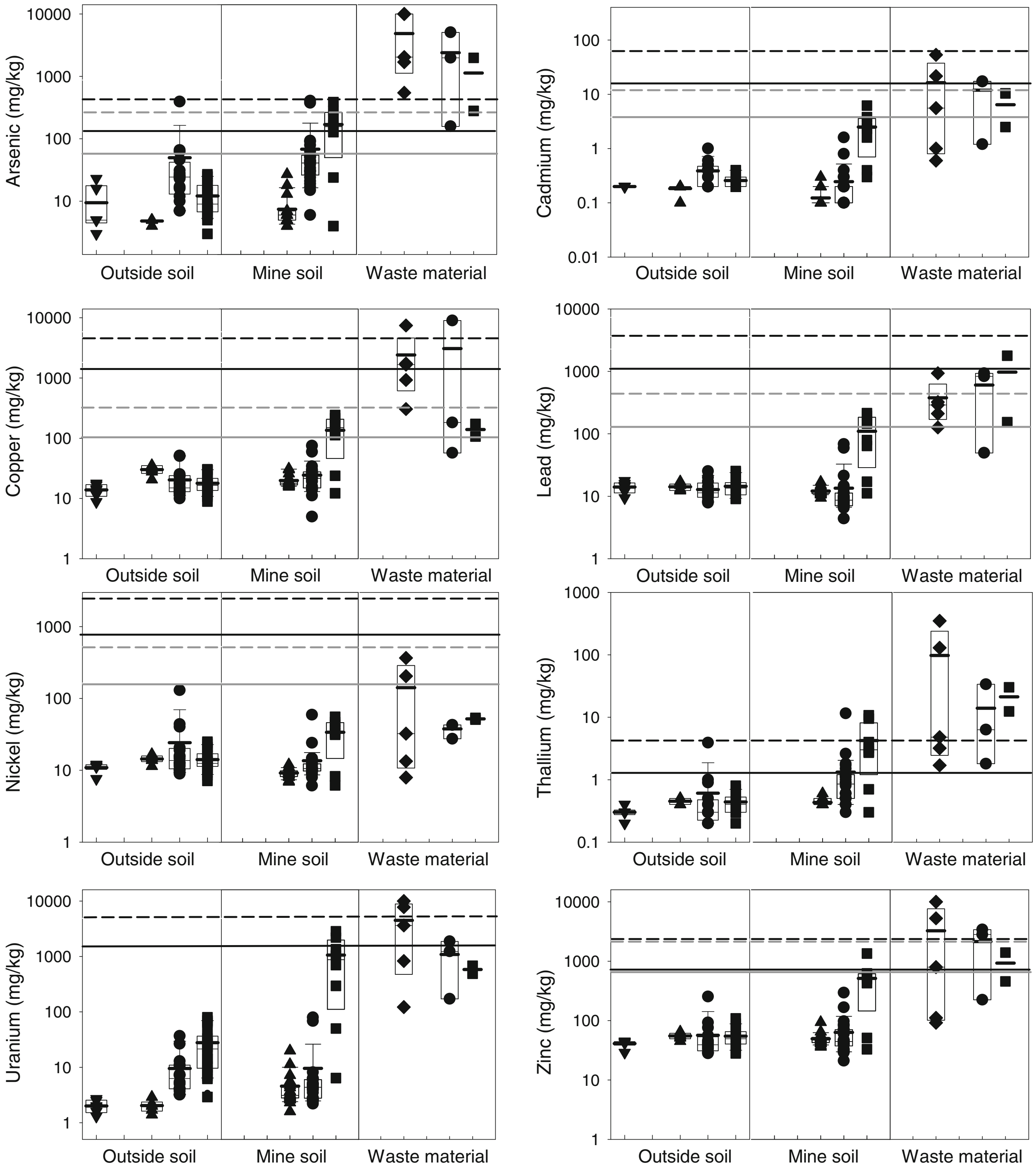

Fig. 2 Inorganic contaminants in soil outside the mine perimeter, inside the mine perimeter, and weathered mine wastes from breccia pipe uranium mines, including Kanab South Mine (*inverted black triangles*), Hack Canyon Mine complex (*black diamonds*), Hermit Mine (*black triangles*), Pigeon Mine (*black circles*), and Kanab North Mine (*black squares*). Horizontal reference lines on graphs are mammal TRVs (*gray*) and soil threshold concentrations derived in this study (*black*) to protect juvenile (*solid*) and adult (*dashed*) kangaroo rats (see text for calculation). Shown for each box plot are the mean (*bold black horizontal line*), median (*black horizontal line*), interquartile range (*box*), and the 10th and 90th percentiles (*whiskers*)

account for additive, antagonistic, or synergistic effects of chemical mixtures. Our risk analysis focused on single chemicals in the diet of experimental rodents; empirical data from feeding trials of chemical mixtures, such as those encountered by kangaroo rats in their environment, were not available in the literature.

The outcome of any risk analysis can be influenced by TRV selection. We found few studies for our selected chemical constituents that had dietary only (no drinking water) exposure of laboratory rats, the scenario selected to emulate field exposure of kangaroo rats. Few of these studies met our additional criteria of chronic exposures at multiple doses and end points related to survival, growth, or reproduction. Consequently, we selected TRVs from the study with the lowest NOAEL for each contaminant. This type of screening-level analysis is appropriate for prioritizing chemical contaminant risks to kangaroo rats and highlights ecotoxicological data gaps for desert species.

The mammal TRVs were designed to be used for screening-level ecological risk assessments to determine if additional ecological site studies are needed, not to establish remediation levels. The mammal TRVs from the USEPA available for arsenic (USEPA 2005b), cadmium (USEPA 2005c), copper (USEPA 2007a), lead (USEPA 2007d), nickel (USEPA 2007b), and zinc (USEPA 2007c) were all lower than the krat TRVs we derived, in part because oral gavage and drinking water exposure studies generally yield lower thresholds than those from dietary only exposure studies for some chemicals and were designed to be protective of ecological receptor groups (soils, plants, birds, and mammals) rather than individual species within those groups. Given the natural history of kangaroo rats (Genoways and Brown 1993), such toxicity thresholds developed under the auspices of a regulatory process may be appropriate to screen for potential risk, but they were not designed to aid resource managers in developing site-specific clean-up goals to protect kangaroo rats or other burrowing desert species. Although soil-screening thresholds derived in our analysis may face criticism because they are based on TRVs from individual studies, they outline an approach for risk analysis that considers how to select thresholds based on the life history of a specific species (e.g., behaviors, physiological adaptations) rather than forcing a particular species into a regulatory threshold paradigm.

Although there is uncertainty associated with how much kangaroo rats use mining sites, animal activity (e.g., burrows, tracks, cut vegetation at burrow entrances) was observed at all of the mine sites (Hinck, personal observation). The extent to which kangaroo rats or other animals would use these areas during active mining activities is largely unknown, but animals requiring external sources of water are drawn to the stormwater-holding ponds during active mining (Hinck, personal observation; USEPA 2007d).

The near exclusive reliance on food-derived or metabolic water and physiological adaptations to conserve water in kangaroo rats strongly indicates that toxicity thresholds posited under regulatory guidance must be revisited when exposures in the field are considered beyond a preliminary assessment. In addition to dietary pathway, other exposure conditions unique to kangaroo rats influence exposed dose. Use of subterranean habitats, such as burrows in uranium-rich and reclaimed mining areas, in the seasonally variable but consistently arid environment of northern Arizona is of particular concern in these historical mining areas because natural-history strategies of burrowing animals may lead to increased chemical and radiation exposure. However, chemical toxicity data for burrowing desert mammals, such as the kangaroo rat, are lacking; therefore, screening-level risk analyses must rely on toxicity data derived for test species, such as laboratory rodents. Exposure differences between these biomedical test species and wild mammals likely contribute as much or more uncertainty than presumptive toxicity thresholds used as benchmarks for evaluating exposed dose. For example, certain behaviors of kangaroo rats, such as seed foraging and caching, preening, dust bathing, and burrowing, increase contact with soils (Reynolds 1958; Hayssen 1991); other studies have shown that such activities increase contaminant exposure and concluded that incidental soil ingestion is an exposure pathway that requires consideration in wild species (Gerstenberger et al. 2006; Morris and Thompson 2011; Niethammer et al. 1985). Some species of kangaroo rats can move 0.4 cubic feet of soil to construct their burrow and spend 75 % of their life below ground (Reynolds 1958). Potential inhalation and ingestion of soils by kangaroo rats are likely during these activities; however, quantification and analysis of effects of these exposures are unknown and may vary as contaminant concentrations differ as subsurface depth increases. Although wildlife test species are increasingly involved in assessing chemical toxicity, standard toxicity tests applied to evaluations of ecological risks commonly involve laboratory rodents exposed by way of drinking water and diet and do not account for these potentially important exposure pathways. Therefore, the current toxicity threshold data available for laboratory rodents likely underestimate contaminant exposure and risk to kangaroo rats. Rather than merely applying a more conservative TRV to estimate risk (e.g., using a mammal TRV), studies to establish chemical toxicity thresholds using kangaroo rats and other burrowing desert species (including invertebrates, amphibians, and reptiles) are needed to better characterize risk to biota that have evolved and thrived in desert conditions. Developing effects data is expensive and unlikely to occur for most wildlife species. However, site-specific exposure estimates and subsequent risk can be refined by measuring tissue concentrations in native biota, developing bioaccumulation factors using colocated soil and tissue concentrations, and estimating incidental soil ingestion in native biota. Ideally, toxicity thresholds, coupled with empirical biological data from northern Arizona, could yield refined risk analyses that provide resource managers with a better understanding of potential impacts of uranium mining to biota.

Acknowledgments We thank Kim Chojnacki for creating the map and W. Nelson Beyer, Brad Sample, Chris Schmitt, and two anonymous reviewers for reviewing earlier drafts of the manuscript. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the United States Government.

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