Surveys

Exposure Pathways and Biological Receptors: Baseline Data for the Canyon Uranium Mine, Coconino County, Arizona

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Abstract

Recent restrictions on uranium mining within the Grand Canyon watershed have drawn attention to scientific data gaps in evaluating the possible effects of ore extraction to human populations as well as wildlife communities in the area. Tissue contaminant concentrations, one of the most basic data requirements to determine exposure, are not available for biota from any historical or active uranium mines in the region. The Canyon Uranium Mine is under development, providing a unique opportunity to characterize concentrations of uranium and other trace elements, as well as radiation levels in biota, found in the vicinity of the mine before ore extraction begins. Our study objectives were to identify contaminants of potential concern and critical contaminant exposure pathways for ecological receptors; conduct biological surveys to understand the local food web and refine the list of target species (ecological receptors) for contaminant analysis; and collect target species for contaminant analysis prior to the initiation of active mining. Contaminants of potential concern were identified as arsenic, cadmium, chromium, copper, lead, mercury, nickel, selenium, thallium, uranium, and zinc for chemical toxicity and uranium and associated radionuclides for radiation. The conceptual exposure model identified ingestion, inhalation, absorption, and dietary transfer (bioaccumulation or bioconcentration) as critical contaminant exposure pathways. The biological survey of plants, invertebrates, amphibians, reptiles, birds, and small mammals is the first to document and provide ecological information on >200 species in and around the mine site; this study also provides critical baseline information about the local food web. Most of the species documented at the mine are common to ponderosa pine *Pinus ponderosa* and pinyon–juniper *Pinus–Juniperus* spp. forests in northern Arizona and are not considered to have special conservation status by state or federal agencies; exceptions are the locally endemic Tusayan flameflower *Phemeranthus validulus,* the long-legged bat *Myotis volans*, and the Arizona bat *Myotis occultus*. The most common vertebrate species identified at the mine site included the Mexican spadefoot toad *Spea multiplicata*, plateau fence lizard *Sceloporus tristichus*, violet-green swallow *Tachycineta thalassina*, pygmy nuthatch *Sitta pygmaea*, purple martin *Progne subis*, western bluebird

Sialia mexicana, deermouse *Peromyscus maniculatus*, valley pocket gopher *Thomomys bottae*, cliff chipmunk *Tamias dorsalis*, black-tailed jackrabbit *Lepus californicus*, mule deer *Odocoileus hemionus*, and elk *Cervus canadensis*. A limited number of the most common species were collected for contaminant analysis to establish baseline contaminant and radiological concentrations prior to ore extraction. These empirical baseline data will help validate contaminant exposure pathways and potential threats from contaminant exposures to ecological receptors. Resource managers will also be able to use these data to determine the extent to which local species are exposed to chemical and radiation contamination once the mine is operational and producing ore. More broadly, these data could inform resource management decisions on mitigating chemical and radiation exposure of biota at high-grade uranium breccia pipes throughout the Grand Canyon watershed.

Keywords: biological surveys; Colorado Plateau; contaminants; Grand Canyon; risk; uranium mining

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Introduction

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. Despite decreasing market values in the early 1980s, uranium mining persists in the Grand Canyon area at low levels because of the relatively high ore grades found in these deposits (Otton and Van Gosen 2010). Price increases of uranium 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 a 2-y 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 (U.S. Bureau of Land Management 2011). These federal parcels were subsequently withdrawn from mineral extraction for 20 y in 2012 partially based on uncertainty associated with toxicological risks to wildlife and humans (Hinck et al. 2010; U.S. Department of the Interior 2012). However, uranium mining will continue elsewhere in the region because existing valid claims were not affected by the federal land withdrawal.

Several mines are scheduled for development during the withdrawal period. This provides a unique opportunity to characterize concentrations of uranium and other trace elements, as well as radiation levels, in biota found in the vicinity of the mine before ore extraction begins, during active ore production, and after mine remediation. Such data can be used to determine whether temporal changes in radiation and chemical concentrations in plants and animals result in greater exposure, and thus risk, to the surrounding environment. This was one scientific data gap noted in the record of decision (U.S. Department of the Interior 2012). The breccia pipe mines have a limited life-span (<7 y from development to remediation). The Canyon Mine breccia pipe, which is located 6 mi (9.7 km) south of Tusayan, Arizona near the south rim of the Grand Canyon (Figure 1), was chosen for the study described herein. Surface mining operations (e.g., construction of buildings and storm-water detention pond (henceforth, detention pond), scraping and stockpiling of topsoil, head-frame construction) were under development from 1986 to 1992 when the operator placed the mine on standby. Development of the mine resumed in the autumn of 2012 with enlargement of the detention pond and construction of the production shaft. Ore production at the mine was scheduled to begin in 2014; therefore, the opportunity to characterize premining (or baseline) concentrations of uranium and other trace elements and radiation levels in biota was limited. Sample collection began in 2013. Baseline characterization for this study includes effects from surface operations development.

The overarching goal of this project was to determine whether concentrations of chemical and radiation contamination are increased from mining activities and pose risks to biota within the environs of the Canyon Mine site. Collecting biota that are representative of the local food web before mining starts, during active

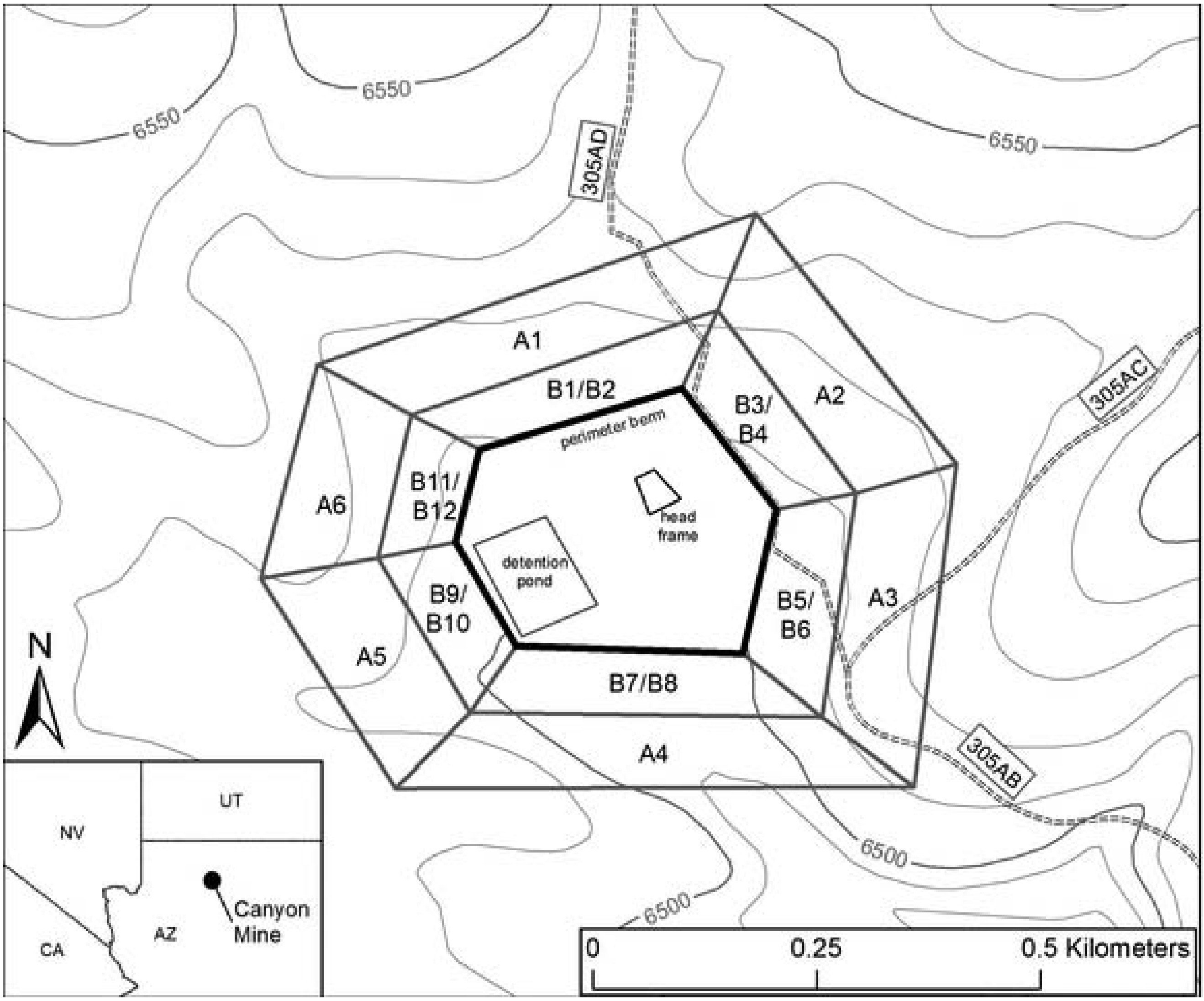

Figure 1. Canyon Uranium Mine, Kaibab National Forest, Coconino County, Arizona. Bold line denotes the bermed, fenced perimeter of the mine. Polygons represent vegetation sampling areas.

mining, and post–mine-closure and remediation is essential to understanding ecological risks at this and other uranium mining sites. Therefore, our objectives were to 1) identify contaminants of potential concern and critical contaminant exposure pathways (ingestion, inhalation, absorption, etc.) for ecological receptors; 2) conduct biological surveys of plants, invertebrates, amphibians, reptiles, birds, and small mammals to understand the local food web and refine the list of target species (ecological receptors) for contaminant analysis; and 3) collect target species to determine baseline chemical contaminant concentrations and radiation levels for the site.

Methods

Study area

The Canyon Mine breccia pipe (35°52′57.50″N, 112°05′44.52″W, 6,556 ft [1,998 m] elevation) is located in the Tusayan Ranger District of the Kaibab National Forest 6 mi (~10 km) south of Tusayan, Arizona, in a natural clearing. Surface mining operations at the site (~17 ac) are contained within a bermed, fenced perimeter (Figure 1). Habitats outside of the fenced mine area are primarily ponderosa pine *Pinus ponderosa* and pinyon–juniper *Pinus–Juniperus* forest with some areas of sagebrush *Artemisia* spp. Areas within the bermed perimeter have been mostly scraped clear for the mine to become operational including the construction of various facility buildings, unlined ore and waste rock pads, and a synthetically lined detention pond. Little vegetation is present within the mine perimeter. The material extracted during the construction of the shaft will be deposited and stored in the waste-rock pad area and will be backfilled into the shaft during mine closure. Once the mine is operational, rock containing enriched uranium ore will be broken underground, brought to the surface at the head-frame, and transported to the ore pad. The ore will then be loaded onto trucks, covered with tarps, and transported off-site for processing; no milling will be done on site. The 2.32-acre (0.94-ha) detention pond, constructed in late 2012, holds water during some parts of the year and is engineered to meet requirements for a 100-y 24-h flood event. The waste rock (red siltstone and sandy siltstone from the Moenkopi Formation) from the construction of the detention pond has been placed around the perimeter of the pond to create a berm. The berm is primarily used to anchor the synthetic liner and to serve as a safety barrier for mine workers. Some berm material has washed into the detention pond, creating a sediment layer on top of the synthetic liner. Surface runoff from rain and snow events and any water pumped from the mine will remain on-site in the detention pond as a result of the berm surrounding the mine perimeter. Surface-water drainages outside the mine perimeter are generally dry but flow ephemerally during rainfall or snowmelt events. Water diversion structures have been constructed in an attempt to ensure that surface runoff from outside the bermed mine perimeter does not enter the site but will flow around the site into local stream courses (to the south). Nearby sources of surface water are minimal and generally limited to various catchments, reservoirs, and stock tanks.

Conceptual site model

Breccia pipe deposits generally occur as uraninite (uranium oxide). Associated sulfide, arsenide, sulfate, and arsenic–sulfosalt minerals are also present as disseminated replacements and minor fracture fillings in near-vertical cylindrical solution-collapse breccia pipes. Economically recoverable quantities of copper, gold, molybdenum, nickel, silver, thorium, and vanadium can also occur with the uranium deposits (Wenrich 1985).

A conceptual site model for Canyon Mine that represents known or suspected contaminant sources and physical, chemical, and biological processes that affect contaminant transport to ecological receptors was developed prior to surveying and sampling. Contaminants of potential concern (COPCs) to ecological receptors at Canyon Mine include arsenic, cadmium, chromium, copper, lead, mercury, nickel, selenium, thallium, uranium, and zinc for chemical toxicity and uranium and associated radionuclides for radiation toxicity based upon concentrations of these constituents in other breccia pipe deposits (e.g., Wenrich 1985). Mining activities are likely to release COPCs and potentially increase exposure to biota at the mine site. Transport by wind, overland flow, and leaching could release COPCs from primary contaminant sources, which include the ore pad, waste rock area, vent shaft, and haul road (Figure 2). The COPCs could then be transported through air, seeps, and surface water. Potential pathways of contaminant exposure include direct contact (absorption), inhalation, ingestion, and dietary transfer but differ among terrestrial and aquatic receptors. Terrestrial receptors include plants, terrestrial invertebrates, reptiles, birds, and mammals; aquatic receptors include aquatic invertebrates and amphibians. This model along with the generalized local food web allowed for identification of target species and collection for contaminant and radiation analyses; complete exposure pathways that were sampled are noted (Figure 2).

Baseline biological surveys

Literature searches and communication with biologists from the Kaibab National Forest indicated that biological survey information was not available for the Canyon Mine. Surveys and compilations for surrounding areas (e.g., Brown et al. 1987; Huisinga et al. 2006; Persons and Nowak 2006; Stumpf and Monroe 2012) provided reference information for our study. Chemical and radiation contaminant data in biota were also not available for Canyon Mine or the surrounding areas in the Kaibab National Forest. Therefore, we conducted biological surveys of plants, invertebrates, amphibians, reptiles, birds, and small mammals to understand the local food web, refine the list of target species for contaminant analysis, and collect target species for contaminant analysis using the conceptual site model as a guide (Figure 2; Data S1, *Supplemental Material*). Although large game species, including elk *Cervus canadensis* and mule deer *Odocoileus hemionus*, and predators such as coyote *Canis latrans* are found in the area, their exposure to contaminants associated with the mine was believed to be minimal, given their relatively large home ranges and limited access inside the mine perimeter fence. Accordingly, this project focused on characterizing chemical and radiation exposure in animals with smaller home ranges and greater site fidelity to the area around the mine. To the greatest extent possible, multiple receptor groups (e.g., amphibians, mammals) were surveyed and collected from the same areas to validate exposure pathways described in the conceptual site model (Figure 2).

Field sampling was segregated by areas largely determined by the fenced-perimeter of the mine, physical habitat, and prevailing wind direction (Figures 1 and 3). As such, the area to the east–northeast of the bermed perimeter likely presents a high probability of contaminant dispersion via windblown dusts, given that local prevailing winds are from west–southwest (Figure 3; Davis Instruments, Vernon Hills, IL). Hydrologically, areas downstream of the mine (south) are also likely deposition zones for any surface runoff that follows local stream courses and diversion channels around the mine, especially if institutional controls fail or are otherwise compromised. Within an exposure setting, the area west of the mine likely represents a zone that will experience less deposition of windblown dusts, but animals may use the detention pond as a water source. Because all surface runoff within the mine site is directed into the detention pond, the water and sediments trapped in the pond may become a potential contaminant source. The area north–northwest of the mine will likely experience less deposition of atmospheric dusts or surface runoff. In addition, the haul-road surface and adjoining areas may also be contaminated by spillage from ore-laden trucks leaving the site.

During the biological surveys, we collected whole-body specimens for contaminant analysis; we preferred

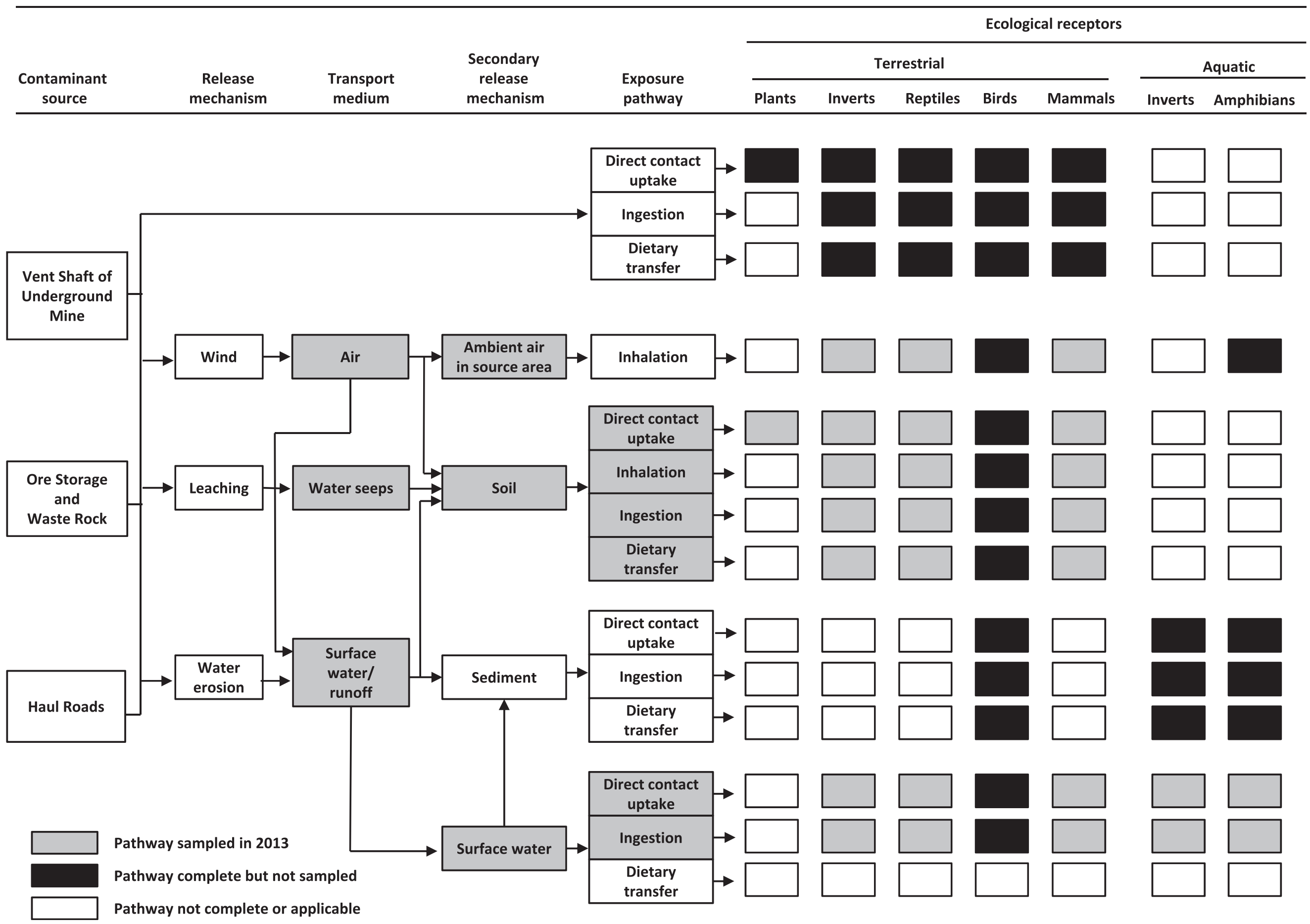

Figure 2. A conceptual site model for Canyon Uranium Mine, Coconino County, Arizona, that represents known or suspected contaminant sources and physical, chemical, and biological processes that affect contaminant transport to ecological receptors. Gray boxes represent exposure pathways that are complete for a receptor and were sampled in 2013; black boxes are complete exposure pathways that were not sampled; white boxes are incomplete exposure pathways.

species that were most abundant, provide a specific component of the food web (Figure 4), and represent aquatic and terrestrial exposure pathways (Figure 2). We did not collect tissues from birds for contaminant analysis because a federal migratory bird permit to collect appropriate specimens (eggs and fledglings) could not be obtained prior to the beginning of the resident breeding season (June). All collection, handling, and euthanasia procedures followed animal care and use guidelines approved by U.S. Geological Survey and Northern Arizona University Institutional Animal Care and Use Committees and allowed under Arizona Game and Fish Department's Scientific Collecting Permit and the U.S. Federal Bird Banding and Marking Permit. After euthanasia, we placed whole-body specimens individually in labeled plastic bags and kept them frozen until shipment to the analytical laboratory. We took digital photos of each collected specimen to confirm and record species identification. We georeferenced collection locations of samples using hand-held Global Positioning System navigation units. Background levels of radiation were anticipated to be low in all samples during the premine phase based on historical soil data from this site (Van Gosen and Wenrich 1991); biological samples screened with a calibrated Geiger counter (Ludlam Measurements Inc., Sweetwater, TX) in the field were $\leq$40 μrem/h. We shipped all biological samples on ice to the U.S. Geological Survey Columbia Environmental Research Center (Columbia, Missouri) and stored them frozen (-20°C) pending contaminant and radiation analyses.

In addition to biological samples, we collected soil, sediment, and surface-water samples to aid in the confirmation of critical exposure pathways for specific ecological receptors (Figure 2). We collected soil samples at the mine and surrounding area using incremental sampling methods in June 2013 (Interstate Technology Regulatory Council 2012). Given the objective to characterize soils as a component of exposure pathways for specific ecological receptors, the incremental sampling method was preferred over discrete sampling at the Canyon Mine site. Contaminant concentrations in discrete soil samples can have much variability from the particulate nature of soil and heterogeneous distribution of contaminants. The incremental sampling method composites samples over an area, known as a decision unit, to reduce this sampling variability and to provide an estimate of mean concentration of analytes over

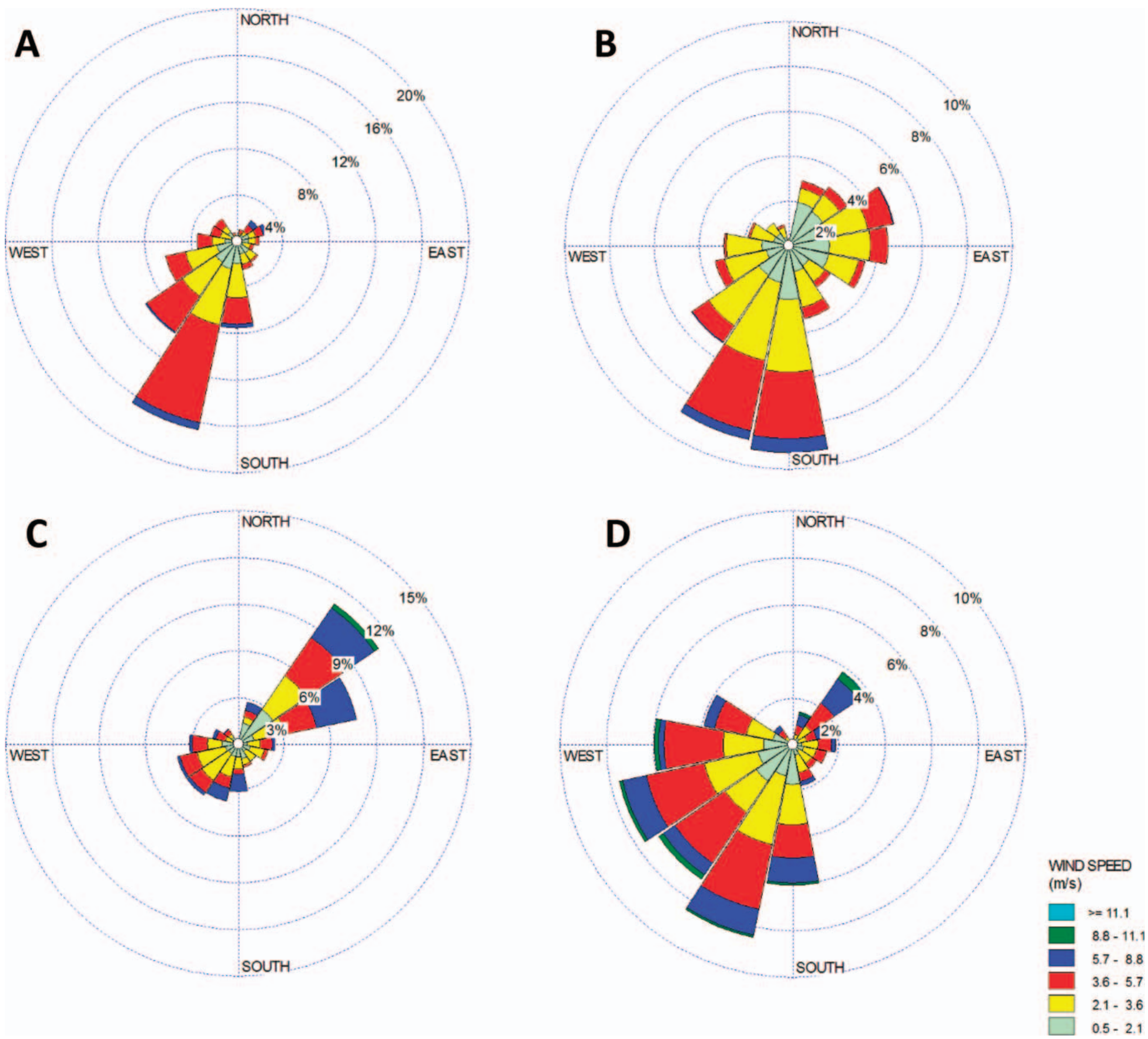

Figure 3. Summary of wind speed and direction for Canyon Uranium Mine, Coconino County, Arizona. May 2013–July 2013 **(A)**, August 2013–October 2013 **(B)**, November 2013–January 2014 **(C)**, and February 2014–April 2014 **(D)**.

a specific soil volume. Decision units for this study followed natural breaks in the surrounding habitat (grassland, shrubland, and pine forest) on each side of the mine. Specifically, decision units included the area within the bermed perimeter of the mine, areas A1–A6 (forest), and B1–B12 (grassland–shrubland; Figure 1). Within a decision unit, we collected triplicate soil increments of 5-cm depth at 30–100 equally spaced increments (Walsh 2009) and composited them into three separate samples for contaminant analysis. In addition to these soil samples, we collected a sediment sample from Owl Tank (1.5 km south of the mine site along the haul road) using incremental sampling methods when the tank was dry. We collected soil samples at selected active valley pocket gopher *Thomomys bottae* burrow locations ($n = 6$) by compositing multiple grab samples ($\geq$10) taken from up to 0.75 m into the burrow. We sieved all dry soil and sediment samples to <2 mm in the field. Final sample mass was $\geq$1 kg. A sediment slurry sample collected from the detention pond was decanted, dried, and submitted for analysis along with other soil and sediment samples. Using U.S. Geological Survey protocols (U.S. Geological Survey, variously dated), we collected surface-water samples from the detention pond on 2 May and 2 August 2013. Soil, sediment, and surface-water samples have been submitted for analysis of a suite of major and trace elements, including the COPCs.

Plants. A spatial design for vegetation sampling outside the bermed perimeter of the mine mirrored soil-sampling polygons (Figure 1). We randomly generated 3 transects, and selected 30 sampling points from the points generated by the soil sampling team for each of the 12 vegetation sampling polygons using ArcGIS

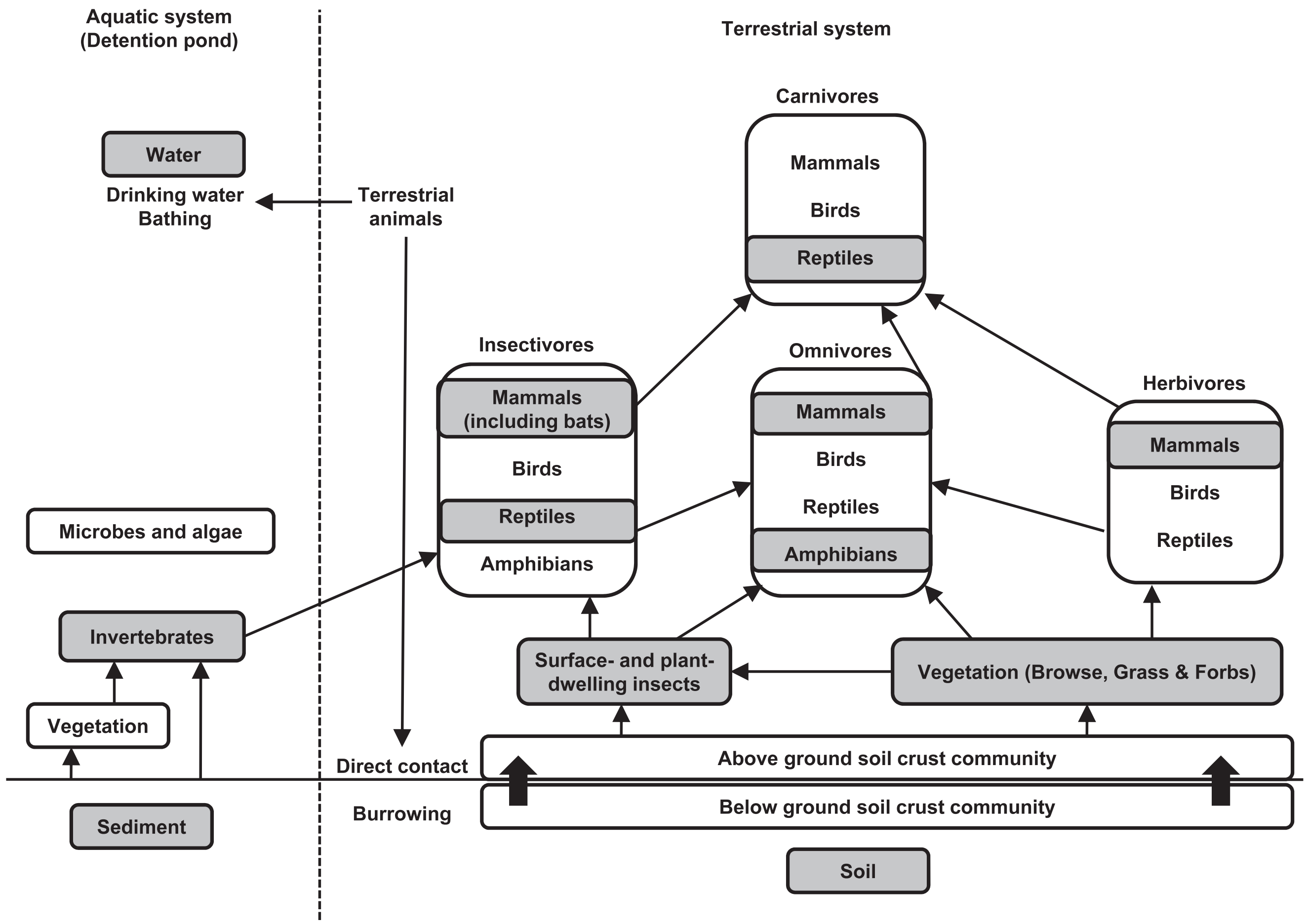

Figure 4. Diagrammatic representation of a generalized local food web for Canyon Uranium Mine, Coconino County, Arizona. Gray boxes represent food-web components that were sampled and collected for contaminant analysis in 2013.

(v. 10.0 Service Pack 5; ESRI, Redlands, CA). To achieve a representative and randomized transect layout, we subdivided inner- and outer-ring polygons into three separate, evenly sized polygons. Next, we generated 15 random beginning and end points within each subpolygon with Geospatial Modeling Environment software (www.spatialecology.com). We then randomly selected two points with the Geospatial Modeling Environment r.sample tool. Lines were drawn between the transect points within each polygon and labeled accordingly for a 36 total transects. Transects were 50 m long for larger polygons (A polygons) and 25 m for smaller polygons (B polygons).

We measured vegetation cover and composition of each sampling polygon using the line-point intercept method (Herrick et al. 2005) on 23–26 July 2013. We collected data using a 1-m spacing for the 50-m transects and 0.5-m spacing for the 25-m transects, for 50 total sampling points per transect and 150 points per polygon. A basic species list following nomenclature of Springer et al. (2009) was completed for each polygon by one person walking around the polygon for 30 min to 1 h to record infrequent species not identified by line-point intercept.

To establish baseline data on plant community contaminant concentrations, we collected and composited plant tissue for contaminant analysis by life form (grass, forb, shrub) using a random sampling design. This was achieved by randomly selecting 30 ordered sampling points per polygon (Geospatial Modeling Environment r.sample tool). We sampled the first 15 identified points in each polygon. If fewer than 10 collections of each functional group or insufficient sample mass were obtained, the next 5 ordered random points were visited (up to 30 point collections). At each sampled point, we collected triplicate samples by harvesting nonwoody, active plant parts (e.g., grass blades, grass stems, and shrub leaves). Triplicates consisted of the generated point and two related points a random distance and direction away from the original point. We collected all tissues within a 25-cm-diameter circle of the selected point for the first three polygons sampled (A3, B3–B4, and B5–B6). The sample diameter was increased to 1-m-diameter for the remainder of the polygons to ensure sufficient mass of plant tissue was collected. We recorded species collected at each sampling point.

Aerial and terrestrial invertebrates. We used two insect light traps (Universal Light Trap, 12-watt black light; BioQuip, Rancho Dominguez, CA) to sample dusk, night-time, and dawn-flying insects near the north and south ends of the detention pond on 3–7 June 2013. We started each light trap at dusk and it ran continuously until morning. The collection funnel contained 95% ethanol as a preservative. We retrieved insects at 0730 h, and closed traps during the day. Insects removed from the light traps were placed in containers in the field and then separated by date and collection location under laboratory settings. We collected ground-dwelling terrestrial insects using pitfall traps set at 10 locations to the north and east of the mine site from 5 to 11 June 2013. A site reconnaissance indicated the presence of colonial mounds of western harvester ant *Pogonomyrmex occidentalis* (Hymenoptera: Formicidae). We placed unbaited pitfall traps around western harvester ants mounds to obtain a mass of individuals adequate for contaminant and radiation analyses. Composite collections of insects fallen into the traps were taken every 1–3 d and stored frozen until sorted. We identified insects using a stereo dissecting microscope and grouped them taxonomically to at least family level (Myers et al. 2014); we preserved some samples as voucher specimens.

Herpetofauna. We collected amphibian tadpoles from the detention pond and Owl Tank using dip nets (Shaffer et al. 1994) on 2 August 2013. Collections were not made using a stratified sampling design, because small, discrete bodies of water do not lend themselves to this strategy.

We placed plywood coverboards (60 × 122 × 2 cm) flush on the surface of the ground to create artificial cover for reptiles (Fitch 1987; Fellers and Drost 1994) in April and May 2013. Coverboard placement used a modified stratified sampling design that emphasized colocation of multiple biotic and abiotic sample-collection sites. We placed the coverboards (n = 30) ≥10 m apart around the mine site and inside the bermed perimeter near the detention pond; we placed 30 additional boards in three transects on the edges of the haul road leading to the mine. We cut a 5 cm × 5 cm piece from the corner of 10 randomly selected coverboards using a hand saw with a tungsten–carbide blade to evaluate chemical contaminants potentially introduced to the soil around the coverboard through weathering; we archived these samples for contaminant analysis. We checked coverboards by flipping them up and catching animals sheltering underneath on 3 May, 6–7 June, and 2 August 2013. Common lizard and snake species were lethally sampled and frozen for contaminant and radiation analyses. Reptiles not lethally sampled were identified to species; common species were released without being marked, but less common species were uniquely branded on the center (lizards) or subcaudal scales using cautery pens (Winne et al. 2006).

Birds. We conducted visual and aural surveys on 30 May, 27 June, and 6 August 2013. We targeted resident breeding birds because they likely have the greatest risk of contaminant exposure and possible effects compared with nonbreeding migrants. We established four 500-m linear transects oriented in the four cardinal directions, each beginning at the edge of the shrubland and heading out toward the ponderosa pine forest. For each transect, we recorded all species seen or heard, the perpendicular distance of the bird from the transect line, detection time, and whether or not the bird was singing.

One survey (14 June 2013) used an area search technique. We started at the entrance road and walked a circle around the mine site, remaining ~50 m into the forest from the edge of the shrubland. We recorded all species seen or heard within 100 m of the observer by recording number of individuals, detection type (seen, heard, or both), distance from observer, and substrate the bird was using (e.g., tree species if perched, air if flying) if seen.

Mammals. We captured bats on 3 June 2013, using mist-nets over the detention pond (Kunz et al. 2009; Ellison et al. 2013). Individuals were lethally sampled using standard approved methods (Ellison et al. 2013). During the period of sampling for aerial insects and mist-netting for bats, we also recorded ultrasonic calls of bats flying in the area by using solar-powered, bioacoustic monitoring stations (Song Meter SM2BAT+; Wildlife Acoustics, Inc., Concord, MA). Two acoustic monitoring stations were located on the north and south ends of the detention pond, adjacent to each of the insect light traps. Although we used insect light traps only in early June, we ran acoustic monitoring stations continuously from dusk to dawn, in an effort to document temporal and nightly activity. We periodically downloaded recorded calls, and processed calls away from field site using Kaleidoscope (Wildlife Acoustics, Maynard, MA) and SonoBat (SonoBat ™, Arcata, CA) bat acoustic identification software. We manually examined select calls to determine accuracy of identification through the software programs. The species list presented here includes acoustic analysis from June to August 2013. These monitoring stations will continue to collect data at the mine site until the summer of 2014 to document seasonal presence and activity of bats as well as determine whether migratory species use the detention pond for feeding or drinking.

We used live-traps (Sherman Traps, Tallahassee, FL; Havaharts®, Lititz, PA) to collect small terrestrial mammals from 4 to 10 June 2013. We used three sizes of live-traps—small (2 in × 2.5 in × 9 in [5.1 cm × 6.4 cm × 22.9 cm]); large (3 in × 3.5 in × 9 in [7.6 cm × 8.9 cm × 22.9 cm]); and extra-large (4 in × 4.5 in × 15 in [10.2 cm × 11.4 cm × 38.1 cm]). We selected trapping locations based on availability of suitable habitat and evidence of small mammal presence (Wilson et al. 1996). Orientation of trap lines and number of traps were consistent among areas to assure trap effort was equally weighted across all areas. We baited traps with mixed grains, opened them in the evening, and checked them early in the morning. A limited number of more common species captured were collected ($n \leq 10$) for contaminant and radiation analyses. Mammals not lethally sampled were identified to species and then released without being marked. We also photographed fresh fecal material to identify terrestrial mammals using the area around the mine but not captured in the live-traps.

We used kill-traps (Victor® Gopher Traps and Gophinators) to collect fossorial mammals from 9 to 12 June 2013 after live-traps (6.5-cm internal diameter; Baker and

Williams 1972) proved to be ineffective. We selected trapping locations based on evidence of active burrow systems, and set traps during the day. We checked kill-traps every 1–2 h to collect animals for contaminant and radiation analyses.

Results

Baseline biological surveys

Plants. Vegetation communities in the area are a mosaic of blue grama *Bouteloua gracilis*–dominated grasslands, basin big sagebrush *Artemisia tridentata* shrublands, and ponderosa pine forest. We identified 127 species of trees, shrubs, graminoids, succulents, and forbs at Canyon Mine (Table 1). One species, the Tusayan flameflower *Phemeranthus validulus*, has a vulnerable conservation status because of its restricted range. Species richness was generally lowest to east and immediate north of the mine and greatest to south and west of the mine (Table 2). We collected shrub and perennial grass tissues in all polygons; we collected forbs in polygons A3, B3–B4, and B5–B6. Forbs, though highly diverse, did not compose enough of the site biomass to continue being collected in other polygons. Blue grama, two-needle pinyon *Pinus edulis*, and ponderosa pine were the dominant species cover in most sampling polygons. We collected composite samples by life form (grass, forb, shrub) and retained them for contaminant analysis.

Aerial and terrestrial invertebrates. We collected invertebrates from the Order Araneae, Coleoptera, Diptera, Entomobryomorpha, Hemiptera, Hymenoptera, Lepidoptera, and Orthoptera representing a range of feeding guilds (Table 3). The most diverse order represented was Coleoptera, with seven families identified. Moths (Noctuidae, Saturniidae, and Sphingidae) had the greatest biomass of aerial insects in the light traps, whereas terrestrial invertebrates in the pitfall traps were primarily western harvester ants and to a lesser extent darkling beetles (Colepotera: Tenebrionidae). These results are consistent with the known bias of the light and pitfall traps used and their placement (e.g., MacKay 1983; Raimondo et al. 2004; Gibb and Oseto 2006).

The phototactic behavior of moths draws them to light traps, but midges (Chironomidae) contributed equally to moths in relative abundance when compared with other insects collected in light traps. The high abundance of midges coincided with their seasonal presence and their associated aquatic habitat (i.e., detention pond). We collected composite samples by family and retained them for contaminant analysis.

Herpetofauna. We collected Mexican spadefoot tadpoles *Spea multiplicata* opportunistically in the detention pond ($n = 20$) and at Owl Tank ($n = 20$; Table 4) and retained them for contaminant analysis. Tadpoles had concentrated in shallow areas of the detention pond (the northeast end) and Owl Tank. These amphibians were abundant at both locations in August.

We observed three species of reptiles at the mine site (Table 4). We commonly saw the plateau fence lizard *Sceloporus tristichus* in and around the mine site; we collected nine individuals (six males, two females, and one juvenile) and retained them for contaminant analysis. The many-lined skink *Eumeces multivirgatus* is considered rare and/or cryptic in this area; we captured, measured, and released an adult south of the mine. We collected an adult female terrestrial gartersnake *Thamnophis elegans* on the mine property and retained it for contaminant analysis, and we measured a juvenile male and released it near Owl Tank. This snake species is common in northern Arizona.

Birds. We detected 44 species of birds at Canyon Mine during the summer of 2013 (Table 5). Most of these species have been detected in the Grand Canyon watershed prior to our surveys, but several species have a limited distribution in northern Arizona (Brown et al. 1987; Corman and Wise-Gervais 2005). These species include red crossbill *Loxia curvirostra*, Grace's warbler *Setophaga graciae*, and hepatic tanager *Piranga flava*. Insectivorous species were the most common guild observed, but granivorous, omnivorous, and carnivorous species were also present at the site. Violet-green swallow *Tachycineta thalassina* was the most commonly observed species (>14.3 individuals/500-m transect) at the site; individuals were often observed feeding and drinking at the mine detention pond. The other species most often detected at the site were the pygmy nuthatch *Sitta pygmaea* (9.2 individuals/500-m transect), purple martin *Progne subis* (4.4 individuals/500-m transect), and western bluebird *Sialia mexicana* (3.9 individuals/500-m transect). We did not collect samples for contaminant analyses for birds in 2013.

Mammals. Mist-netting over the detention pond resulted in the capture of three female big brown bats *Eptesicus fuscus*, one female long-legged bat *Myotis volans*, and one male western small-footed bat *Myotis ciliolabrum* that we collected for contaminant analysis. Acoustic analysis revealed seven additional bat species using the detention pond at the mine site (Table 6). Two species, the long-legged bat and Arizona bat *Myotis occultus*, have special conservation status. The Brazilian free-tailed bat *Tadarida brasiliensis* and the silver-haired bat *Lasionycteris noctivagans* were the only species detected that are considered migratory in this area of Arizona. We found extensive burrow systems of the valley pocket gopher along the mine fence and berm as well as in the blue grama grassland surrounding the mine. We collected four females (two adult and two subadult) and two adult male pocket gophers and retained them for contaminant analysis. This omnivorous species provides a critical fossorial species component in the conceptual site model (Figure 4).

Mammal captures in the shrubland were dominated by the deermouse *Peromyscus maniculatus*. Abundance, trap type, and to a lesser extent bait preference likely affected our relatively high captures of deermice. Bait and trap type were not preferred by insectivores (such as shrews *Notiosorex* spp.). We documented evidence of vole *Microtus* spp. tunnels in the grass under the herpetofauna coverboards, but did not capture voles. We collected 10 deermice (6 males, 3 females, and 1 unknown gender) and retained them for contaminant

Table 1. Plants identified by life form and species at Canyon Uranium Mine, Coconino County, Arizona, in July 2013. Species in bold were included in the composite samples for contaminant analysis.

Common name	Species name
Trees	
Utah juniper	*Juniperus osteosperma*
Two-needle pinyon	*Pinus edulis*
Ponderosa pine	*Pinus ponderosa*
Gambel oak	*Quercus gambelii*
Shrubs	
Carruth's sagewort	***Artemisia carruthii***
Tarragon	***Artemisia dracunculus***
Prairie sagewort	***Artemisia frigida***
Big sagebrush	***Artemisia tridentata***
Fourwing saltbush	*Atriplex canescens*
Desert sweet	***Chamaebatiaria millefolium***
Yellow rabbitbrush	***Chrysothamnus viscidiflorus* ssp. *viscidiflorus***
James' buckwheat	***Eriogonum jamesii***
Rubber rabbitbrush	***Ericameria nauseosa***
Apache plume	***Fallugia paradoxa***
Threadleaf snakeweed	***Gutierrezia microcephala***
Winterfat	***Krascheninnikovia lanata***
Fremont's mahonia	***Berberis fremontii***
Stansbury cliffrose	***Purshia mexicana* var. *stansburyana***
Skunkbush sumac	***Rhus aromatica***
Wax currant	***Ribes cereum***
Spineless horsebrush	***Tetradymia canescens***
Narrowleaf yucca	*Yucca angustissima*
Graminoids	
Indian ricegrass	***Achnatherum hymenoides***
Crested wheatgrass	*Agropyron cristatum*
Purple threeawn	***Aristida purpurea***
Blue grama	***Bouteloua gracilis***
Smooth brome	*Bromus inermis*
Cheatgrass	***Bromus tectorum***
Ross' sedge	*Carex rossii*
Longflower rabbitbrush	***Chrysothamnus depressus***
Squirreltail	***Elymus elymoides***
Needle and thread	***Hesperostipa comata***
Prairie Junegrass	***Koeleria macrantha***
Muhly	***Muhlenbergia* sp.**
Spike muhly	***Muhlenbergia wrightii***
Western wheatgrass	***Pascopyrum smithii***
Littleseed ricegrass	***Piptatherum micranthum***
Muttongrass	***Poa fendleriana***
Alkali sacaton	***Sporobolus airoides***
Sand dropseed	***Sporobolus cryptandrus***
Intermediate wheatgrass	***Thinopyrum intermedium***
Succulents	
Whipple cholla	*Cylindropuntia whipplei*
Pinkflower hedgehog cactus	*Echinocereus fendleri*
Spinystar	*Escobaria vivipara*
Pricklypear	*Opuntia* sp.

Table 1. Continued.

Common name	Species name
Forbs	
Pussytoes	*Antennaria* sp.
Eastwood's sandwort	*Eremogone eastwoodiae* var. *eastwoodiae*
Spreading sandwort	*Arenaria lanuginosa*
Spider milkweed	***Asclepias asperula***
Whorled milkweed	***Asclepias verticillata***
Torrey's milkvetch	*Astragalus calycosus*
Groundcover milkvetch	***Astragalus humistratus***
Freckled milkvetch	*Astragalus lentiginosus*
Woolly locoweed	*Astragalus mollissimus*
Burningbush	***Kochia scoparia***
Indian paintbrush	*Castilleja* sp.
Rose heath	***Chaetopappa ericoides***
Fendler's sandmat	***Euphoria fendleri***
Goosefoot	***Chenopodium* sp.**
Fetid goosefoot	*Dysphania graveolens*
Thistle	*Cirsium* sp.
Wheeler's thistle	*Cirsium wheeleri*
Bastard toadflax	*Comandra umbellata*
Torrey's craglily	*Echeandia flavescens*
Fireweed	***Epilobium* sp.**
Tall annual willowherb	*Epilobium brachycarpum*
Spreading fleabane	***Erigeron divergens***
Winged buckwheat	***Eriogonum alatum***
Redroot buckwheat	***Eriogonum racemosum***
Navajo fleabane	*Erigeron concinnus*
Mahonia fremontii	*Erigeron flagellaris*
Redstem stork's bill	*Erodium cicutarium*
Red dome blanketflower	*Gaillardia pinnatifida*
Harlequinbush	*Oenothera hexandra* ssp. *hexandra*
Pineywoods geranium	*Geranium caespitosum*
Dwarf false pennyroyal	*Hedeoma nana*
Fineleaf hymenopappus	*Hymenopappus filifolius*
Pingue rubberweed	***Hymenoxys richardsonii***
Manyflowered ipomopsis	*Ipomopsis multiflora*
Prickly lettuce	*Lactuca serriola*
Flatspine stickseed	*Lappula occidentalis*
Common pepperweed	*Lepidium densiflorum*
Arizona bladderpod	*Physaria arizonica*
Bristle flax	*Linum aristatum*
Lewis flax	*Linum lewisii*
Wright's deervetch	*Acmispon wrightii*
Lupine	***Lupinus* sp.**
Hill's lupine	***Lupinus hillii***
King's lupine	*Lupinus kingii*
Hoary tansyaster	***Dieteria canescens***
Slender goldenweed	***Xanthisma gracilis***
Sweetclover	***Melilotus officinalis***
Rough menodora	*Menodora scabra*
Narrowleaf four o'clock	***Mirabilis linearis***
Smooth spreading four o'clock	*Mirabilis oxybaphoides*

Table 1. Continued.

Common name	Species name
Evening primrose	*Oenothera* sp.
Purplewhite owl's-clover	*Orthocarpus purpureoalbus*
Purple locoweed	*Oxytropis lambertii*
Hoary groundsel	*Packera werneriifolia*
Beardlip penstemon	*Penstemon barbatus*
Longleaf mock thelypody	*Pennellia longifolia*
Coiled anther penstemon	*Penstemon ophianthus*
Thickleaf beardtongue	***Penstemon pachyphyllus***
Thompson's beardtongue	***Penstemon thompsoniae***
Tusayan flameflower	*Phemeranthus validulus*[a]
Mountain phlox	*Phlox austromontana*
Longleaf phlox	***Phlox longifolia***
Groundcherry	***Physalis* sp.**
Woolly plantain	*Plantago patagonica*
White milkwort	*Polygala alba*
Purslane	*Portulaca* sp.
Little hogweed	*Portulaca oleracea*
Pennsylvania cinquefoil	*Potentilla pensylvanica*
Greenstem paperflower	*Psilostrophe sparsiflora*
Purple locoweed	***Oxytropis lambertii***
Prickly Russian thistle	*Salsola tragus*
Desert globemallow	*Sphaeralcea ambigua*
Fendler's globemallow	*Sphaeralcea fendleri*
Smallflower globemallow	*Sphaeralcea parvifolia*
Small wirelettuce	*Stephanomeria exigua*
Common dandelion	*Taraxacum officinale*
Stemless four-nerve daisy	***Tetraneuris acaulis***
Hoary Townsend daisy	***Townsendia incana***
Yellow salsify	***Tragopogon dubius***
Branched noseburn	*Tragia ramosa*
Vervain	*Verbena* sp.
MacDougal verbena	*Verbena macdougalii*
Common mullein	*Verbascum thapsus*

[a] Global (G3 species) and subnational (S3 species) conservation status of vulnerable to extirpation because of its restricted range.

analysis. We captured a rock squirrel *Otospermophilus variegatus* and released it near a fallen ponderosa pine. Other species present in the shrubland based on the abundant amount of fresh fecal material included elk, mule deer, black-tailed jackrabbit *Lepus californicus*, and eastern cottontail rabbit *Sylvilagus floridanus* (Table 6). Two American badger *Taxidea taxus* burrows were also active in the shrubland area during field collections.

The cliff chipmunk *Tamias dorsalis* was the dominant species captured in the ponderosa pine forest around the mine site. We collected 10 cliff chipmunks (5 males and 5 females) and retained them for contaminant analysis. We captured and collected two eastern cottontail rabbits (a juvenile female and an adult male) and an adult male pinyon deermouse *Peromyscus truei*. We captured several species of woodrat and released them in the forest, including the Mexican woodrat *Neotoma mexicana* and Stephens' woodrat *Neotoma stephensi*; we did not collect woodrats for contaminant analysis because they represent the same food-web compartment (mammalian herbivore) as the cliff chipmunk. Fecal material from elk, mule deer, and black-tailed jackrabbit was also abundant in the forest.

Discussion

This study documented >200 plant and animal species in the first extensive survey for the area around Canyon Mine. However, the species list should not be considered a complete inventory for the site because we spent only a few days surveying during one season and used limited sampling methods. For amphibian and reptiles, the most common species expected from this area were detected, but other amphibian species could be present (e.g., true toads *Bufo* spp. and treefrogs *Hyla* spp.) dependent on the type of habitat (Brennan and

Table 2. Dominant plant species by sampling area at Canyon Uranium Mine, Coconino County, Arizona, in July 2013. See Figure 1 for polygon location.

Primary direction from the mine and sampling area (polygon)	Total no. of species	Dominant species (in order of greatest cover)
North		
Inner (B1–2)	34	blue grama *Bouteloua gracilis*, rubber rabbitbrush *Ericameria nauseosa*, big sagebrush *Artemisia tridentata*, spike muhly *Muhlenbergia wrightii*
Outer (A1)	58	blue grama, two-needle pinyon *Pinus edulis*, ponderosa pine *Pinus ponderosa*, Utah juniper *Juniperus osteosperma*, rubber rabbitbrush
Northeast		
Inner (B3–4)	37	yellow rabbitbrush *Chrysothamnus viscidiflorus* ssp. *viscidiflorus*, blue grama, rubber rabbitbrush
Outer (A2)	43	ponderosa pine, two-needle pinyon, blue grama
Southeast		
Inner (B5–6)	44	blue grama, big sagebrush, ponderosa pine
Outer (A3)	44	ponderosa pine, two-needle pinyon, blue grama, muttongrass *Poa fendleriana*
South		
Inner (B7–8)	64	blue grama, ponderosa pine, big sagebrush
Outer (A4)	66	ponderosa pine, blue grama
West		
Inner (B9–10)	61	blue grama, ponderosa pine, spike muhly
Outer (A5)	57	ponderosa pine, blue grama
Northwest		
Inner (B11–12)	55	blue grama, two-needle pinyon, western wheatgrass *Pascopyrum smithii*
Outer (A6)	51	Utah juniper, two-needle pinyon, ponderosa pine, blue grama

Holycross 2006). Importantly, Mexican spadefoot toads bred in the detention pond despite its construction being completed only as recently as December 2012. This finding supports the concern that the mine, specifically the detention pond, may be an attractive nuisance to biota if contaminant concentrations in water, soil, and sediments exceed protective ecological thresholds. We were able to document a wide variety of bird species at the site, but avian tissues for contaminant and radiation analyses were not collected because of logistical constraints. However, a bird nest box study was initiated in 2014 to characterize baseline exposure in this important receptor group (J.E. Hinck, personal communication). Additional visual and aural surveys are also being conducted to document species at the mine during spring and autumn migration periods. Nevertheless, the species data acquired thus far provide essential baseline documentation of bird species presently utilizing the area and their position in the local food web. Additional time has become available to further collect baseline biological information at Canyon Mine. The operator once again placed the mine on standby in November 2013 because of dropping uranium ore prices; development operations are expected to resume no sooner than 2015.

Most of the species documented at Canyon Mine are common in northern Arizona and are not considered to have special conservation status by state or federal agencies. One exception is the Tusayan flameflower, which has a global (G3 species) and subnational (S3 species) conservation status of vulnerable to extirpation because of its restricted range. Other exceptions are the long-legged bat (National Park Service species of management concern, Bureau of Land Management species of concern) and the Arizona bat (Bureau of Land Management species of concern; U.S. Bureau of Land Management 2011). The U.S. Bureau of Land Management species of concern (or special status species) are included because much of the mining withdrawal area is U.S. Bureau of Land Management land even

Table 3. Invertebrates identified and collected for contaminant analysis at Canyon Uranium Mine, Coconino County, Arizona, in June 2013.

Order, Family (if known)	Common name	Feeding guild
Araneae		
Sicariidae	Six-eyed venomous spiders	Invertivores
Unidentified Araneae	Other spiders	Invertivores
Coleoptera		
Carabidae	Ground beetles	Invertivores
Cerambycidae	Long-horned beetles	Herbivores
Coccinellidae	Lady beetles	Herbivores, Invertivores
Curculionidae	Weevils	Herbivores
Curculionidae: Scolytinae	Bark beetles	Herbivores
Elateridae	Click beetles	Herbivores, Invertivores
Scarabaeidae	Scarab beetles	Herbivores, Invertivores, Omnivores
Tenebrionidae	Darkling beetles	Herbivores
Unidentified Coleoptera	Other beetles	Herbivores, Invertivores, Omnivores
Diptera		
Chironomidae	Midges	Herbivores
Muscoidea[a]	House flies and kin	Omnivores
Unidentified Diptera	Other flies	Herbivores, Omnivores
Entomobryomorpha		
Entomobryidae	Slender springtails	Omnivores
Hemiptera		
Cicadellidae	Leafhoppers	Herbivores
Unidentified Hemiptera	Other true bugs	Herbivores
Hymenoptera		
Braconidae	Parasitoid wasps	Carnivores
Formicidae	Black ants *Messor* spp.	Omnivores
Formicidae	Western harvester ants *Pogonomyrmex occidentalis*	Omnivores
Ichneumonidae	Ichneumon wasps	Carnivores
Unidentified Hymenoptera	Other bees, wasps, and ants	Omnivores, Carnivores
Lepidoptera		
Noctuidae	Owlet moths	Herbivores
Saturniidae	Saturniid moths	Herbivores
Sphingidae	Hawk moths, sphinx moths, hornworms	Herbivores
Noctuidae	Owlet moths	Herbivores
Saturniidae	Saturniid moths	Herbivores
Sphingidae	Hawk moths, sphinx moths, hornworms	Herbivores
Unidentified Lepidoptera	Other moths and butterflies	Herbivores
Orthoptera		
Stenopelmatidae	Jerusalem crickets	Omnivores
Unidentified Orthoptera	Grasshoppers, crickets, etc.	Omnivores

[a] Superfamily.

though the Canyon Mine is on U.S. Forest Service land (U.S. Department of the Interior 2012). The Arizona bat was previously documented at the mine in the autumn of 2012 (Alexander 2012); however, this is the first report of the long-legged bat, fringed bat *Myotis thysanodes*, and canyon bat *Parastrellus hesperus* at the site. Although these latter two species are not special status species, their occurrence highlights the importance of temporal sampling to document species occurrence.

Western harvester ants are common throughout temperate grasslands and arid lands of southwestern North America. Harvester ant hills were found throughout the surrounding area of the mine with the greatest abundance in the blue grama grassland. Harvester ant

Table 4. Amphibians and reptiles observed at Canyon Uranium Mine, Coconino County, Arizona, in 2013. Species in bold were collected for contaminant analysis.

Common name	Species name	Feeding guild
Amphibians		
Mexican spadefoot[a]	*Spea multiplicata*	Omnivores (tadpoles)–insectivores (adults)
Lizards		
Plateau fence lizard	*Sceloporus tristichus*	Insectivores–carnivores
Many-lined skink	*Eumeces multivirgatus*	Insectivores
Snakes		
Western terrestrial gartersnake	*Thamnophis elegans*	Insectivores–carnivores

[a] Only tadpoles were collected in 2013.

colonies in the trapping area denuded the vegetation surrounding ant hills (radial distance of 1–3 m). The ants' harvesting activities increased the amount of bare soil microhabitat, which affected spatial distribution of other surface-dwelling and burrowing invertebrates. To ensure adequate terrestrial invertebrate biomass for contaminant analysis, pitfall traps were placed around the hills, which introduced a bias for harvester ants into our

Table 5. Avifauna detected at Canyon Uranium Mine, Coconino County, Arizona, in 2013, categorized by primary feeding behavior and diet guild. Species are nonmigratory unless otherwise noted.

Primary summer feeding behavior		
Ground forager	**Tree–shrub forager**	**Aerial forager**
Granivores		
Brown-headed cowbird *Molothrus ater*[a]	Lesser goldfinch *Carduelis psaltria*[b]	None
House finch *Carpodacus mexicanus*	Red crossbill *Loxia curvirostra*[a]	
Mourning dove *Zenaida macroura*		
Insectivores		
Chipping sparrow *Spizella passerina*[a]	Black-throated gray warbler *Setophaga nigrescens*[b]	Ash-throated flycatcher *Myiarchus cinerascens*[b]
Dark-eyed junco *hyemalis*[a]	Grace's warbler *Setophaga graciae*[b]	Cassin's kingbird *Tyrannus vociferans*[b]
Lark sparrow *Chondestes grammacus*[b]	Hepatic tanager *Piranga flava*[b]	Common nighthawk *Chordeiles minor*[b]
Northern flicker *Colaptes auratus*	Juniper titmouse *Baeolophus ridgwayi*	Cordilleran flycatcher *Empidonax occidentalis*[c]
Rock wren *Salpinctes obsoletus*	Mountain chickadee *Poecile gambeli*	Dusky flycatcher *Empidonax oberholseri*[b]
Song sparrow *Melospiza melodia*	Plumbeous vireo *plumbeus*[b]	Gray flycatcher *Empidonax wrightii*[b]
White-crowned sparrow *Zonotrichia leucophrys*[c]	Pygmy nuthatch *Sitta pygmaea*	Purple martin *Progne subis*[b]
	Ruby-crowned kinglet *Regulus calendula*[c]	Violet-green swallow *Tachycineta thalassina*[b]
	White-breasted nuthatch *Sitta carolinensis*	Western wood-pewee *Contopus sordidulus*[b]
	Yellow-rumped warbler *Dendroica coronata*[c]	
	Western tanager *Piranga ludoviciana*[b]	
Omnivores		
American robin *Turdus migratorius*[a]	Hairy woodpecker *Picoides villosus*	Broad-tailed hummingbird *Selasphorus platycercus*[b]
Common raven *Corvus corax*		Mountain bluebird *Sialia currucoides*[a]
Steller's jay *Cyanocitta stelleri*		Townsend's solitaire *Myadestes townsendi*[c]
Western scrub jay *Aphelocoma californica*		Western bluebird *Sialia mexicana*[a]
Carnivores		
Turkey vulture *Cathartes aura*[b]	None	None
Great blue heron *Ardea herodias*		
Red-tailed hawk *Buteo jamaicensis*		

[a] Migratory; local movements, but likely present year-round.
[b] Migratory; summer breeding.
[c] Migratory; winter visitor or transient.

Table 6. Mammals detected at Canyon Uranium Mine, Coconino County, Arizona, in 2013. Species in bold were collected for contaminant analysis.

Common name	Species name
Herbivores	
Elk	*Cervus canadensis*
Black-tailed jackrabbit	*Lepus californicus*
Mexican woodrat	*Neotoma mexicana*
Stephens' woodrat	*Neotoma stephensi*
Mule deer	*Odocoileus hemionus*
Eastern cottontail	*Sylvilagus floridanus*
Cliff chipmunk	*Tamias dorsalis*
Valley pocket gopher	*Thomomys bottae*
Insectivores	
Big brown bat	*Eptesicus fuscus*
Silver-haired bat[a]	*Lasionycteris noctivagans*
California bat	*Myotis californicus*
Western small-footed bat	*Myotis ciliolabrum*
Arizona bat [b]	*Myotis occultus*
Fringed bat	*Myotis thysanodes*
Long-legged bat[b,c]	*Myotis volans*
Yuma bat	*Myotis yumanensis*
Canyon bat	*Parastrellus hesperus*
Brazilian free-tailed bat [a]	*Tadarida brasiliensis*
Omnivores	
Deermouse	*Peromyscus maniculatus*
Pinyon deermouse	*Peromyscus truei*
Rock squirrel	*Otospermophilus variegatus*
Carnivores	
American badger	*Taxidea taxus*

[a] Migratory.
[b] Bureau of Land Management species of concern.
[c] National Park Service species of management concern.

survey. However, other species (e.g., tenebrionid beetles) are known to co-occur with harvester ant colonies (Cole 1968; Slobodchikoff 1979; Crist and Wiens 1994).

We anticipated that a wide range of body sizes in wild mammals would be encountered near Canyon Mine. In recognition of the differential response of species to traps (e.g., Tanaka 1963; Weiner and Smith 1972; Slade et al. 1993), different sizes and types of traps were used to sample mammals. Therefore, our primary sampling targets were animals no larger than 1 kg that are vulnerable to our trap types. This approach was designed to sample locally abundant small mammals, increases the likelihood of collecting the same species several years from now during active mining, and does not target more rare species for lethal sampling. However, this design does not allow for the evaluation of relative species sensitivity differences with respect to chemical exposure.

Uranium mines are sources of radiation from uranium and its daughter products and chemical contaminants from uranium and other co-occurring inorganic constituents in the ore. Many of these other inorganic constituents do not pose radiation hazards in field exposures; however, some are potentially as toxic, if not more toxic, to biota than is uranium (e.g., Hinck et al. 2013). Therefore, contaminant exposure characterization will include arsenic, cadmium, chromium, copper, lead, mercury, nickel, selenium, thallium, uranium, and zinc for chemical toxicity and uranium and associated radionuclides for radiation as the COPCs for this site. The biological sampling and tissue collection represents numerous components of the local food web. For example, plants accumulate contaminants via direct contact uptake from the soil and may introduce contaminants to herbivores through assimilation in tissues or dust on browsed surfaces (e.g., seeds, leaves). The animals collected in 2013 can accumulate contaminants via direct contact uptake, inhalation, incidental ingestion, and dietary transfer (Figure 2) and may introduce contaminants to insectivores, omnivores, and carnivores that prey upon them (Figure 4). The contaminant information from these food-web components will provide a baseline of empirical data prior to active mineral extraction. Future collections will validate contaminant-exposure pathways and potential threats related to contaminant exposures to ecological receptors, including 1) windblown dust and aerosol that could be inhaled or ingested via contaminated food sources (e.g., deposition on vegetation), 2) chemical contamination of off-site surface waters if institutional controls fail, and 3) development of an attractive nuisance as ore and waste rock enter the detention pond. Critical contaminant-exposure pathways will be refined in the future when contaminant concentrations and radiation levels in biological samples collected during active mining are compared with those collected during this baseline sampling effort.

The development of the COPC list, conceptual site model, and biological survey data presented in this study provide essential components for an ecological risk analysis, which will allow us to evaluate the possible effects that uranium mining has on resident biota. Contaminant concentrations and radiation levels in samples collected for analysis will establish the only baseline concentration data available for biota within the withdrawal area, prior to active mineral extraction. The mineralogy between the Canyon Mine breccia pipe and other breccia pipes in the region is consistent (Wenrich 1985, 1986; Wenrich et al. 1989, 1995). The top of the breccia pipes that have been mined historically and those currently being developed (e.g., Canyon Mine) extend to the surface and are considered exposed. The geochemistry of soil directly above the breccia pipe is related to the plateau horizon where the pipe is exposed, primarily in the Harrisburg member of the Kaibab Limestone for pipes mined to date (Wenrich and Aumente-Modreski 1994). These factors indicate that the genesis, geochemistry, and ultimately the bioavailability of inorganic constituents and radionuclides are similar among breccia pipe deposits in the Grand Canyon watershed. In other words, the relative toxicity of co-occurring constituents with known ecotoxicological effects (e.g., arsenic, selenium) should be consistent among high-grade uranium breccia pipes. As a result, contaminant concentrations in soil and biota from Canyon Mine can be applicable in characterizing baseline conditions at other mines within the withdrawal area.

The next steps will be to determine the extent to which local species are exposed to chemical and radiation contamination and to predict effects to the biota once the mine is operational and producing ore. A subsequent report characterizing baseline chemical and radiation contamination in target species that represent the various components of the food web and critical exposure pathways will be forthcoming. These data will be compared with concentrations in biological samples collected during active mining (estimated to be several years from present) and after mining has ended and the site reclaimed (estimated to be >5 y from present) to determine whether inorganic contaminant concentrations and radiation levels increase during active ore extraction. At each of these temporal scales (premining, active mining, postmining–reclamation), risk analyses will be conducted to determine whether chemical and radiation concentrations measured in biological receptors pose an unacceptable risk and how risk changes temporally. Ultimately, these data could inform resource management decisions on mitigating chemical and radiation exposure of biota at high-grade uranium breccia pipes throughout the withdrawal area.

Supplemental Material

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Data S1. Species location data for Canyon Mine.
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