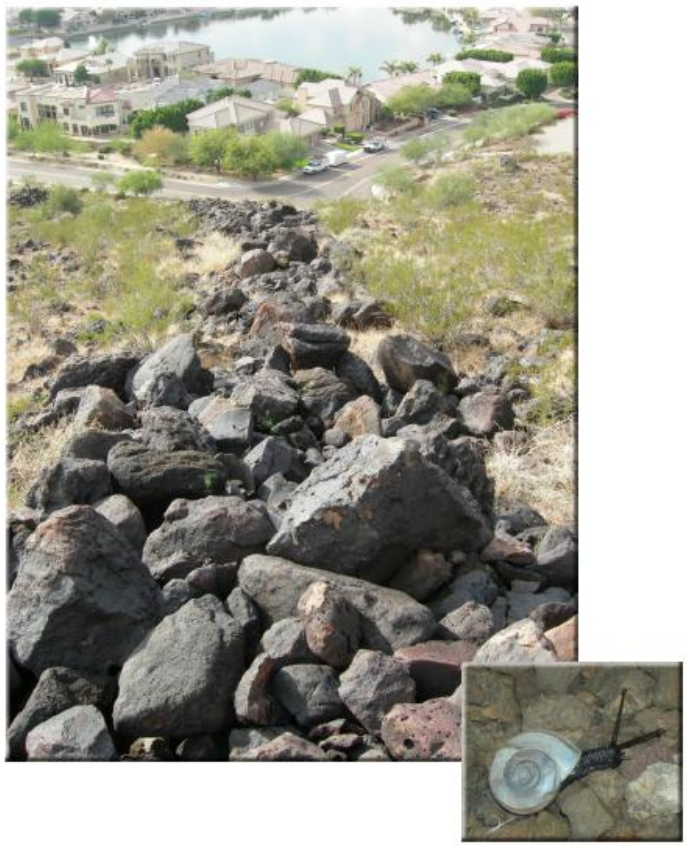
DISTRIBUTION AND ECOLOGY OF THE PHOENIX TALUSSNAIL, *SONORELLA ALLYNSMITHI*

Nick Dana Waters



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EXECUTIVE SUMMARY

The Phoenix talussnail was detected at 16 new localities, bringing the total to 20 within the greater Phoenix metropolitan area of northeastern Maricopa County. The species was detected within discontinuous ranges of central and north Phoenix, Scottsdale, Fountain Hills, Glendale, Peoria, Cave Creek, Carefree, and New River. Snails inhabit hillside talus and rocky desert washes. Within appropriate talus habitat, formed by dense igneous and metamorphosed bedrock, snails were detected on all slope aspects and only when slope gradient was minimally 18º, or 32%. Snails were not evenly detected throughout talus where present, nor were they always detected on neighboring hills with appropriate habitat. Snail surface activity periodically occurs after rainfall from December through March when surface temperatures range from 7°C–15°C and soil moisture is greater than 60%. Summer surface activity, following monsoon rainfall from July to September, was not detected in 2011 but has been reported in the past during wet years. Snails were observed estivating during dry hot periods on average 0.37 m below the surface. Summer temperatures at this depth average 34°C. Snails were tested on a thermal gradient and found to avoid temperatures < 1°C and > 34ºC. Snails perished rapidly at or below 0ºC. Upper estivation thermal limits are unknown. The introduced decollate snail, a predator of snails and slugs, was not detected at any sample sites. Introduced buffelgrass was detected and poses a significant threat to talus habitat. Hillside talus is well conserved within the greater Phoenix metropolitan area and there do not appear to be any significant threats to talus via development or mining. Washes have been heavily altered throughout the valley and continue to be modified due to ongoing, rapid development near mountains. Substantial areas of talus habitat are unoccupied by the species and the extent of wash occupancy is unknown. To reduce the danger of wildfire impacts to talus slopes, exotic fire-tolerant buffelgrass needs to be controlled. Further study is recommended to determine whether widely separated talussnail populations are genetically distinct or cryptic species, and whether their populations are stable or in decline. Additional research is needed to determine habitat correlates of occupied washes, whether washes are suitable for dispersal, and to determine the critical thermal and moisture parameters the species requires of its microhabitat at sensitive life stages.

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Introduction

Desert adapted terrestrial snails of the genera *Sonorella*, *Eremarionta*, *Coyote*, *Cahuilus*, *Helminthoglypta*, and others, are distributed discontinuously across the Southwestern United States from California, Nevada, Arizona, New Mexico, and Texas, as well as Baja California and Mexico. Arizona representatives include *Sonorella*, with more than 80 species, and *Eremarionta* with 2 species. They are collectively adapted to a diverse array of environmental conditions ranging from hot arid desert to cool mesic sub-alpine forest (Gregg and Miller 1969; Bequaert and Miller 1973; Pilsbry 1939). Of these, the Phoenix talussnail *Sonorella allynsmithi* Gregg and Miller, 1969) (Figure 1), is considered to occupy among the most arid conditions of all Southwestern desert land snails (Gregg and Miller 1969). The species occupies steep talus slopes and rocky washes within the lower Sonoran Desert life zone (Lowe 1964) of the greater Phoenix metropolitan area (Figure 2). Annual precipitation typically ranges from 10-25 cm, occurring intermittently from December-March and July-September. There are extended dry periods of 90-150 consecutive days with daily air temperature exceeding 40°C from May through September (Schmidli and Jamison 1996).

Figure 1. The Phoenix talussnail (*Sonorella allynsmithi* Gregg and Miller, 1969), photographed *in situ*.

STATUS AND DISTRIBUTION

The Phoenix talussnail is identified as a Species of Greatest Conservation Need (tier 1B) in Arizona's State Wildlife Action Plan (2005; 2010, in review). The basis for the designation is the lack of data on the species genetic diversity, ecology, and limited distribution coupled with the rapid expansion of the Phoenix metropolitan area which now encompasses the known range of the species.

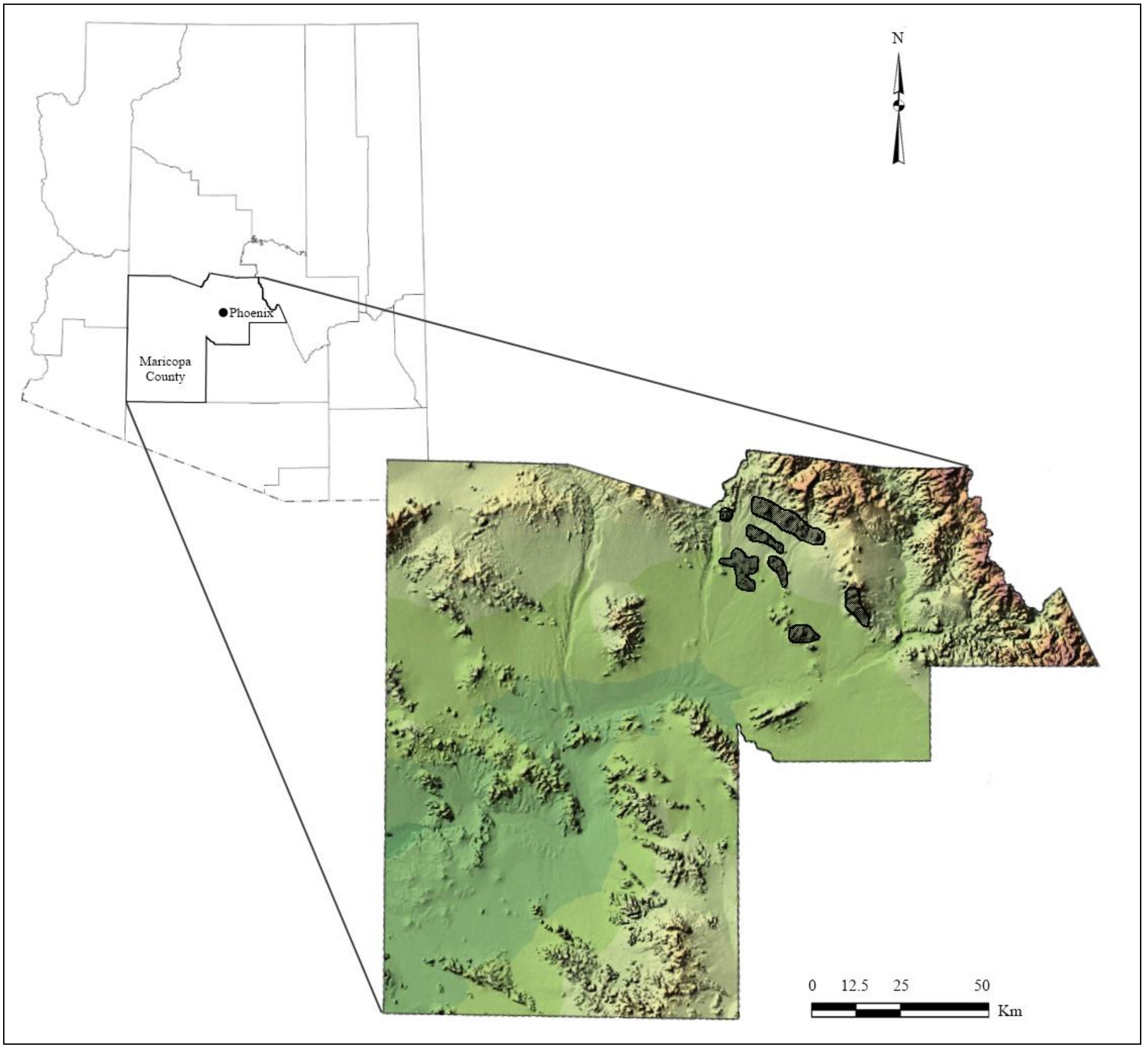

Figure 2. Distribution of the Phoenix talussnail in the greater Phoenix metropolitan area (indicated in the shaded areas), northeastern Maricopa County, Arizona. Basemaps from Arizona Geological Survey.

SPECIES INFORMATION NEEDS

The Phoenix talussnail lacks critical life history, organismal and behavioral biology, demographic, population, community, genetic, and habitat data. Only three sources of information are available. Two peer reviewed papers focus on taxonomy (Gregg and Miller 1969; Roth 1996) and one unpublished agency report (Hoffman 1995) which focuses on distribution.

THREATS

The fragmented distribution of the Phoenix talussnail suggests it may have been extirpated over portions of its range. No imminent threats to talus habitat visited in this study are known. All but a few mountains in the Phoenix area have been set aside as reserves. Appropriate habitat occurs on steep talus slopes where construction is not feasible without significant and expensive alteration to the hillside. Quarry operations in the Union Hills (Holloway and Leighty 1998) occur adjacent to occupied slopes and may affect local populations. The effect upon the species by widespread wash channelization and development within the Phoenix metropolitan area is unknown. Washes continue to be impacted due to ongoing, rapid development near mountain parks (Waters, personal observation). Trail building disrupts talus habitat. Repeated off-trail hiking and travelling up rocky washes would disrupt habitat. Off-trail hiking is discouraged by mountain park regulations.

Temperature and moisture are limiting factors in their survival, especially during hot dry years. Particularly lengthy periods of drought would be expected to affect survival. Synergistic urban heat island effects may exacerbate conditions within the talus environment during severe drought periods (Guhathakurta and Gober 2007). Data from this study indicate the Phoenix talussnail estivates in talus conditions which reach 30ºC-37ºC. Moisture requirements and thermal limits by age class are unknown; in particular, the moisture requirements and thermal tolerances of eggs and oviposition site conditions, which may be the most sensitive to climate variation.

PRIOR SURVEY EFFORTS

From 1953 to 1992 the species was known only from the type locality at Piestewa Peak. In 1992, a USFWS status survey (Hoffman 1995) explored the type locality (then still known as Squaw Peak), the hills throughout the Phoenix Mountains Reserve, North Mountains Reserve, Lookout Mountain Reserve, Mummy Mountain, the McDowell Mountains, South Mountain, the Sierra Estrella, White Tank Mountains, Maricopa Mountains and Santan Mountains.

The species was found at 14 locations within talus slopes at Squaw Peak, one at Sunset Hill within the Phoenix Mountains Reserve, and two at Mummy Mountain (Table 1; Figure 3). The findings expanded the total known localities from one to three (Hoffman 1995). Note that Sunset Hill was lumped with Squaw Peak (Hoffman 1995) but is separated here because it is 2 km northeast on a separate butte.

The species was not detected north of Squaw Peak and no further effort was made past Lookout Mountain in North Phoenix. The species was not detected anywhere south of Squaw Peak. Further to the north and west, the Deem Hills, Union Hills, Hieroglyphic Mountains, and Vulture Mountains were not considered to possess the vertical relief necessary to provide sufficient habitat and were not explored (Hoffman 1995).

Table 1. Phoenix talussnail localities, and locations within, from Hoffman (1995). GPS data obtained by replotting dot locations from topographic maps provided by Hoffman (1995).

SiteID	Locality	Location UTM (NAD83)	Elev. (M)[1]	Aspect º
PP	Piestewa Peak (Type Locality)	12S 404865mE 3711289mN	443	330
PP	Piestewa Peak (1)	12S 405182mE 3711456mN	497	18
PP	Piestewa Peak (2)	12S 404992mE 3711872mN	522	40
PP	Piestewa Peak (3)	12S 405944mE 3711945mN	516	200
PP	Piestewa Peak (4)	12S 406013mE 3712074mN	521	30
PP	Piestewa Peak (5)	12S 406546mE 3712317mN	520	140
PP	Piestewa Peak (6)	12S 406031mE 3712489mN	524	340
PP	Piestewa Peak (7)	12S 404809mE 3712457mN	537	165
PP	Piestewa Peak (8)	12S 405433mE 3712629mN	624	335
PP	Piestewa Peak (9)	12S 405087mE 3712799mN	581	45
PP	Piestewa Peak (10)	12S 405291mE 3713190mN	574	150
PP	Piestewa Peak (11)	12S 405078mE 3713410mN	531	30
PP	Piestewa Peak (12)	12S 405675mE 3713438mN	527	330
PP	Piestewa Peak (13)	12S 405900mE 3713239mN	522	340
PM1	Sunset Hills (14)	12S 408197mE 3713316mN	562	340
MM1	Mummy Mountain (15)	12S 410864mE 3712294mN	611	230
MM1	Mummy Mountain (16)	12S 411114mE 3712660mN	531	25

1. Mean elevation 538 m, range 443 m– 624 m.

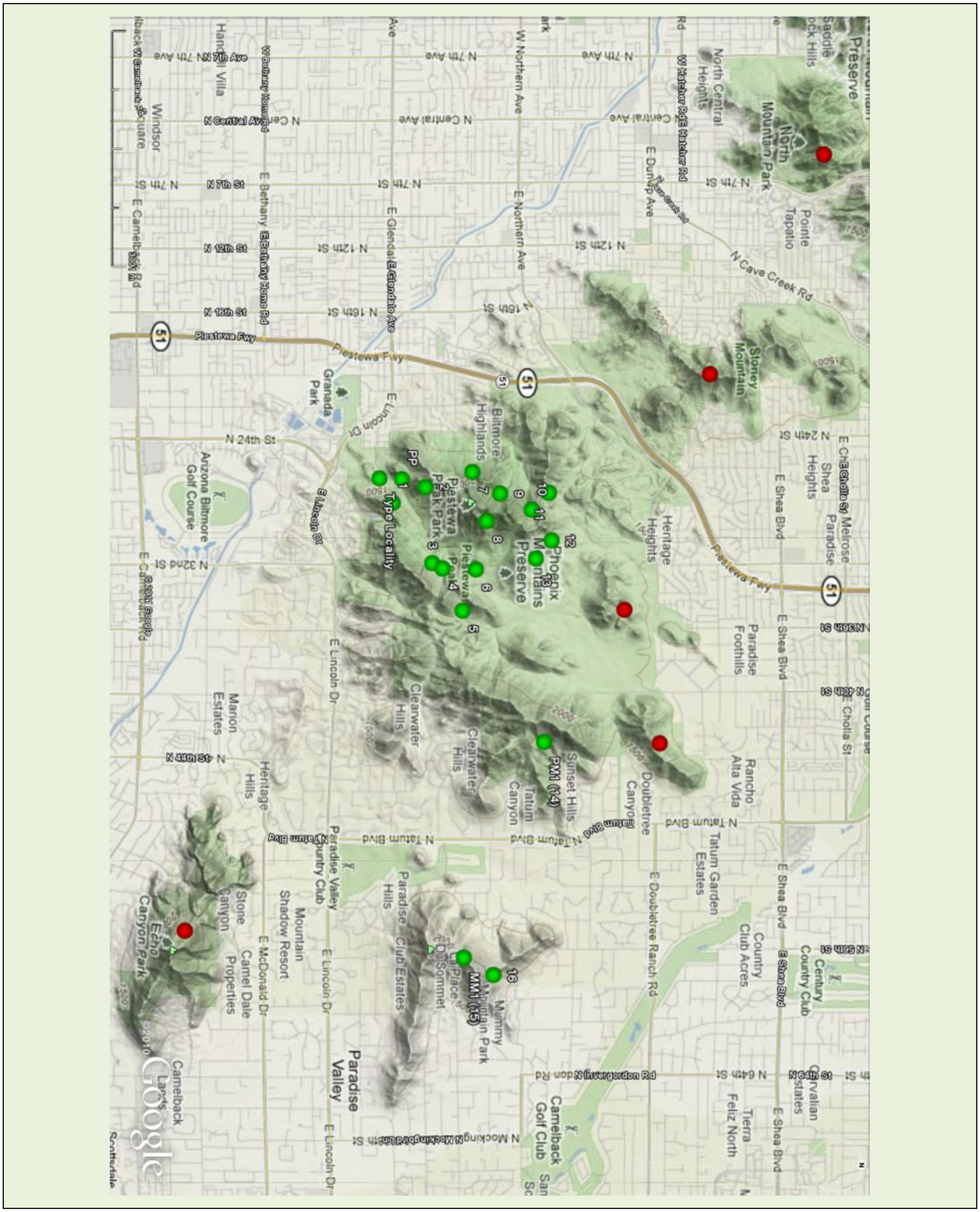

Figure 3. Phoenix talussnail detections (green) at Piestewa Peak, Phoenix Mountains Reserve, and Mummy Mtn. Negative detections red (Hoffman 1995). Terrain view © 2011 Google, Inc.

TAXONOMIC HISTORY

The Phoenix talussnail is a member of the Helminthoglyptidae, clade Sonorellamorpha, a family of pulmonate, air-breathing, terrestrial gastropods. The genus *Sonorella* Pilsbry, 1900 contains well in excess of 80 described species with new species continuing to be described (Bequaert and Miller 1973; Christensen and others 1981; Gilbertson and Radke 2006; Miller 1984).

The Phoenix talussnail was discovered in 1953 at Squaw Peak Park, Phoenix, Arizona (Gregg and Miller 1969). Roth (1996) recommended the Phoenix talussnail be placed in the monotypic genus *Maricopella*, which he considered sister to *Sonorella*, with *Eremarionta* likely ancestral to both genera. However, molecular evidence (Waters and others, in preparation) does not support separation as the species is nested within *Sonorella*.

In 2008, the U.S. Board on Geographic Names officially changed the type locality name from Squaw Peak to Piestewa Peak. Due to this and the distribution within the greater Phoenix metropolitican area this report recommends the species designation change from the Squaw Park talussnail to the Phoenix talussnail.

The Phoenix talussnail is distinguishable from other species of *Sonorella* and *Eremarionta*, which occur in close proximity, by reproductive anatomy. It differs from other *Sonorella* species (within the immediate vicinity of Phoenix) based on a small penis enveloped by a thick muscular sheath (the penial sheath), with a vestigial or absent verge (Gregg and Miller 1969; Roth 1996), and from *Eremarionta* species due to the lack of dart sac and mucus glands (Roth 1996). Based on apparent anatomical similarities Gregg and Miller (1969) thought the Phoenix talussnail was "closely related" to *Sonorella rooseveltiana* ssp which is distributed along the eastern flank of the Four Peaks, the periphery of Roosevelt Lake (Bequaert and Miller 1973). However, phylogenetic analysis revealed that a thick penial sheath is an unreliable trait to determine the degree of inter-relatedness having been independently derived in unrelated snail genera (Roth 1996; Barry Roth, personal communication).

The classical method employed to distinguish snail species and determine their taxonomic relationships relies upon characteristics of reproductive anatomy. Established taxonomic relationships among *Sonorella* species (Bequaert and Miller 1973; Pilsbry 1939) are being challenged by ongoing molecular work which has demonstrated widespread anatomical convergence (Weaver and others 2010) which will require further systematic work to settle, likely resulting in the description of additional species. It should be noted that while imperfect, reproductive anatomy within *Sonorella* remains useful to confirm that a specimen belongs to a certain species provided the locality is known, but even this is potentially problematic as there can be anatomical variation among widely separated populations (Kathleen Weaver, personal communication).

Historically, four lineages were described and explained by episodic Pleistocene glaciations or pluvial periods, when the climate may have been favorable to dispersal (Bequaert and Miller 1973; Pilsbry 1939). However, based on molecular phylogeny, only a single radiation occurred with *in situ* differentiation among the sky islands (Weaver and others 2010). Nearest neighbors were more closely related despite more similarity exhibited by species distributed further afield.

BIOLOGY

Terrestrial snails are dependent upon cool, moist conditions to carry out basic biological functions. A suite of behavioral, morphological, and physiological adaptations enable desert dwelling snails to escape oncoming hostile climatic conditions, mitigate moisture loss, and tolerate high temperatures (Moreno-Rueda and others 2009), although the mechanisms and adaptations by which this is accomplished are unknown. The species diet reportedly consists of fungal hyphae and vegetative matter (Hoffman 1995). The species is a simultaneous hermaphrodite. Each coupling potentially results in two clutches of eggs. Snails mature after at least 4 years (Hoffman 1995).

Information gaps are many with genetic diversity data chief among them. Demographic, population, physiological, and ecological data are also lacking. Reproductive biology is unknown as is the ability of the species to disperse to, or recolonize, adjacent habitat. Identifying physiological adaptations to the low desert climate, the conditions and behavioral mechanisms that trigger estivation or activity, and physiological tolerances to extended drought or cold conditions will help identify how the species may respond to climatic trends. The subterranean climate and how it responds to climatic variation is unknown, which is basic ecological data needed by dozens of other desert adapted species on the Arizona State Wildlife Action Plan (2005; 2010, in review).

ESTIVATION

Snails enter into estivation (Figure 4) when conditions become unfavorable for activity (Boss 1974). Moisture loss is mitigated by the secretion of one or more internal epiphragms which greatly reduce the rate of desiccation (Asami 1993). Initial secretion of a calcareous seal serves the dual purpose of providing the first barrier to desiccation and secure attachment to the substrate, either rock or other snails as evidenced by their durable and distinctive calcareous rings. Retraction of the body from the epiphragm creates an air pocket which may reduce heat exchange with the substrate. Heat shock proteins may be a significant factor increasing their thermal tolerance (Arad and others 2010).

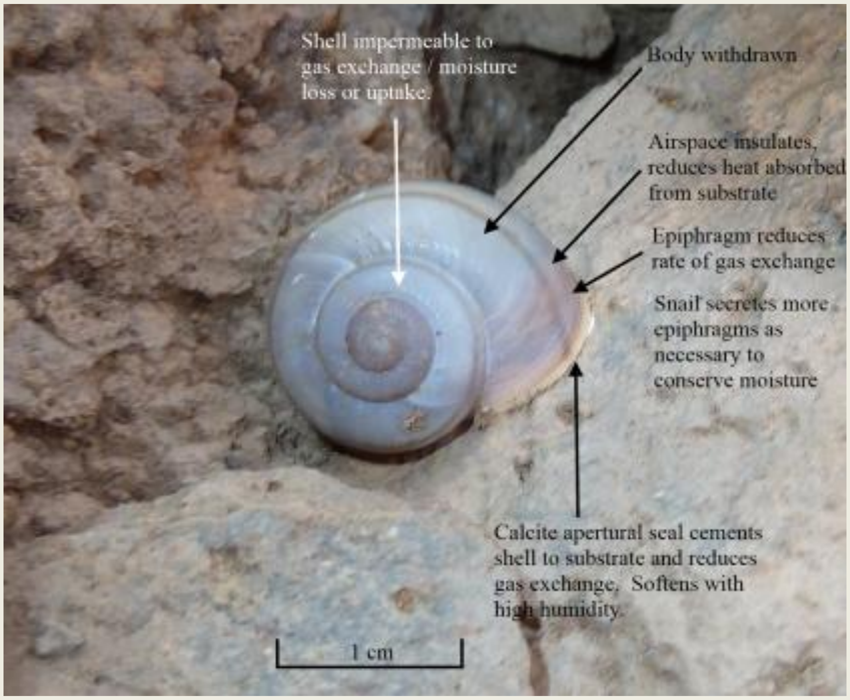

Figure 4. Estivating Phoenix talussnail *in situ*.

HABITAT

Snails occupy talus slopes, outcrops, and rocky desert streams. Talus impacted by soil and gravel appear to limit the amount of available habitat by reducing access to subsurface interstitial space (Hoffman 1995; Waters personal observation). Snails require a ready source of calcium, such as limestone to grow shells and physiological function. However, soils within xeric regions, known as aridosols, are rich in $CaCO_3$. Calcium is readily available to snails in the form of gravel and sand fragments of caliche. Geologic formations such as limestone are therefore not required for talussnail occupation in the greater Phoenix metropolitan area (contrary to Hoffman 1995).

METHODS

SURVEY

Effort was made to visit as many of the mountains in the Phoenix metropolitan area and periphery as possible within the limited time available. Particular survey sites were based on accessibility.

A survey involved traversing a slope as directly upward as site conditions permitted, and then when feasible taking a different route downhill to increase coverage of the slope. Each survey is considered analogous to a belt transect without a pre-determined length but with an effective width of 3 meters.

Data recorded include the day, date, start time, end time, locality, major geologic type, geomorphologic characteristics, perennial plant species, and general weather conditions if remarkable. Temperature data include air (1.5 meters), soil (0.05 m- 0.10 m), surface (0 m), and temperatures at greater than 0.10 m depth when feasible. Air temperature was taken using a Quick Read cloacal thermometer. Soil temperature was taken with a Weksler Bi-metal 20 cm dial probe (-10°C to 80°C). Soil and surface temperatures were taken with a Cen-Tech 93984 IR Thermometer (-33°C to 250°C). Soil moisture and pH were recorded using a Kelway Soil Tester when ground conditions were sufficiently moist for accurate measurement.

GPS coordinates were taken using a Garmin nüvi 500 (NAD83/WGS84 datum) at the start, turn-around point, and endpoint, where changes to vegetation, habitat, and slope characteristic were notable, and where shells, estivation sites, mucous trails, or living snails were encountered. GPS coordinates were verified using Google Earth 6.0 © 2011 Google, Inc. The survey path was drawn using Google Earth 6.0.

Digital photographs were taken at irregular points during traversal corresponding to the tangent of the slope to the left and right, directly ahead, upslope, at close range to the substrate, and snail shells, estivation sites, slime trails and living snails. Digital photographs taken with a Nikon Coolpix P1 include date and time metadata. Digital photographs taken with a Panasonic Lumix DMC-ZS7 include date, time, and GPS coordinates (WGS84) metadata. Digital photographs taken with a Nikon D90 equipped with Nikon GP-1 receiver include date, time, and GPS coordinates (WGS84) metadata.

All shells, excluding minor fragments, were collected within the survey area to aid in species identification and describing morphology. Snails were taken to observe behavior, positively identify by reproductive anatomy, and for genetic diversity research. Physical characteristics of slopes were determined from examination of digital photographs and field data. Percent slope was calculated by taking the tangent of the slope in degrees and multiplying by 100 before rounding to nearest integer. Parent material was determined by examination and comparison to type material (Chronic 1983; Kamilli and Richard 1998; Ludman and Marshak 2009).

Species Identification via Anatomical Characters

Reproductive anatomy of the Phoenix talussnail is richly described in Gregg and Miller (1969), Hoffman (1995), and Roth (1996). Reproductive anatomy of snails from the Deem Hills population, examined by Dr. Lance Gilbertson, was similar to the reproductive anatomy of the holotype from Piestewa Peak (Gregg and Miller 1969). Based on the diagnosis, shell and external morphologic characters of Piestewa Peak and Deem Hills populations were used to identify the species elsewhere in the Phoenix metropolitan area.

SPECIES IDENTIFICATION VIA SHELL AND MORPHOLOGIC CHARACTERS

Species identification by shell alone may be unreliable due to convergence with neighboring or cryptic species. Collecting a series of shells from a locality facilitates identification. Certain shell characters, such as whorls, shell robustness, size, and color may be useful to experienced collectors, especially when species distribution is known. For example, shells of the South Mountain talussnail (*Sonorella superstionis taylori*) are not as wide, have a brassy hue and more sharply defined shoulderband than Phoenix talussnails.

Significantly decayed shells make species identification challenging which necessitates multiple visits to secure either living snails or fresh shells. At stage 1 decomposition (Figure 5), fresh empty Phoenix talussnail shells are a pearlescent light tan color; living snails' shells have a deeper hue because the mantle and viscera darken the shell. The diffuse tan shoulderband, with very narrow light halo, remains a useful character midway through decomposition. As shells age the periostracum, the keratinous outer layer which protects the shell itself, begins to decay which further lightens the shell. At stage 2 the periostracum is noticeably weathered but remains useful. However, at stage 3 only the calcite shell, the ostracum, remains. Very old shells are considered subfossils and will be chalky and very brittle. Shining a black light upon shells in a darkened room enables rapid detection of the extent of decomposition. Light yellow-orange (or peach) fluorescence indicates the periostracum is intact. As the shell decays the color grades to patchy light purple and finally fully deep purple at stage 3 (Waters, personal observation).

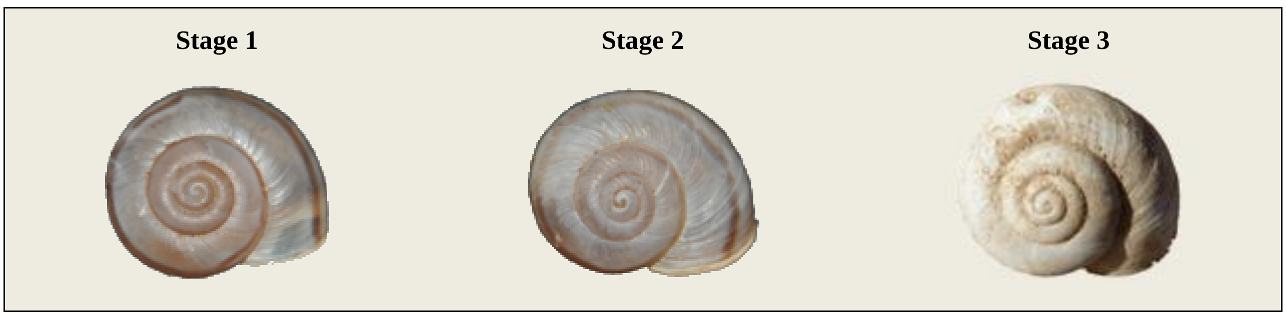

Figure 5. Decomposition stages of dead Phoenix talussnail shells. Shells in later stage 3 decomposition are also known as subfossils.

Phoenix talussnail shells are relatively depressed, but elevated slightly at the apex, the highest point of the shell corresponding to the embryonic whorl (Figure 6 "E"; Gregg and Miller 1969). Adult shell dimensions are from 14 mm-18 mm long, 10 mm -13 mm tall, 6 mm-8 mm wide, shell thickness 0.2 mm, and 4-4.5 whorls (data from this study).

The general shell color is light tan, pearlescent, smooth, and glossy. Light conditions and decomposition stage (Figure 5) may affect perception due to the textured coloration. The shoulderband is narrow, tan; uneven edges bleed into the adjacent narrow and poorly defined light band (or halo) which itself bleeds into the general tan background color (Figure 6). This characteristic gives the shoulderband a fuzzy, diffuse appearance. The underside of the shell is light tan.

Living snails are recognizable by the diffuse shoulder band with diffuse light halo. The tan mantle is shared by other species of snails but the Phoenix talussnail may be more dark (Figure 6). Body is dark grey to black with or without a faint, narrow dorsal stripe. Inspection under dissecting microscope shows the edge of the foot contains numerous white chromatophores, particularly near the head. Adult snails exhibit a minor upward deflected apertural lip with at least 4 complete whorls.

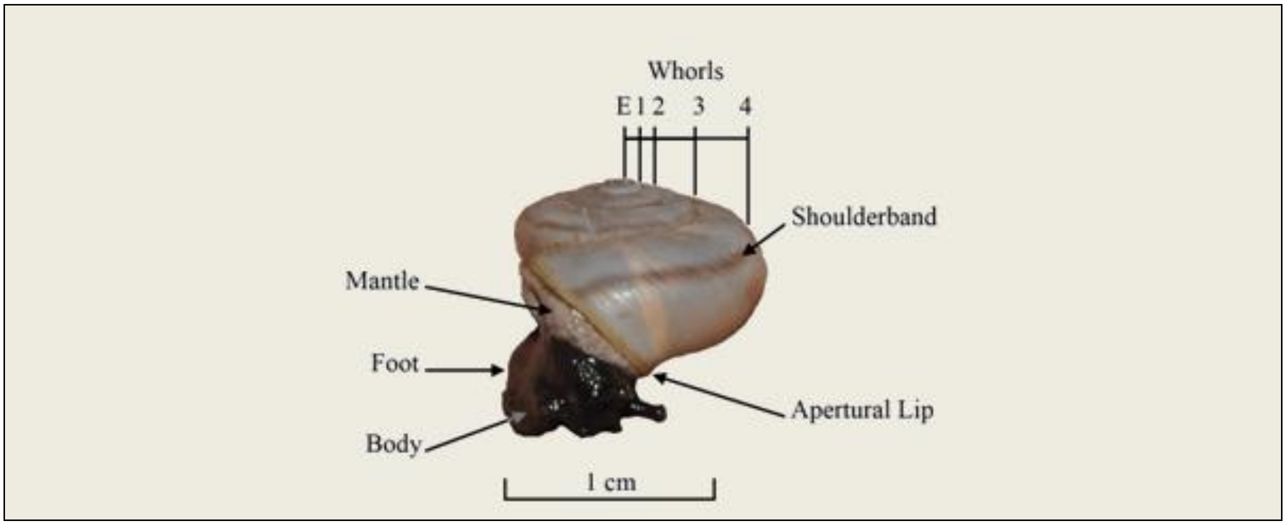

Figure 6. Notable shell and morphologic characters of an adult Phoenix talussnail. Note the diffuse shoulderband with diffuse light halo and tan mantle.

SPECIMENS

The light colored shell contrasts well against soil, leaf litter, and stones. Shells tend to be scattered irregularly across talus fields, within and above soil, under stones, deep within talus openings and between boulders. Shells may be concentrated at the tailings of small mammal burrows within talus where shallow excavation may yield shells. The presence of snails is also indicated by mucous trails during moist conditions, by feces, and the remains of the semi-circular calcareous apertural seal often abundant at estivation sites (Figure 7).

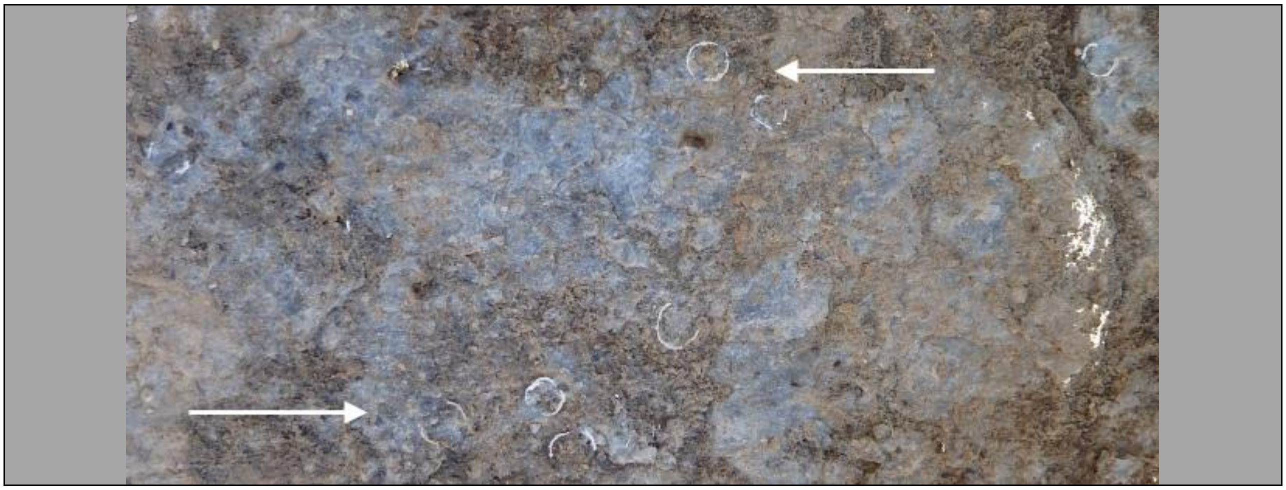

Figure 7. Remains of calcareous apertural seals on the underside of a boulder (30 cm x 15 cm). Two of ten seals are indicated by white arrows.

Shells were collected for species identification, morphology, predation, and parasite study. Living snails were collected for species identification, morphology, behavior, and tissue sampling. Shells were labeled with alphanumeric codes to uniquely identify each to its locality (e.g. 1DH1 is shell 1 from Deem Hills proper). Labels were written on the dextral side near the aperture with a fine tip permanent ink marker and after a brief drying period covered with clear acrylic nail polish which prevents smudging during handling.

Morphologic characteristics include shell color and texture characteristics, width, height, length, apical angle, number of whorls, apertural width and height, and inner apertural shell width and height. Shell volume was estimated by calculating the volume of a cone based on the apertural measurements and then subtracting the inner cone volume based upon the inner apertural measurements.

Estivating snails recovered from the field were weighed to the nearest milligram prior to rehydration on moist paper towels, and then weighed again once active.

Tissue samples were preserved in 95% EtOH for future genetic study. All specimens will remain in the private collection of the author until completion of the project whereupon they will be deposited into the collections of a zoological museum specializing in gastropods.

ANALYSIS

To determine the distribution of localities across slope aspect, degrees were converted to radians, polar x, y coordinates were calculated using cosine and sine functions, and then multiplied by 100. The coordinates were summed and overall magnitude and direction computed. The magnitudes were compared to the center of the plot 0, 0 and tested using one-tailed t-test at a significance level of $\alpha = 0.05$.

RESULTS

SURVEY

A total of 83 surveys at 58 locations throughout the greater Phoenix metropolitan area were performed from March 2010 to July 2011. A total of 142 hours were spent traversing 73 km of hillside and wash in search of the Phoenix talussnail. The average duration of a survey was 1 hour 44 minutes (SD = 1 hr 3 min) and covered an average of 0.89 km (SD = 0.72 km).

The Phoenix talussnail was detected at 16 new localities by this study, 15 by surveys and one reported by others (EM1), bringing the total to 16. This brings the total number of localities to 20 (Table 2; Figure 8). The species is not ubiquitous throughout its known range; appropriate habitat is available but unoccupied notably in the vicinity of North Mountain Park (Figure 9). Despite intensive searching at multiple locations, snails were not detected at Shaw Butte, North Mountain Park, Moon Hill, Sunset Mountain, Adobe Mountain, and various unnamed hills which mirrors the results of Hoffman (1995). Only a fraction of available habitat has been surveyed within any particular mountain or wash, nor have all mountains and washes in the Phoenix area been surveyed.

OTHER DESERT ADAPTED SNAIL SPECIES

Additional species of desert adapted snails were observed within the greater Phoenix metropolitan area. These include *Eremarionta rowelli hutsoni* (Hoffman 1993; Waters, personal observation), *Sonorella superstionis taylori* (Hoffman 1995; Waters, personal observation), *S. s. superstionis* (Waters, personal observation), and possibly seven undiagnosed or undescribed species of *Sonorella or Eremarionta* (Bequaert and Miller 1973; Christensen and Reeder 1981; Hoffman 1995; Miller 1984; Waters, personal observation). Minute terrestrial snails, *Chaenaxis tuba* and *Pupoides alibilabris*, were reported from the Table Top Mountains, a range immediately south of Phoenix in Pinal County (Christensen and Reeder 1981), and at Tempe Butte along the Salt River (Bequaert and Miller 1973), but have not been detected by this study.

TALUS PARENT MATERIAL

The Phoenix talussnail was primarily detected in talus composed of igneous parent materials (Table 3): Basalt (n = 9), dacite (n = 2), diorite (n = 1), granite (n = 2), and granodiorite (n = 1). Snails were also detected in talus composed of metamorphic schist (n = 4).

Table 2. Phoenix talussnail localities and visitations in the greater Phoenix metropolitan area, northeastern Maricopa County, Arizona.

SiteID	Locality	UTM (NAD83)	Elev. (m)	Date	Source
BM1	Black Mountain 2km Northeast of Lake Pleasant Harbor off 87th Avenue	12S 385927mE 3747531mN	638	01/04/2011 01/11/2011 05/31/2011	This study
CCR	Cave Creek Region Outstanding Natural Area, Southeast End	12S 409499mE 3741828mN	607	09/25/2010 12/24/2010	This study
DH1	Deem Hills, Northwestern Butte	12S 392575mE 3732869mN	635	03/23/2010 05/14/2010 02/13/2011	This study
DH2	Deem Hills, Southwestern Butte	12S 392104mE 3732269mN	495	07/24/2010	This study
DMT	North slope of Gavilan Peak, New River	12S 395870mE 3752524mN	760	04/15/2011	This study
EM1	Elephant Mountain, Northeast of E Cahava Ranch Rd and 50th Street	12S 407629mE 3749822mN	817	06/23/2011	Kevin Smith and John Gunn (pers. comm)
HPH	Hedgpeth Hills, 51st Ave and Potter Dr	12S 391683mE 3726704mN	433	12/01/2010 12/17/2010	This study
HHK	Hedgpeth Hills, 55th Ave and Pinnacle Peak Rd	12S 390492mE 3729365mN	448	11/27/2010	This study
JH2	McDowell Mountains, 1 mile North of McDowell Peak	12S 423266mE 3726034mN	743	04/09/1992	Hoffman (1995) gave coordinates for one and mentions others
LM1	Ludden Mountain, South and Northeast Slopes	12S 390058mE 3731570mN	655	12/22/2010 02/12/2011	This study
LD1	Wash NW of Horse Trailer Parking and Hill (LD2) at Lost Dog Trailhead	12S 424476mE 3718090mN	525	07/11/2011	This study
MM1	Mummy Mountain	-	-	04/02/1992	Hoffman (1995) reports two locations (Table 2)
ND1	Northeast Slope of Hill at New River and Deadman Wash	12S 387015mE 3737433mN	496	05/11/2011	This study
PH1	Butte North of Ben Avery Shooting Facility	12S 393072mE 3742838mN	532	01/01/2011	This study
PM1	Sunset Hill, Phoenix Mountain Preserve			03/09/1992	Hoffman (1995)
PMG	Phillips Mountain	12S 397002mE 3741394mN	562	04/19/2011	This study
PP	Piestewa Peak (=Squaw Peak), Just North of the Arizona Biltmore Hotel	-	-	1953	Allyn G. Smith Gregg and Miller (1969)
		-	-	01/28/1954	Munroe L. Walton Gregg and Miller (1969)
		-	-	04/23/1954	Munroe L. Walton Wendell O. Gregg Gregg and Miller (1969)
	Piestewa Peak (=Squaw Peak), 0.3 mi from Lincoln Drive, Type Locality	12S 404865mE 3711289mN	457	10/30/1965	Munroe L. Walton Joseph C Bequaert Walter B. Miller Gregg and Miller (1969)
	Piestewa Peak (=Squaw Peak), Slopes encompassing circumference of peak and Phoenix Mountain Park	-	-	03/09/1992	Hoffman (1995) Reports 13 locations (Table 2)
	Piestewa Peak (=Squaw Peak), Type Locality	12S 404865mE 3711289mN	443	03/09/1992	Hoffman (1995)
	Piestewa Peak	12S 404945mE 3711592mN	450	03/10/2011	This study
PP2	Butte Just Southeast of Pyramid Peak	12S 402593mE 3748046mN	695	04/22/2011	This study
UHC	Union Hills, Creedence Blvd and 21st St	12S 403503mE 3729214mN	483	01/14/2011	This study
WW1	West Wing Mountain, East End	12S 385087mE 3733547mN	503	04/25/2011	This study

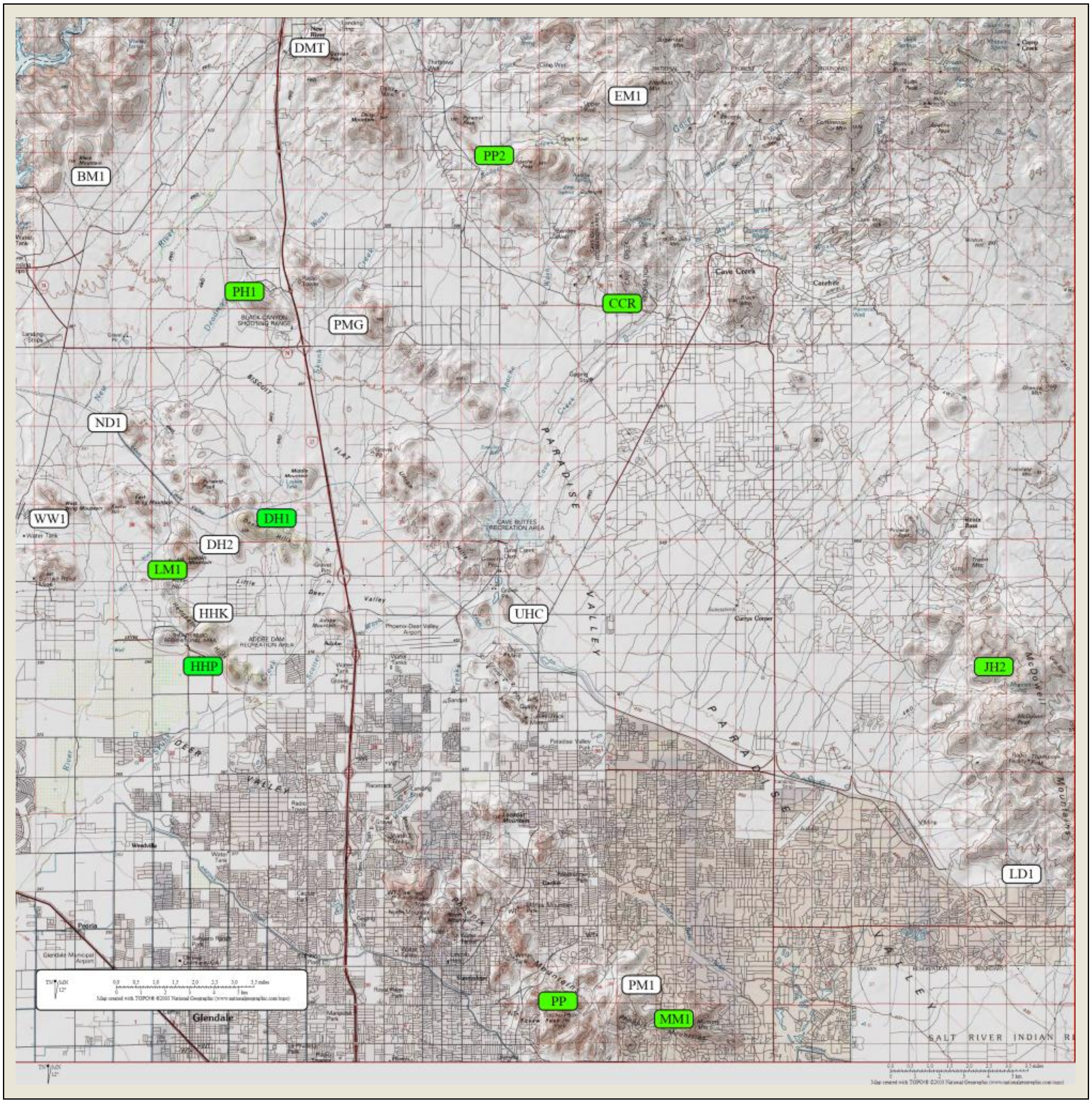

Figure 8. Phoenix talussnail localities in the greater Phoenix metropolitan area, Northeastern Maricopa County, Arizona. Living snails (green) observed by this study and Hoffman (1995). Topographic view © 2003 TOPO! Arizona and the USGS.

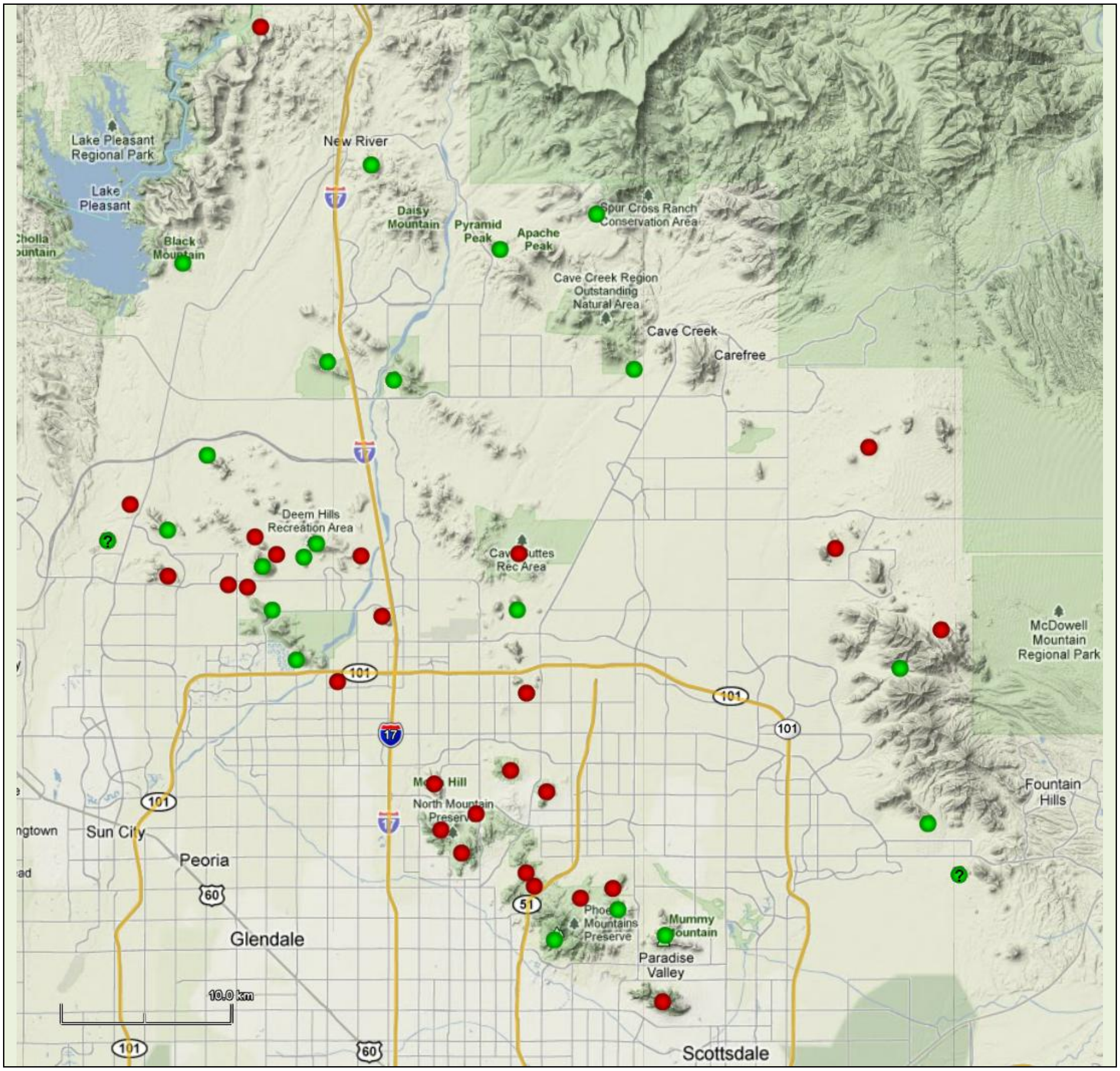

Figure 9. Phoenix talussnail survey localities. Positive detections are green. Negative detections are red. Uncertain species are green with question mark. Only negative detection localities in close proximity to positive detection localities included. Includes results of present study, Gregg and Miller (1969), and Hoffman (1995). Terrain view © 2011 Google, Inc.

SLOPE ASPECT

The relationship between slope aspect and Phoenix talussnail detections (Table 1; Table 3; Figure 10) was not significant for detections across the range (p = 0.469, t-test = 0.469,df = 14, SD = 80.8). The relationship between slope aspect and snail detections was significant for locations sampled by Hoffman (1995) within Piestewa Peak, Phoenix Mountains Reserve, and Mummy Mountains (p = 0.038, t-test = 1.899, df = 17, SD = 81.0).

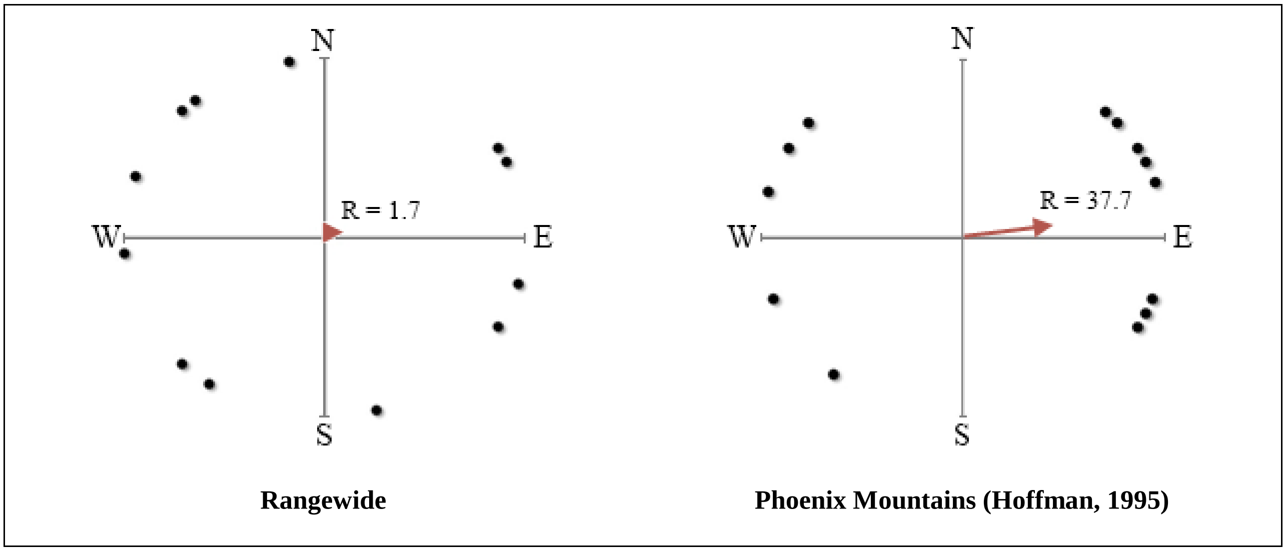

Figure 10. Slope aspect of Phoenix talussnail localities. R is the vector from center indicating the strength of the relationship (out of 100 units) to aspect and directional tendency.

ELEVATION

Mean elevation of Phoenix talussnail localities was 574 m ± 110 m (n = 21; Range = 443 m - 817 m).

SLOPE GRADIENT

Phoenix talussnails were only detected on talus slopes with a minimum gradient of 18º or 32%. Average gradient was 24º ± 5º (n = 15; Range = 18º–33º). This corresponds to an average percent slope of 45% ± 10% (n = 15; Range = 32%–65%).

Table 3. Slope characteristics of Phoenix talussnail localities.

SiteID	Locality[1]	Parent Material	Aspect º	Slope º	% Slope
BM1	Black Mountain 2km Northeast of Lake Pleasant Harbor off 87th Avenue	Basalt	185	30	58
CCR	Cave Creek Region Outstanding Natural Area, Southeast End	Diorite	135	25	47
DH1	Deem Hills, Northwestern Butte	Basalt	225	18	32
DH2	Deem Hills, Southwestern Butte	Basalt	345	21	38
DMT	North slope of Gavilan Peak, New River	Dacite	330	25	47
EM1	Elephant Mountain, Northeast of E Cahava Ranch Rd and 50th Street	Basalt	215	-	-
HHK	Hedgpeth Hills, 51st Ave and Potter Dr	Basalt	25	19	34
HPH	Hedgpeth Hills, 55th Ave and Pinnacle Peak Rd	Basalt	235	20	36
JH2	McDowell Mountains, 1 mile North of McDowell Peak	Schist	-	-	-
LM1	Ludden Mountain, South and Northeast Slopes	Basalt	345	29	55
MM1	Mummy Mountain	Schist	-	-	-
ND1	Northeast Slope of Hill at New River and Deadman Wash	Granite	285	30	58
PH1	Butte North of Ben Avery Shooting Facility	Basalt	30	20	36
PM1	Sunsent Hills, Phoenix Mountains Preserve	Schist	340	-	-
PMG	Phillips Mountain	Granodiorite	330	33	65
PP	Piestewa Peak (=Squaw Peak), Just North of the Arizona Biltmore Hotel	Schist	130	24	45
PP2	Butte Just Southeast of Pyramid Peak	Dacite	160	25	47
UHC	Union Hills, Creedence Blvd and 21st St	Basalt	100	21	38
WW1	West Wing Mountain, East End	Granite	135	24	45

1. EM1 and PM1 added late and not included in analysis of aspect.

ESTIVATION

Snails estivate on average 0.37 m ± 0.31 m deep within the substrate (n = 11 estivation sites; range 0.1 – 1 m or more). One snail at the surface (0 m) was apparently trapped by sudden onset of hot weather following rainfall. Snails observed at 1 m+ were discovered by exposure due to trail building at Deem Hills in May 2010 (Figure 11).

Figure 11. Estivating Phoenix talussnails exposed for over a month following trailbuilding at Deem Hills in May 2011. Arrows indicate where snails were observed.

THERMAL EXPOSURE

Talus and streambed temperature vary by depth and seasonal weather conditions. Ground and sub-surface temperatures recorded throughout the study were compiled (Figure 12). June surface temperatures are particularly severe, ranging from 18°C–74°C. Ambient talus temperature stabilized from 30°C–37°C within 0.1 m–0.5 m depth prior to monsoon rain. The thermal profile observations within talus are consistent with studies of small mammal burrows (Burda and others 2007). Following monsoon rain the substrate reached 40°C at a depth of 0.2 m–0.3 m.

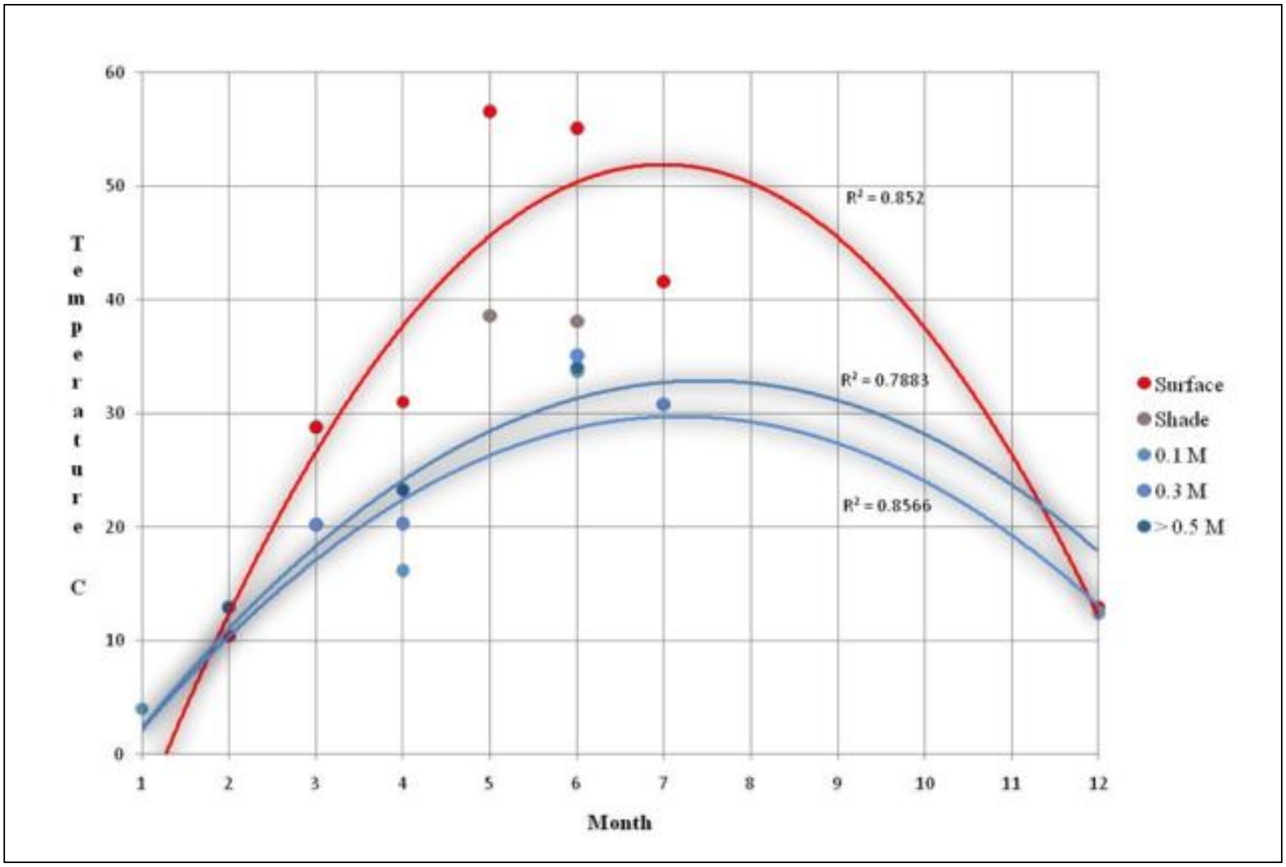

Figure 12. Thermal profile of talus from July 2010 to June 2011.

DESICCATION TOLERANCE

During early April 2010, trails were excavated by mini-bobcat throughout the Deem Hills. On May 14, 2010, three estivating snails were observed on a fractured basalt boulder approximately 1 m in diameter (Figure 11). The three snails were collected and kept in a container at stable temperature (23°C) and humidity (~40%) until June 30, 2010.

Table 4. Mass regained after estivation

Snail	Dessicated Mass (g)	Rehydrated Mass (g)	% Mass Regained
1	0.59	1.03	57.3
2	0.47	0.74	63.5
3	Deceased	-	-
Average (n = 2)	**0.53 ± 0.06**	**0.89 ± 0.15**	**60.4 ± 3.1**

While a very small sample, it is telling that the species is capable of losing 60% of their mass to dehydration and successfully revive upon the return of sufficient moisture.

Surface Activity Environmental Conditions

Twenty-six active snails were observed during winter from December 2010 to January 2011. They were found an average of 9 cm ± 8 cm (n = 26, range = 0 cm–25 cm) below the surface under cobbles and boulders within soil pockets which they may have excavated. These observations were made the day of the first soaking rain of winter and after significant rainfall of at least 1 cm. Soil moisture averaged 72% ± 11% (n = 4, Range = 59%–82%). Soil temperature averaged 11.4°C ± 5.1°C (n = 4, Range = 4.0°C –15.0°C). Air temperature averaged 14.5°C ± 6.4°C (n = 4, Range 5.5°C –20.7°C).

Phenology

Surface activity occurs following heavy rains during the winter and early spring. Activity during the summer monsoon has not been observed in the Phoenix metropolitan area.

Hatchling snails (~1.5 mm shell length) have been observed in December and January. All age classes, juveniles, sub-adults, and adults were observed at all times of year either active or estivating.

Predators and Parasites

The introduced decollate snail, *Rumina decollata*, was not detected at any of the sample sites.

Predators and parasites of terrestrial gastropods have been compiled (Table 5). Information available from related taxa of the Phoenix talussnail was collated from Barker (2004), Gilbertson and Radke (2006), and Miller (1967) with *in situ* observations from this study.

Table 5. Predators and parasites[1] of terrestrial snails (Gastropoda: Pulmonata) with representative species within the range of the Phoenix talussnail.

Species Groups	Type	Local Representatives	Observations
Beetles (Coleoptera)	Predator		Numerous species observed
Birds (Aves)	Predator		Numerous species observed. Snails concentrate calcium and it is likely that living and dead shells are consumed.
Coyotes & Foxes (Canidae)	Predator	Coyote (*Canis latrans*), Gray Fox (*Urocyon cinereoargenteus*)	Observed within talus areas. Likely opportunitistic predator.
Centipedes (Chilopoda)	Predator	Desert Centipede (*Scolopendra sp)*	Commonly encountered. Paired pinch marks on shells attributed to centipedes.
Frogs and Toads (Anura)	Predator	*Hyla arenicolor, Anaxyrus sp., Scaphiopus couchi*	May aestivate within talus adjacent to riparian zones.
Ground Squirrels (Sciuridae)	Predator	Round-tailed Ground Squirrel (*Xerospermophilus tereticaudus)*	Observed within talus areas
Kangaroo Rats & Mice (Heteromyidae)	Predator		Numerous within talus areas. Shells with apex removed commonly encountered within middens / burrow tailings.
Lizards (Squamata)	Predator		Numerous species observed. Interaction with snails unknown.
Mice and Rats (Muridae)	Predator	*Peromyscus* sp, *Neotoma* sp	Numerous within talus areas. Shells with apex removed commonly encountered within middens / burrow tailings.
Millipedes (Diplopoda)	Predator	Desert Millipede (*Orthoperus* sp)	Commonly encountered within talus.
Rabbits and Hares (Lagomorpha)	Predator	Desert Cottontail (*Sylvilagus audobonii*), Jackrabbit (*Lepus* sp)	Not observed within talus areas
Racoons (Procyonidae)	Predator	Racoon (*Procyon lotor*)	Known to occur in North Mountain park but not directly observed
Snails (Pulmonata)	Predator	Introduced: Decollate snail (*Rumina decollata*)	Not observed in talus areas but commonly encountered in landscaped areas and yards. Can burrow and aestivate through summer in non-irrigated areas. Many developments abut talus areas with known populations of the Phoenix talussnail.
Snakes (Serpentes)	Predator		Numerous species observed. Interaction with snails unknown but several species known to prey upon invertebrates.
Spiders (Arachnida)	Predator	Tarantula	Burrows observed in talus areas
Tortoises & Turtles (Testudinates)	Predator	Desert Tortoise (*Gopherus agassazi*), Sonoran Mud Turtle (*Kinosternon sonoriense*)	Tortoises observed in close proximity to talus areas. Kinosternids likely aestivate in talus slopes adjacent to riparian zones.
Weasels (Mustelidae)	Predator		Odor detected within talus areas
Flatworms (Planaria)	Parasite		Unknown - Requires dissection
Flies (Diptera)	Parasite	Scoleomyzids and likely other orders	Dead shells with remains of pupae very common. Specimens sent to specialist.
Fungi (Microsporidia)	Parasite		Requires dissection
Mites (Chelicerata)[2]	Parasite & Predator	*Trombidium* sp	Mites commonly encountered in talus. Adult mites known to predate eggs and juveniles to parasitize pneumostome and lung.
Nematoda	Parasite		Nematodes observed at bottom of captive snail container.
Protozoa (Ciliophora)	Parasite		Requires dissection
True Bugs (Heteropteran)	Parasite		Numerous species observed
Wasps (Hymenoptera)	Parasite		Numerous species observed

1 Snails serve as intermediate hosts for many types of parasites.
2 Mites serve dual predator and parasitic roles consuming eggs, hatchlings, and juveniles, and parasitizing the pneumostome.

DISCUSSION

SURVEY

Failure to detect shells at a survey site does not necessarily indicate the Phoenix talussnail, or other snail species, are absent. Effort was made to visit additional locations at sites where snails were not detected (for example two surveys at Adobe Mountain, four surveys at Sunrise Mountain, four surveys at Shaw Butte). While repeat visits during this study have not resulted in positive detections, other talussnail studies have had chance encounters with snails even though shells were not detected (Jeff Sorensen, personal communication).

Presence of shells does not necessarily indicate that snails are currently extant. Sub-fossil shells (stage 3 decomposition and those infiltrated by partially mineralized substrate) are the predominant type of shell present at localities (Waters, unpublished data). However, the presence of a range of life stages, gauged by shell size, and stage 1 shells are likely indicators of an extant population.

TAXONOMIC UNCERTAINTY

Gregg and Miller (1969) stated that snails from the type locality secreted a bright orange substance, apparently in self-defense. This behavior was not observed at the new localities (Table 2; Figure 8). While the difference in reproductive anatomy is slight between Deem Hills and Piestewa Peak (type locality), as well as the McDowell Mountains, the defense behavior indicates the potential for significant divergence. Shell size and morphology also differ throughout the range, with four potential clusters occupying the vicinity of the Deem Hills, the base of New River Mesa, the McDowell Mountains, and Piestewa Peak (Waters, unpublished data).

The taxonomy of desert snails is uncertain (Roth 1996; Waters and others, in preparation; Weaver and others 2010). Additional known species of snails (Hoffman 1993; Miller 1969; Miller 1984; Waters, personal observation) and undescribed snails (Hoffman 1995; Waters, personal observation) have been observed throughout the mountains of the greater Phoenix metropolitan area. Furthermore, genetic study may reveal the presence of multiple cryptic species currently thought of as the Phoenix talussnail.

DISTRIBUTION

The Phoenix talussnail occurs within northeastern Maricopa County on the isolated southeast to northwest trending mountains between the Verde River to the east, the Gila and Salt River to the South, the Agua Fria River to the west, and the base of New River Mesa to the north (Figure 2). The greater Phoenix metropolitan area encompasses the range of the species. Municipalities include Phoenix, Glendale, Peoria, New River, Cave Creek, Carefree, Scottsdale, and Fountain Hills. It is likely the species also occurs within the Salt River Pima-Maricopa Indian Community in the southern portion of the McDowell Mountains.

The species occupies isolated talus habitat which is unevenly distributed across mountainous areas. Snails occupy washes (Figure 13) but how widespread they are within and the conditions which favor occupation are unclear. It is tempting to state that they may serve as corridors for dispersion, however substrate conditions vary and washes are heavily modified throughout the valley, interrupted by urban development and channelization. It is also unknown whether the species is currently able to disperse between adjacent talus slopes or mountains at this time, but may have been capable during past periods of increased rainfall.

ECOLOGY

Within occupied mountains, the species is restricted to talus slopes with a minimum gradient of 18º, or 32%. Snails were principally detected in talus composed of erosionally resistant bedrock material (Table 3; Figure 14), predominantly basalt and schist. These rock types are composed of metamorphosed, dense grains that do not rapidly break down into soil (Friend and others 2000). Exposed soil dries more rapidly than soil protected by talus because of the reduced effects of capillary action and evaporation due to reduced subterranean temperatures (Nobel and others 1992; Perez 1998). Reduced erosion and steep slopes foster conditions that increase humid interstitial space required by the species to hide from predators, reproduce, and estivate during unfavorable environmental conditions on the surface.

Populations can be found on all aspects of a mountain (Figure 10). A slight trend towards increased detection on east-northeast slopes may indicate more favorable microhabitat conditions including lower average temperature and increased prevalence of moisture within talus. Slopes with east–northeast aspects receive less daily solar radiation (Iqbal 1983) thereby remaining cooler and conserve moisture for longer periods within talus (Nobel and others 1992). The Phoenix talussnail was reported to primarily occur on slopes with northern aspects (Hoffman, 1995), however re-analysis of data from Hoffman (1995) does not support this.

PHYSIOLOGY

Data suggest that estivating snails must be capable of tolerating temperatures ranging upwards of 30°C-37°C (Figure 12) based on the depth at which they estivate, 0.37 m ± 0.31 m. Following monsoon rain, substrate temperatures at 0.2 m – 0.3 m depth measured upwards of 40ºC, likely due to heat transport by water due to its high thermal conductivity. Sustained rains would dissipate heat to the atmosphere. Summer surface activity has thus far not been observed but particularly wet summers may promote surface activity.

The Phoenix talussnail exhibits at least two adaptations to manage desiccation. The species mitigates moisture loss through secretion of a calcareous seal which secures the shell to a surface and reduces gas exchange, and one or more internal epiphragms which further reduce gas exchange. It is further able to tolerate moisture loss of up 60% of its mass and revive following rehydration. In other parts of the world desert adapted snails utilize thick shells to further reduce moisture loss, grow larger to possess more initial moisture, or possess physiological adaptations that employ glycogen to bind water during estivation.

Wash at Lost Dog Trailhead (LD1), Scottsdale. Snails estivate in the streambed and bank.

Side-channel of Cave Creek at New River Road crossing (CCR), Cave Creek Region Outstanding Natural Area. Snails estivate in the bank.

Figure 13. Wash habitat occupied by the Phoenix talussnail.

Favorable Habitat Characteristics	**Marginal Habitat Characteristics**
	
Ludden Mountain (LM1). Basalt talus forms deep, extensive fields of heterogeneous talus. Abundant, open interstitial space. Slope 36% (20º) on NE side.	Phillips Mountain (PMG). Granodiorite and granite impacted by grus. In this case the slope is 65% (33º). Active transport of sediments provides sufficient interstitial space below surface rock.
	
Cave Creek Outstanding Natural Resource Area (CCR). Dacite and granite. Abundant interstitial space. Deep fractures on outcrops enable access deep underground. Slope 47% (25º).	Butte on NW Corner of Jomax Rd and Dysart. Soil and caliche impaction. Lack of interstitial space prevents snails from reaching shelter. Lower slopes generally heavily impacted by soil. Slope 18% (10º)
	
Piestewa Peak (PP). Metamorphic phyllite and schist form deep open talus. Outcrops provide deep fractures providing abundant interstitial space. Slope 45% (24º).	Pilcher Hill at 67th Ave and Happy Valley Rd. Soil impaction, slope 12º (21%). At a distance talus may appear to exhibit favorable qualities but require direct inspection to observe impaction and slope.

Figure 14. Examples of potential Phoenix talussnail talus habitat exhibiting favorable (left) and marginal qualities (right).

Experimental evidence from two Phoenix talussnails, tested on a thermal gradient, shows they actively avoid temperatures < 1°C and > 34°C. Avoidance of temperatures > 34°C is consistent with upper temperatures detected and modeled by the thermal profile of talus and the depth at which they estivate (Figure 12).

Lower thermal limits were, unfortunately, discovered via freezer malfunction which dropped the temperature for several hours below 0°C, killing 28 snails. This result is consistent with other Sonoran desert adapted poikilotherms such as the Saguaro, *Carnegiea gigantean*, whose range closely follows the elevationally related minimum temperature of 0°C lasting less than 24 hours (Nobel 1980, 1982).

Further research is required to assess the adaptations the Phoenix talussnail, and other closely related taxa in the Sonoran desert, employs to tolerate and mitigate desiccation and thermal extremes across life stages. Current data are suggestive, but not conclusive, regarding critical thermal minima, maxima, and desiccation tolerances of adults. Nothing is known about ecologic parameters required by ova, hatchlings, and juveniles. Understanding these variables by age class will clarify microhabitat conditions the species requires.

Invasive Species

The introduced Mediterranean decollate snail, *Rumina decollata*, is a voracious predator of snails and slugs, including eggs. It was not detected at any of the sample sites. The species has been present in the Phoenix area since at least 1952 (Bequaert and Miller 1973) which suggests the species is poorly adapted for the particularly arid conditions found outside of developed areas. They are common in residential areas, have invaded riparian habitat along the Verde River, and are increasing their range upstream. They are present at numerous drainages and municipalities across Arizona (Waters, personal observation; Jeff Sorensen, personal communication). It is unknown whether they are able to disperse across arid habitat, overland or via washes, or whether they could survive in talus habitat if directly transported.

Buffelgrass (*Pennisetum ciliare*) and fountaingrass (*Pennisetum setaceum*), have become widespread throughout mountains occupied by the Phoenix talussnail, particularly adjacent to heavily landscaped developments at the type locality, Piestewa Peak, and at Hedgpeth Hills, Deem Hills, and Ludden Mountain. Effects of these introduced, fire tolerant, grass species within the Sonoran desert are well documented (Rogstand and others 2009; Stevens and Falk 2009). These species grow densely and pose an increased fire danger not only in close proximity to talus but also across the landscape. They rapidly colonize burned areas and deprive native species of already scant moisture, suppressing regrowth of native vegetation. Moisture drawn from the soil likely affects subterranean moisture required for talussnail estivation and reproduction. These grass species have profound effects upon the ecology of the Sonoran Desert. Both buffelgrass and fountaingrass burn rapidly and at high temperature. While rocky soils and talus mitigate temperature extremes caused by fire (Stoof and others 2010), high temperatures rapidly shatter and break down rock into smaller particles, reducing shade and forming soil which subsequently reduce interstitial space (Blackwater 1927; Chen and others 1999; Dorn

2003; Dragovich 1993). Over time these factors may negatively impact the habitat of the Phoenix talussnail and other talus dwelling species.

RECOMMENDATIONS

1) Invasive species. Control buffelgrass and fountaingrass. Physical removal methods are preferable because herbicidal treatments may interrupt the ecology of slopes, affecting not only the Phoenix talussnail, but other talus dwelling species including small mammals, reptiles, and other invertebrates.

2) Genetic diversity. Collect tissue samples from all localities, at multiple locations within, to determine genetic diversity within and among populations. These studies will also address taxonomic uncertainties between other local forms of *Sonorella* and other desert adapted species including *Eremarionta rowelli hutsoni*, also isolated to ranges throughout the greater Phoenix metropolitan area.

3) Surveys. Continue surveys, especially during the winter and spring rainy season. Numerous areas within the greater Phoenix metropolitan area remain under-explored. Certain mountain ranges, such as the White Tank Mountains, Sierra Estrella, New River Mesa, McDowell Mountains, lower slopes of the Bradshaw Mountains, Hieroglyphic Mountains, and Vulture Mountains are comparably vast to areas such as the Deem Hills or Piestewa Peak. Washes have not been surveyed and relatively unmodified reaches within the metropolitan area are scarce or no longer exist. These surveys will also yield information on other desert adapted talussnails whose status, distribution, and biology are unknown (particularly *Eremarionta rowelli hutsoni* and several *Sonorella* species).

4) Biology. Study the species behavioral responses to moisture and thermal parameters. Understanding these interactions will provide basic data on how the species interacts with the environment, regulates population dynamics, and its physiological tolerances to extended durations of estivation and thermal extremes. Establishment of a captive population will enable reproductive studies without disrupting natural habitat and assist study of the microhabitat conditions needed for estivation and activity.

5) Habitat. Extensively survey and map one hill per geologic type to refine the characterization of appropriate talus habitat as well as wash habitat. Necessary data include moisture and thermal regimes, and interstitial space across different geomorphologic formations. This will facilitate the estimation of appropriate available habitat and the proportion occupied versus unoccupied habitat across the species range.

6) Monitoring. Establish permanent study plots to monitor the Phoenix talussnail and conduct population studies. Monitoring environmental conditions within talus habitat will reveal how these factors influence population dynamics. This effort will also elucidate life history, diet, predator, and parasite interactions. Information can be gained on the species ability and tendency to disperse between adjacent habitat patches and adjacent hills.

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