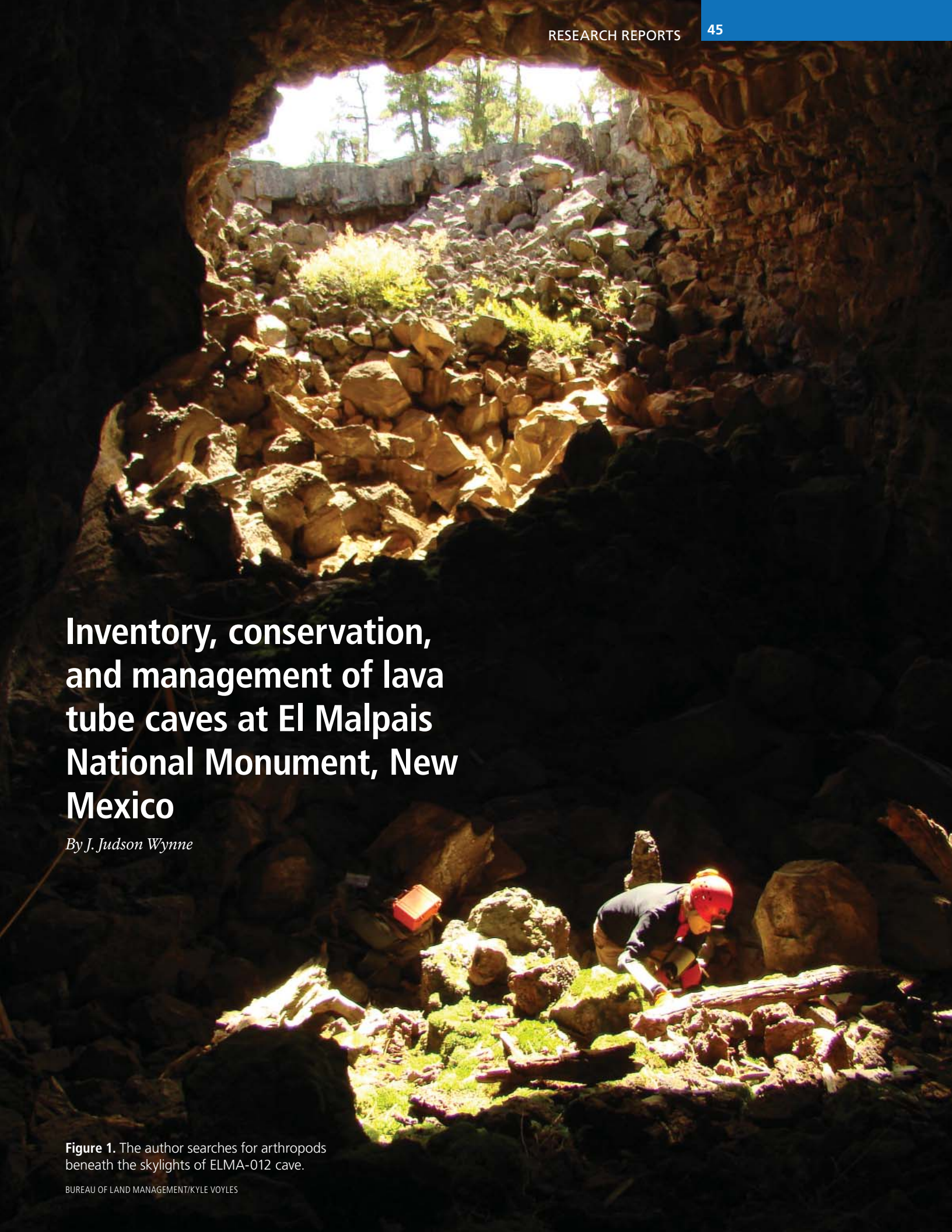

Inventory, conservation, and management of lava tube caves at El Malpais National Monument, New Mexico

By J. Judson Wynne

Figure 1. The author searches for arthropods beneath the skylights of ELMA-012 cave.

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Abstract

Lava tube caves at El Malpais National Monument have received little scientific attention with regard to their bat and arthropod populations. From an all taxa biological inventory of 11 caves, I identified seven new species of cave-dwelling arthropods (including two potential troglobites) and range expansions of two parasitoidal wasps. The presence of unique microhabitats, tree root "curtains" hanging from the ceilings, and moss gardens in cave entrances resulted in higher species richness of arthropods at four caves. For bats, I confirmed continued use of one large bat hibernaculum cave and one significant bat maternity roost. While several recommendations have been made to better conserve and manage sensitive cave resources, additional research and monitoring will be required for the long-term management and protection of several caves. Finally, I introduce three new terms to cave biology: two for entrance-dwelling animals (eisodophiles and eisodoxenes) and one for animals that hunt deep within or near the entrances of caves (xenosylles).

Key words

cave, cave biology, cave-dwelling arthropods, cave-roosting bats, conservation, eisodophile, eisodoxene, El Malpais National Monument, land management, lava tubes, xenosylle

LOCATED IN WESTERN NEW MEXICO, EL MALPAIS National Monument encompasses approximately 1,522 km² [~588 mi²]. Featuring at least eight major volcanic eruptions ranging in age from 100,000 to 3,000 years old (Cascadden et al. 1997), the national monument is a dramatic landscape comprising vast expanses of pahoehoe and ʻaʻā lava flows, cinder cones, ice caves, and at least 290 lava tube caves (fig. 1, previous page). Despite the large number of lava tube caves, this region has received little scientific attention with regard to bat and arthropod populations that occur within these features.

Bats are often considered keystone species of cave ecosystems. When bats populate caves in large numbers, they transport a significant amount of organic material (as guano) from the surface into the cave. Although bats have been studied throughout most of the western United States, how these animals use caves remains underresearched. Bat maternity roosts (sites where female bats rear their pups) and hibernacula (winter hibernation sites) are highly sensitive to human disturbance (Brown et al. 1993; McCracken 1989; Elliott 2000; Hamilton-Smith and Eberhard 2000). With the westward advance of white-nose syndrome, a disease responsible for the mortality of more than five million bats in eastern North America (USFWS 2012), inventory and monitoring of all roost sites will be critically important to the long-term management of bats at El Malpais National Monument.

Other animals of high conservation and management value are arthropods that occur exclusively in caves. Prior to this study, at least five cave-adapted arthropods (presumed sensitive species) were known from six lava tube caves at El Malpais (Northup and Welbourn 1997). Many troglomorphic (cave-adapted) animals are endemic to a single cave or region (Reddell 1994; Culver et al. 2000; Christman et al. 2005) and are generally characterized by low population numbers (Mitchell 1970). Additionally, numerous human-induced impacts threaten subterranean ecosystem health and the very persistence of cave-obligate species. Many cave-obligate species are therefore considered imperiled. Nonnative species introductions (Elliott 1992; Reeves 1999; Taylor et al. 2003; Howarth et al. 2007), global climate change (Chevaldonné and Lejeune 2003; Badino 2004), and recreational use (Culver 1986; Howarth and Stone 1993; Pulido-Bosch et al. 1997) are among the impacts that present challenges for the long-term management of cave-obligate arthropod populations at El Malpais.

An all taxa biological inventory focusing on bats, cave-dwelling arthropods, and other vertebrates was not only important to characterizing the fauna that use El Malpais lava tubes, but also was required to provide resource managers with the information necessary to best conserve and manage these sensitive resources. My objectives for this study were to (1) catalog all taxa using caves, including the identification of endemic and sensitive cave-adapted invertebrates, (2) apply and examine a systematic sampling protocol for inventorying arthropods, (3) draw comparisons across the national monument to gain inference into patterns of invertebrate species distributions, biodiversity, biogeography, and endemism, and (4) provide recommendations to enhance management of El Malpais lava tube caves. I addressed objectives 1 and 4 in this article and will address objectives 2 and 3 in subsequent publications.

Methodology

During 7–15 October 2007 and 8–15 October 2008, research teams and I conducted two site visits per cave at 10 caves at El Malpais National Monument and 1 cave on adjacent Bureau of Land Management lands. We scheduled site visits around deployment and collection of baited pitfall traps for sampling cave-dwelling arthropods. At the monument's request, I used cave codes rather than actual cave names for all caves on National Park Service lands. A copy of this report, which includes a table of cave names with associated cave codes, is on file with monument headquar-

ters in Grants, New Mexico, and the National Cave and Karst Research Institute, Carlsbad, New Mexico.

Arthropod sampling

I used both opportunistic and systematic sampling to search for arthropods. During each cave visit, a team of three researchers uniformly applied three techniques: opportunistic collecting, baited pitfall trapping, and timed searches. For opportunistic collecting, the team collected invertebrates encountered as they walked between sampling stations while deploying and removing pitfall traps and conducting timed searches.

Because I wanted to maximize the number of invertebrate species detected, we sampled each cave from its entrance (i.e., drip line) to the back of the cave. Using available cartographic cave maps, teams applied an interval sampling approach whereby 10% of each cave's length was used as the sampling interval (e.g., for a 100 m–long cave [328 ft], sampling interval was every 10 m [33 ft]). All sampling stations were plotted on each cave map. Three sampling stations (one at either wall and one at the cave centerline) were established at each sampling interval. Fewer than three sampling stations per sampling interval were established in only two cases: (1) when the cave passageway width was ≤5 m (16 ft), one station was designated in the best available location and (2) when exposed lava floors were encountered and no materials were available to aid in countersinking the trap, the sampling station was skipped.

At each sampling station we deployed one pitfall trap and conducted two timed searches. Traps consisted of two 907 g (32 oz) plastic containers (13.5 cm high, 10.8 cm diameter rim, and 8.9 cm base [5.3 in high, 4.3 in diameter, 3.5 in base]) placed inside one another, with bait (a teaspoon of peanut butter) placed in the outer container and holes punched in the base of the inner container. This design attracts arthropods and keeps most animals separated from the bait. With the assistance of field technicians, I buried containers to the rim where possible, built rock ramps to the trap rim in other cases, and covered all traps with a caprock. The team conducted timed searches within a 1 m (3.3 ft) radius of each pitfall trap station for a period of 1 to 3 minutes before traps were deployed and prior to checking traps (modified from Peck 1976). Each search was concluded after 1 minute if no arthropods were detected and continued for a total of 3 minutes when arthropods were observed.

Because some caves contain unique microhabitats that support distinct arthropod communities and endemic populations, I augmented this sampling protocol by conducting direct intuitive searches in those areas. Unique microhabitats at El Malpais include moss gardens (refer to Northup and Welbourn 1997) at cave entrances and beneath skylights (i.e., holes in the ground formed by the partial collapse of the cave roof), and tree root "curtains" hanging from the ceilings in cave deep zones (fig. 2). Within each unique microhabitat we spent one hour (3 observers × ~20 minutes) searching for arthropods. Specifically, we searched tree root curtains hanging from the ceilings in two caves (one hour per cave) and moss gardens in two caves (one hour per cave).

Figure 2. Both moss gardens (top row) and root curtains (bottom row) are important microhabitats and support new and unique arthropod species. At least three lava tube caves contain moss gardens within cave entrances and beneath skylights, and two caves contain plant root curtains within cave deep zones at El Malpais National Monument.

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Arthropod identification

For arthropod groups actively being studied by taxonomic specialists, I sent either specimens or high-resolution images of specimens to various taxonomic experts for identification. Otherwise, we used existing keys to identify specimens to the lowest taxonomic level possible.

Bat sampling

I visited and inventoried three known bat roosts: a Mexican free-tailed bat (*Tadarida brasiliensis*) maternity colony, a Townsend's big-eared bat (*Corynorhinus townsendii*) maternity roost, and a Townsend's big-eared bat hibernaculum. Additionally, for sites where bat use was unknown, these caves were surveyed for midfall use by bats. Research teams scanned ceilings and walls throughout the length of each cave, and searched for any evi-

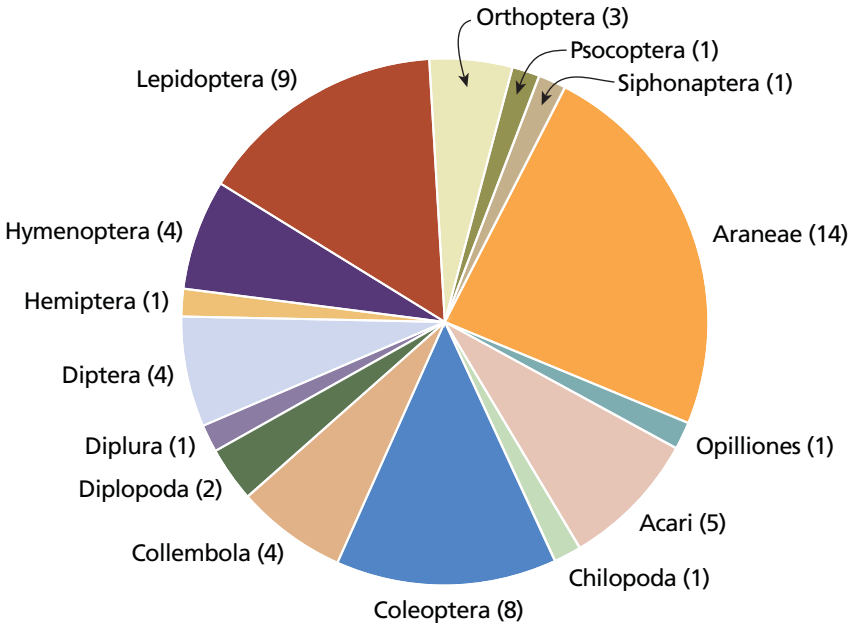


Figure 3. Number of arthropod morphospecies detected by order (including classes Chilopoda and Diplopoda) at El Malpais National Monument in 2007 and 2008. The surveys were conducted at 11 caves: ELMA-062, ELMA-008, ELMA-110, ELMA-262, ELMA-012, ELMA-054, ELMA-029, ELMA-303, ELMA-315, ELMA-061, and Hummingbird.

dence of bats (e.g., guano). When bats were encountered, I attempted to identify them to species visually. No bats were handled during this study.

Documenting other vertebrates

Within each cave, I searched for and recorded the presence of all other vertebrate species. Sign of other vertebrates included direct observation, scat, feathers, and skeletal remains.

Cave specificity functional groups

I divided El Malpais cave-dwelling taxa into nine cave specificity functional groups. The following functional group terminology was taken from Barr (1968) and Howarth (1983): (1) *troglobites*, obligate cave dwellers who can only complete their life cycle within the cave environment; (2) *troglophiles*, species that occur facultatively within caves and complete their life cycles there, but also exist in similar surface microhabitats; (3) *trogloxenes*, taxa that frequently use caves for shelter but forage on the surface; and (4) *accidentals*, morphospecies occurring within caves, but which cannot survive within the cave environment. Additionally, because this project sampled cave entrances for arthropods and documented other vertebrate (i.e., non-bat taxa) use of caves, I propose three additional groups for categorizing cave-dwellers: (5) *eisodophiles*, species facultatively using cave entrances and twilight zones (areas where light faintly penetrates into the cave, but is sufficient for humans to see) that may complete their life cycles there, but also occur in similar partially sheltered surface environments; (6) *eisodoxenes*, animals that frequently use cave entrances and twilight zones for shelter but return to the surface to forage; and (7) *xenosylles*, surface-dwelling animals that hunt deep within caves or in the cave entrances. For eisodophiles and eisodoxenes, the etymology of the first half of the terms, *eísodo*, is from the Greek word *eísodos*, "entrance," while the second halves were derived from the same naming convention used for functional groups 2 and 3: *philos*, Greek for "love" or "desire," and *xenos*, Greek for "guest." *Xenosylle* is a combination of *xenos* and *syllektis*, Greek for "collector." Finally, (8) *parasites*, the special-case group, describes parasitic arthropods detected in caves due to the presence of their host (e.g., bats or other vertebrates); and (9) *unknown* is used for animals for which information is lacking to reasonably place them in one of the eight other groups.

Results

My work resulted in the identification of at least 66 morphospecies (groups distinguished from others based upon morphological characteristics), including 59 arthropods (representing at least 13 orders and two classes; fig. 3), three bats, and four other vertebrates. Appendix A, available online at http://www.nature.nps.gov/ParkScience/archive/PDF/Article_PDFs/ParkScience30(1)Summer2013_A1–A12_Wynne_3653.pdf, shares the entire list of inventoried species and provides explanations for cave specificity functional group designations.

Arthropods

Cave specificity functional groups for arthropods consisted of one troglobite, two questionable troglobites, five troglophiles, 18

questionable troglophiles, seven trogloxenes, one questionable trogloxene, one accidental, 21 eisodophiles, one parasite, and two unknowns (fig. 4). At least seven new species were discovered and two range expansions were documented. New species discoveries include one potentially cave-adapted spider (family Theridiidae, *Theridion* n.sp.?); a mite (family Histiostomatidae, *Histiostoma* n.sp.); two springtails (order Collembola, *Drepanura* n.sp. and *Pogonognathellus* n.sp.); one new cricket species (*Ceuthophilus* cf *apache* n.sp.); one beetle (family Carabidae, *Rhadine* n.sp., *perlevis* species-group); and a new species of potentially cave-adapted planthopper (order Hemiptera: superfamily Fulgoroidea; Fulgoroidea n.sp.?; refer to fig. 5 for images of select new species). Additionally, I confirmed the persistence of the troglomorphic bristletail (order Diplura: family Campodeidae; Campodeidae n.sp.) within the deep zone of ELMA-054. Northup and Welbourn (1997) identified this as both a troglobite and an "undetermined species." Working with dipluran taxonomist Dr. R. Thomas Allen (Academy of Natural Sciences, Drexel University, Philadelphia, Pennsylvania), we confirmed this animal as a new species in 2013. The likely new species of planthopper was detected within the cave deep zones on roots protruding from the ceiling of ELMA-315 and ELMA-303; this animal has reduced eyes in its nymphal stage and may be troglomorphic. Also, this work resulted in the range expansions of two species of parasitoidal wasps (fig. 6, next page) (family Tiphiidae, *Tiphia andersoni* and *T. nona*; Allen 1971). Both tiphiids were in a torpor and collected from beneath rocks within the moss gardens of ELMA-008 and ELMA-012. Given the season (midfall) and their behavior, I suggest these wasps may have been preparing to hibernate within the moss gardens.

A, B, AND D: NORTHERN ARIZONA UNIVERSITY/JUT WYNNE; C: BUREAU OF LAND MANAGEMENT/KYLE VOYLES

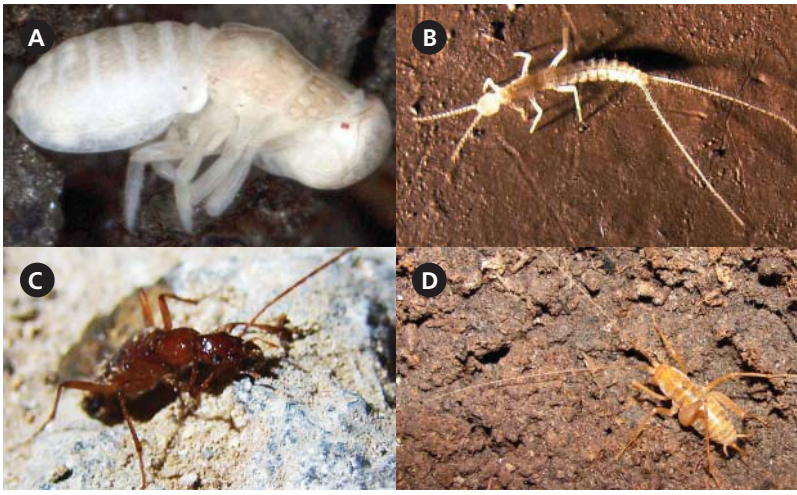
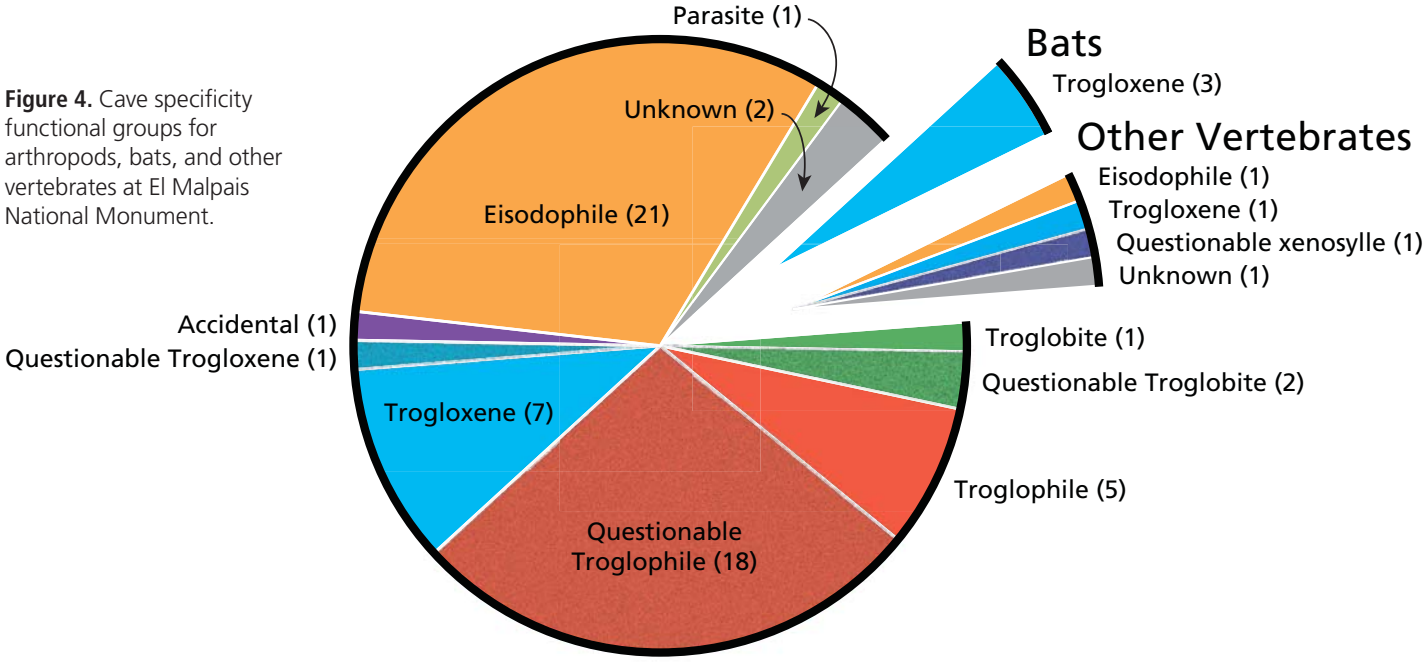


Figure 5. (A) New species of a potentially troglobitic planthopper (order Hemiptera: superfamily Fulgoroidea: Fulgoroidea n.sp.?; body length ~1.5 mm); (B) new species of troglobitic bristletail (order Diplura: family Campodeidae; from Northup and Welbourn 1997; length 2.5 mm); (C) new species of trogloxenic Carabid beetle (*Rhadine* n.sp., *perlevis* species-group; length 15 mm); and (D) new species of trogloxenic cave cricket (*Ceuthophilus* cf *apache* n.sp.; length 25 mm).

Figure 4. Cave specificity functional groups for arthropods, bats, and other vertebrates at El Malpais National Monument.



Caves with the highest arthropod species richness, in rank order, were ELMA-315 (n = 22), ELMA-012 (n = 16), ELMA-303 (n = 15), ELMA-008 (n = 15), ELMA-062 (n = 13), and ELMA-262 (n = 11) (table 1). ELMA-315 and ELMA-303, which had the highest species richness, contain extensive root curtains protruding through ceiling fissures within the cave deep zones. For ELMA-012 and ELMA-008, richness is driven by the large number of species detected within moss gardens at cave entrances and beneath skylights. ELMA-062 supports a large Mexican free-tailed bat maternity roost; because significant nutrients via guano have been transported into this cave, this likely contributed to the high number of morphospecies. In 2007, logistical constraints prevented my team from sampling the moss gardens within the entrance of ELMA-029 and from further sampling ELMA-110 (which supports a bat maternity roost). Thus, I suggest both of these caves likely support more arthropods (in terms of richness and abundance) than are included in this report.

All new species reported here were identified as "new" by taxonomic specialists. Several of these new species ultimately will be formally described and the results published in scientific journals.

Bats

During the 2007 surveys, I observed five hibernating Townsend's big-eared bats in the deep zone of ELMA-054 and one torpid big brown bat (*Eptesicus fuscus*) roosting near the entrance (figs. 7A and 7B, respectively). Additionally, ELMA-062 continues to support a maternity colony of Mexican free-tailed bats. On 10 October 2007, I observed thousands of individuals of this species roosting approximately 75 m (246 ft) within the cave (fig. 7C); however, when I returned four days later to remove arthropod traps, that number dropped to less than 100. Also in October 2007, I did not observe any Townsend's big-eared bats in residence at ELMA-110; once I arrived, this roost was already abandoned for the year. Relatively fresh guano in the main section of the cave (beginning at the northeasternmost skylight, extending to the northeastern ward) suggests they were using this area before they relocated to their winter roosts. During an unrelated study in 2005 and 2006, I observed a maternity roost of this species in both the main cave and tunnel segments directly southwest of the main section of this cave. It seems the colony uses several areas in the tunnel segments and within the main cave passageway during the breeding season. Given the sampling period in early October (after breeding), I was unable to ascertain whether or not additional summer roosts exist on the national monument. However, aside from the two known maternity roosts, I did not observe any significant deposits of fresh guano (suggestive of a large summer roost) in any of the other caves. Thus, I have no evidence to suggest additional large summer roosts occur in the caves sampled. All bats were considered trogloxenes.

Figure 6. *Tiphia andersoni* Allen, 1971. This specimen was collected via a direct intuitive search of moss gardens (beneath the large skylights) of ELMA-012. Prior to this work, this parasitoidal wasp was known to occur in central Mexico, north into southeastern and north-central Arizona (Allen 1971). Detection of this animal in New Mexico represents an expansion of its known range.

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Other vertebrates

I documented small-carnivore (questionable xenosylle) scat, likely ringtail (*Bassariscus astutus*), skunk (*Conepatus* sp.), or raccoon (*Procyon lotor*), in ELMA-054 and ELMA-110. Skunks and raccoons often prey upon infirm bats or bat pups that have fallen from the ceiling (Winkler and Adams 1972), and ringtails are commonly known to hunt bats roosting on cave walls. I found a fully articulated ringtail skeleton near the terminus of the northern extent of ELMA-303. I sent photographs of the skeleton to Eastern Tennessee State University paleontologist Dr. Jim Mead. In an e-mail exchange with him on 4 March 2013, he suggested the remains were between 1,000 and 10,000 years old. This animal may have entered the cave to hunt bats, became disoriented, and, unable to find its way back to the entrance, died in the cave. Given its age, I did not consider this animal's remains as part of this inventory. Recent packrat (*Neotoma* sp.; *N. mexicana* and/or *N. albigula*; refer to Bogan et al. 2007) activity was evident in both ELMA-062 and ELMA-061; packrats are considered trogloxenes. Also, I found the carcass of a gopher snake (*Pituophis catenifer*) in the twilight zone of ELMA-061. The snake was wrapped around

Table 1. Observed morphospecies richness for arthropods, bats, and other vertebrates at El Malpais National Monument caves

Cave	Arthropods	Bats	Other Vertebrates
[M]ELMA-008	15	—	—
[M]ELMA-012	16	—	—
ELMA-029	—	—	—
[B]ELMA-054	2	2	1
ELMA-061	1	—	2
[B]ELMA-062	13	1	1
[B]ELMA-110	4	1	—
[M]ELMA-262	11	—	1
[R]ELMA-303	15	—	—
[R]ELMA-315	22	—	—
Hummingbird	3	—	—

Notes: Some species were detected in two or more caves.
[M]Moss gardens occurred beneath skylights and within entrances of these caves.
[B]Confirmed bat roosts.
[R]Caves with extensive root curtains protruding through the ceiling within the deep zone.

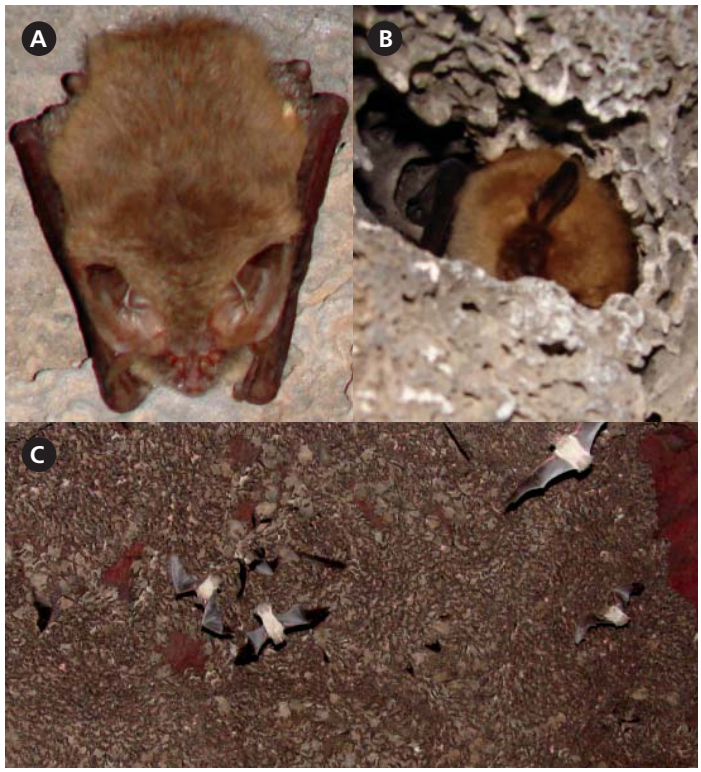

Figure 7. (A) Hibernating Townsend's big-eared bat and (B) big brown bat aroused from torpor at ELMA-054. (C) Late-season maternity colony of Mexican free-tailed bats within ELMA-062. Note that the "rough" surface in this panel is actually tightly clustered roosting bats. For scale, the average wingspan of Mexican free-tailed bats is 301 mm (12 in) (refer to Wilkins 1989).

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a stick and had several lacerations along the length of its body; I suggest a park visitor probably killed this animal. Because I do not know whether the snake was killed in the cave or it was brought into the cave postmortem, its use of the cave is "unknown." Finally, a barn owl (*Tyto alba*; eisodophile) was spooked as my team entered ELMA-262. This owl was roosting near the entrance and then flew to a skylight where it exited the cave.

Conservation and management

This work resulted in the identification of seven new species of cave-dwelling arthropods (including two potential troglobites), range expansions of two parasitoidal wasps, and two caves containing significant root curtains hanging from the ceiling. The presence of root curtains and moss gardens has been shown to be an important driver of high arthropod richness at El Malpais lava tube caves. For bats, I confirmed continued use of one hibernaculum cave and two significant bat maternity roosts. Although all of these caves will require further study, these findings have been useful in highlighting future management directions and research needs.

Arthropods

Four of the new species reported here are dependent on caves for most or all of their life cycle. The potentially new troglomorphic spider (*Theridion* n.sp.?) and the planthopper (Fulgoroidea n.sp.?) are likely to be restricted to the cave environment, while the cricket (*Ceuthophilus* cf *apache* n.sp.) and beetle (*Rhadine* n.sp., *perlevis* species-group) are trogloxenes. Unfortunately, only one specimen of *Theridion* n.sp.? was detected and collected; additional specimens will be required to describe this animal and determine whether it is indeed troglomorphic. In the two caves with root curtains, I identified at least one potential troglobite, a planthopper (Fulgoroidea n.sp.?). Unfortunately, all specimens collected were nymphs, and adults are required to confirm both cave adaptation and whether or not it is a new species. The remaining three newly discovered species likely occur in surface habitats as well as caves. The two new springtail species (*Drepanura* n.sp. and *Pogonognathellus* n.sp.) are edaphic

(soil-dwelling) organisms. *Histiostoma* n.sp. is a very small mite (600–900 µm [0.6–0.9 mm] in length) and is found in association with other insects. Because the deutonymph (early life stage of mites) hitchhikes on larger-bodied insects for dispersal between habitats, this mite may have been transported into the cave by another animal. Both springtails and mites will require further study to determine their affinities for caves and the ecological roles they play in the cave environment.

To address questions concerning population dynamics and distribution patterns of these new arthropod species, additional surveys at caves known or likely to support these animals will be required. This information will be necessary to develop resource management plans to best protect these species and their habitats. All of these new species should be considered important finds because they expand our knowledge of the natural history of El Malpais National Monument and, by extension, the state of New Mexico.

Bats

ELMA-054 supports the largest known hibernaculum of Townsend's big-eared bats on the monument, while ELMA-110 supports the largest known maternity roost of this species. Wynne (2006) counted 100 Townsend's big-eared bats hibernating in the deepest section of ELMA-054. ELMA-110 supports a maternity roost of Townsend's big-eared bats, estimated at 50 individuals in 2006 (Wynne, unpublished data). ELMA-110 has been closed to park visitors for several years while bats are in residence. As a result of this study and the 2006 site visit, ELMA-054 is now closed during the hibernation period (October through mid-April).

Based on our knowledge of Townsend's big-eared bats in other areas, I suggest the same population uses both roosts. In Oklahoma, movements of these bats between maternity roosts and hibernacula averaged 11.6 km (7.2 mi) (range 3.1 to 39.7 km [1.9–24.7 mi], n = 3 individuals; Humphrey and Kunz 1976). Dobkin et al. (1995) documented Townsend's big-eared bats traveling distances ranging from 5 to 24 km (3–15 mi) from summer roost to foraging sites in Oregon. Additionally, Pierson et al. (1999) suggested that this species was in decline throughout its range. The straight-line distance from ELMA-110 to ELMA-054 is 10.5 km (6.5 mi).

Given that this species is likely to be the most affected by white-nose syndrome on the monument, knowledge of this bat's habits, movements, and roost locations will enhance its management and protection. I recommend conducting a radio tagging and telemetry study of Townsend's big-eared bats and their use of these two roosts. For such a project, radio tagging of bats should occur late in the maternity season (late August to early September). This project would enable monument personnel to (1) establish baseline estimates of population size and structure to begin monitoring this species and its two known roosts, (2) determine if the same population is using both ELMA-110 and ELMA-054, (3) potentially identify additional Townsend's big-eared bat roosts by tracking bat movements with telemetry, and (4) make informed decisions regarding potential cave closures and protection of this species.

Scientists and managers know little about the winter habitat requirements of year-round bat residents at El Malpais. Thus, more surveys are needed, particularly winter bat inventories, to identify additional hibernacula. I recommend annual to biennial monitoring of ELMA-054, as well as newly identified hibernacula and long-term microclimatic monitoring in caves supporting hibernating bats. In light of the westward advance of white-nose syndrome and global climate change, this information may be useful in guiding management decisions to protect bat populations in the future. Additionally, information gathered by such an endeavor may be informative for developing similar monitoring strategies for other management units of the National Park System in the southwestern United States.

Deep zones and unique habitats

All deep zone environments that support or have the potential to support cave-adapted animals should be considered high-priority sites for conservation and management. Deep zones are characterized where environmental conditions (e.g., complete darkness, temperature, relative humidity, moisture, airflow) remain relatively stable over time (refer to Howarth 1980 and 1982). When nutrients are added to this equation (via root curtains protruding from the ceiling, bat guano, or dissolved organic material percolating through rock), these areas should be intensively sampled for troglomorphic arthropods. For example, Howarth et al. (2007) stressed the importance of roots in caves for conserving troglomorphic arthropods in Hawaiian lava tubes.

Three caves on the monument meet these criteria. ELMA-315 and ELMA-303 contain deep zones with extensive root curtains hanging from the ceiling. During the arthropod sampling period, these caves were among the warmest on the monument (ELMA-315: mean temperature 12.4°C [54.3°F], standard deviation 0.5°C [0.9°F]; ELMA-303: mean temperature 11.9°C [53.4°F], standard deviation 0.7°C [1.3°F]). I know of no other caves in the region that support this microhabitat type. Additionally, ELMA-110 has the most extensive deep zone microhabitat known on the monument. At the terminus of this cave, water percolates through fissures into the cave chamber. I recommend conducting additional surveys in all of these caves using a bait sampling and direct intuitive search sample design (*sensu* Wynne 2010 and Wynne et al. 2012). These inventories, conducted during the most produc-

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tive times of year (i.e., spring and summer), would likely result in the detection of additional troglomorphic arthropods.

Because cave-adapted animals are cryptic, they are often difficult to detect and researchers must conduct numerous site visits to obtain even a baseline knowledge of community composition. For example, Krejca and Weckerly (2007) reported that 10 to 22 site visits were required to detect three endangered arthropods known to occur in Texas caves. Although it is not directly applicable to terrestrial cave-dwelling invertebrates, Culver et al. (2004) reported that Sket (1981) discovered a new stygobite (an aquatic cave-adapted animal belonging to a new genus) after more than 100 collecting trips to a cave in Slovenia. During this study, I identified two potential troglobites and detected only one of five troglobites originally identified by Northup and Welbourn (1997). This not only underscores the inefficiency in our abilities to effectively detect cave-adapted animals but also emphasizes the need for additional inventory work in deep zone microhabitats.

ELMA-054 is home to a troglomorphic bristletail (order Diplura: family Campodeidae). It has been detected on the mud floors of a small chamber at the terminus of this cave. This animal may prove to be a narrow-range endemic (occurring in this cave and nowhere else on the planet). To best protect this animal and its habitat, in 2013 monument personnel permanently closed the deepest section of ELMA-054 to all recreational use.

Another important and highly sensitive microhabitat is moss gardens. These areas have been identified as relict habitats of the last glacial maximum (approximately 20,000 years ago) and support species now restricted to this environment at both El Malpais (Northup and Welbourn 1997) and in Oregon (Benedict 1979). Species richness for both ELMA-012 and ELMA-008 was driven by the large number of species detected within moss gardens at cave entrances and beneath skylights. Roughly 25% of the arthropods detected during the Northup and Welbourn (1997) study were found within moss gardens.

Because moss gardens are considered relict habitats and have been shown to support large numbers of species, this microhabitat should be afforded the highest level of protection. In 2013 ELMA-012 was closed to recreational use. Moss gardens within ELMA-008 have been roped off and signage has been posted indicating the fragility of these habitats. Based on my observations of both caves since 2005, this approach seems to be deterring foot traffic in these areas. However, some of the posts supporting the rope have fallen. More frequent maintenance of the posts and ropes, and adding more signage in ELMA-008, are relatively inexpensive measures that may serve to better protect these important microhabitats. Should ELMA-012 reopen in the future, I recommend using the same management and maintenance approach described for ELMA-008.

I did not detect any arthropods in ELMA-029 because I did not have an opportunity to sample the moss gardens in the cave entrance (as Northup and Welbourn [1997] did during their work). I observed no signs of recent human use or visitation when I was there in 2007. Given its remote location (approximately 1.6 km [1 mi] from an unmaintained dirt road), this cave and its moss gardens are likely well protected.

ELMA-029 also contains the most significant ice deposit on the monument, with a meters-thick ice sheet extending from near the entrance to the back of the cave. Cave interior and deep zone temperatures fluctuated from near to below freezing (mean temperature = 0.141°C [32.25 °F], standard deviation = 1.21°C [2.18°F]) during the arthropod sampling period. Although this cave is not suitable habitat for most arthropod species, it is possible that ice crawlers (order Notoptera: family Grylloblattidae) occur there and in other ice caves on private lands adjacent to the monument. These animals are known to occur in caves at both Oregon Caves and Lava Beds National Monuments (Jarvis and Whiting 2006) and would be a significant discovery at El Malpais. If ice crawlers exist within this cave, these animals would likely be relict species of the last glacial maximum. I suggest surveys for ice crawlers be conducted at ELMA-029, as well as at other ice caves in the El Malpais region.

Future directions

The information presented here provides a solid foundation on which to continue building knowledge of cave natural resources on the national monument, and has already proven useful in managing these resources. Additional studies targeting the use of lava tubes by cave-roosting bats, the distributional extent of known troglomorphic arthropods in caves or groups of caves, additional sampling for several of the new species discussed here, and further study of cave deep zones, root curtains, moss gardens, and cave ice sheets will be required to obtain the data necessary for optimal conservation and management of lava tube cave biological resources at El Malpais National Monument. My hope is that some of the protocols presented here and the recommendations made will be useful in the development and implementation of a monitoring framework that may be used to gauge the response of sensitive cave-dwelling animals to recreational use, invasive species, global climate change, and white-nose syndrome.

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Literature cited

Allen, H. W. 1971. A monographic study of the genus *Tiphia* of western North America. Transactions of the American Entomological Society 97:201–359.

Badino, G. 2004. Cave temperatures and global climate change. International Journal of Speleology 33:103–114.

Barr, T. C., Jr. 1968. Cave ecology and evolution of troglobites. Pages 35–102 *in* T. Dobzhansky, M. Hecht, and W. Steere, editors. Evolutionary biology, Volume 2. Appleton-Century-Crofts, New York, New York, USA.

Benedict, E. M. 1979. A new species of *Apochthonius* Chamberlin from Oregon (Pseudoscorpionida, Chthoniidae). Journal of Arachnology 7:79–83.

Bogan, M. A., K. Geluso, S. Haymond, and E. W. Valdez. 2007. Mammal inventories for eight national parks in the Southern Colorado Plateau Network. Natural Resource Technical Report NPS/SCPN/NRTR-2007/054. National Park Service, Fort Collins, Colorado, USA.

Brown, P., R. Berry, and C. Brown. 1993. Bats and mines: Finding solutions. Bats 11:12–13.

Cascadden, T. E., A. M. Kudo, and J. W. Geisman. 1997. Discovering the relationships in a family of volcanoes: Cerro Candelaria, Twin Craters, Lost Woman Crater and Lava Crater. New Mexico Bureau of Mines and Mineral Resources 156:41–52.

Chevaldonné, P., and C. Lejeune. 2003. Regional warming-induced species shift in northwest Mediterranean marine caves. Ecology Letters 6:371–379.

Christman, M. C., D. C. Culver, M. K. Madden, and D. White. 2005. Patterns of endemism of the eastern North American cave fauna. Journal of Biogeography 32:1442–1452.

Culver, D. C. 1986. Cave faunas. Pages 427–443 *in* M. Soulé, editor. Conservation biology. Sinauer Associates, Sunderland, Massachusetts, USA.

Culver, D. C., M. C. Christman, B. Sket, and P. Trontelj. 2004. Sampling adequacy in an extreme environment: Species richness patterns in Slovenian caves. Biodiversity and Conservation 13:1209–1229.

Culver, D. C., L. L. Master, M. C. Christman, and H. H. Hobbs III. 2000. Obligate cave fauna of the 48 contiguous United States. Conservation Biology 14:386–401.

Dobkin, D. S., R. D. Gettinger, and M. G. Gerdes. 1995. Springtime movements, roost use and foraging activity of Townsend's big-eared bat (*Plecotus townsendii*) in central Oregon. Great Basin Naturalist 55:315–321.

Elliott, W. R. 1992. Fire ants invade Texas caves. American Caves Winter:13.

———. 2000. Conservation of the North American cave and karst biota. Pages 665–669 *in* H. Wilkens et al., editors. Subterranean ecosystems, ecosystems of the world, Volume 30. Elsevier, Amsterdam, the Netherlands.

Hamilton-Smith, E., and S. Eberhard. 2000. Conservation of cave communities in Australia. Pages 647–664 *in* H. Wilkens et al., editors. Subterranean ecosystems, ecosystems of the world, 30th edition. Elsevier, Amsterdam, the Netherlands.

Howarth, F. G. 1980. The zoogeography of specialized cave animals: A bioclimatic model. Evolution 34:394–406.

———. 1982. Bioclimatic and geological factors governing the evolution and distribution of Hawaiian cave insects. Entomologia Generalis 8:17–26.

———. 1983. Ecology of cave arthropods. Annual Review of Entomology 28:365–389.

Howarth, F. G., S. A. James, W. McDowell, D. J. Preston, and C. T. Imada. 2007. Identification of roots in lava tube caves using molecular techniques: Implications for conservation of cave arthropod faunas. Journal of Insect Conservation 11:251–261.

Howarth, F. G., and F. D. Stone. 1993. Conservation of Hawaii's speleological resources. Pages 124–126 *in* W. R. Halliday, editor. Proceedings of the Third International Symposium on Volcanospeleology, Bend, Oregon, 1982. International Speleological Foundation, Seattle, Washington, USA.

Humphrey, S. R., and T. H. Kunz. 1976. Ecology of a Pleistocene relict, the western big-eared bat (*Plecotus townsendii*), in the southern Great Plains. Journal of Mammalogy 57:470–494.

Jarvis, K. J., and M. F. Whiting. 2006. Phylogeny and biogeography of ice crawlers (Insecta: Grylloblattodea) based on six molecular loci: Designating conservation status for Grylloblattodea species. Molecular Phylogenetics and Evolution 41:222–237.

Krejca, J. K., and B. Weckerly. 2007. Detection probabilities of karst invertebrates. Pages 283–289 *in* W. R. Elliott, editor. Proceedings of 18th National Cave and Karst Management Symposium (St. Louis, Missouri, USA, 8–12 October 2007). Texas Parks and Wildlife Department, Austin, Texas, USA.

McCracken, G. 1989. Cave conservation: Special problems of bats. National Speleological Society Bulletin 51:49–51.

Mitchell, R. W. 1970. Total number and density estimates of some species of cavernicoles inhabiting Fern Cave, Texas. Annales de Spéléologie 25:73–90.

Northup, D. E., and W. C. Welbourn. 1997. Life in the twilight zone—Lava tube ecology, natural history of El Malpais National Monument. New Mexico Bureau of Mines and Mineral Resources, Bulletin 156:69–82.

Peck, S. B. 1976. The effect of cave entrances on the distribution of cave-inhabiting terrestrial arthropods. International Journal of Speleology 8:309–321.

Pierson, E. D., M. C. Wackenhut, J. S. Altenbach, P. Bradley, P. Call, D. L. Genter, C. E. Harris, B. L. Keller, B. Lengus, L. Lewis, B. Luce, K. W. Navo, J. M. Perkins, S. Smith, and L. Welch. 1999. Species conservation assessment and strategy for Townsend's big-eared bat (*Corynorhinus townsendii townsendii* and *Corynorhinus townsendii pallescens*). Idaho Conservation Effort, Idaho Department of Fish and Game, Boise, Idaho, USA.

Pulido-Bosch, A., W. Martín-Rosales, M. López-Chicano, C. M. Rodríguez-Navarro, and A. Vallejos. 1997. Human impact in a tourist karstic cave (Aracena, Spain). Environmental Geology 31:142–149.

Reddell, J. R. 1994. The cave fauna of Texas with special reference to the western Edwards Plateau. Pages 31–50 *in* W. R. Elliott and G. Veni, editors. The caves and karst of Texas. National Speleological Society, Huntsville, Alabama, USA.

Reeves, W. K. 1999. Exotic species of North American caves. Pages 164–166 *in* K. Henderson, editor. Proceedings of the 1999 National Cave and Karst Management Symposium. Chattanooga, Tennessee, USA.

Sket, B. 1981. *Niphargobates orophobata* n.g., n.sp. (Amphipoda, Gammaridae s.l.) from cave waters in Slovenia (NW Yugoslavia). Bioloski Vestnik 29:105–118.

Taylor, S. J., J. Krejca, J. E. Smith, V. R. Block, and F. Hutto. 2003. Investigation of the potential for red imported fire ant (*Solenopsis invicta*) impacts on rare karst invertebrates at Fort Hood, Texas: A field study. Illinois Bexar County Karst Invertebrates Draft Recovery Plan Natural History Survey, Center for Biodiversity Technical Report 2003(28):1–153.

U.S. Fish and Wildlife Service (USFWS). 2012. North American bat death toll exceeds 5.5 million from white-nose syndrome. News release, 17 January 2012. Accessed 1 February 2012 from http://whitenosesyndrome.org/news/201201.

Wilkins, K. T. 1989. *Tadarida brasiliensis*. Mammalian Species 331:1–10.

Winkler, W. G., and D. B. Adams. 1972. Utilization of southwestern bat caves by terrestrial carnivores. American Midland Naturalist 87:191–200.

Wynne, J. J. 2006. Cave trip report and Junction Cave bat hibernacula, 4 February 2006. Unpublished report submitted 15 February 2006 to El Malpais National Monument, National Park Service, Grants, New Mexico. 1 page.

———. 2010. Preliminary results of arthropod baiting and surface sampling at Grand Wash Cave, Grand Canyon–Parashant National Monument, Arizona. On file with National Park Service, Grand Canyon–Parashant National Monument, Saint George, Utah. 11 pages.

Wynne, J. J., L. Pakarati, and C. Tambley. 2012. Artrópodos cavernícolas en zonas profundas en cavernas en Rapa Nui. On file with Corporacíon Nacional Forestal (CONAF), Parque Nacional Rapa Nui, Easter Island, Chile. 11 pages.

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