Species Status Assessment
for the
Arkansas Mudalia (*Leptoxis arkansensis*)

Adult Arkansas mudalia; Thomas Tarpley (Alabama Dept. of Conservation and Natural Resources)

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Executive Summary

The Arkansas mudalia (*Leptoxis arkansensis*) is a freshwater snail endemic to the White River and its tributaries in Arkansas and Missouri (Wu et al. 1997). The species was petitioned for federal listing under the Endangered Species Act of 1973, as amended (ESA), as part of the 2010 petition to list 404 aquatic, riparian, and wetland species from the southeastern United States by the Center for Biological Diversity (Center for Biological Diversity 2010, pp 651-652). In September 2011, the U. S. Fish and Wildlife Service (Service) found that the petition presented substantial scientific or commercial information indicating that the listing of 374 species, including Arkansas mudalia, may be warranted.

The Species Status Assessment (SSA) framework (USFWS 2016) is intended to be an in-depth review of the species' biology and threats, an evaluation of its biological status, and an assessment of the resources and conditions needed to maintain long-term viability. The intent is for the SSA report to be easily updated as new information becomes available and to support all functions of the Endangered Species Program from candidate assessment and listing to consultations and recovery. As such, the SSA report will be a living document used to inform decisions made under the ESA.

The Arkansas mudalia SSA is intended to provide the biological support for the decision on whether to propose to list the species as threatened or endangered and, if so, to determine whether it is prudent to designate critical habitat in areas essential to its conservation. This report is not a decisional document by the U.S. Fish and Wildlife Service (Service); rather, it provides a review of available information strictly related to the biological status of the Arkansas mudalia. A listing decision will be made by the Service after reviewing this document and all relevant laws, regulations, and policies, and the results of a proposed decision will be announced in the Federal Register, with appropriate opportunities for public input.

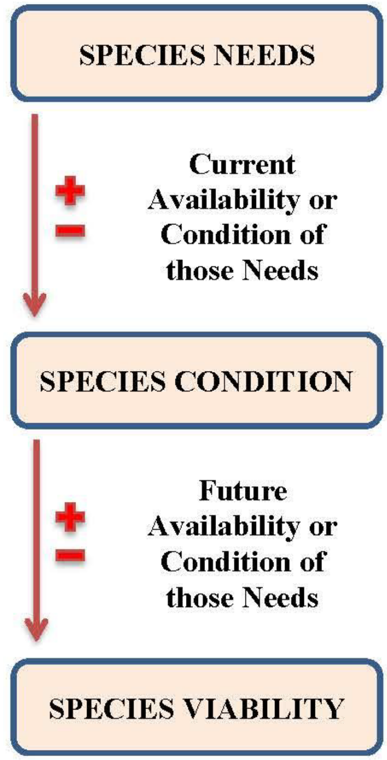

Figure 1. SSA Framework

Using the SSA framework (Figure 1), we consider what the species needs to maintain viability (the species' ability to sustain populations in the wild over time) by characterizing the status of the species in terms of its redundancy, representation, and resiliency (USFWS 2016).

- Resiliency is assessed at the population level and reflects a species' ability to withstand stochastic events (arising from random factors). Demographic measures that reflect population health, such as fecundity, survival, and population size, are the metrics used to evaluate resiliency. Resilient populations are better able to withstand disturbances such as random fluctuations in birth rates (demographic stochasticity), variations in rainfall (environmental stochasticity), and anthropogenic effects.

- Representation is assessed at the species level and characterizes the ability of a species to adapt to changing environmental conditions and is related to the distribution of the species within its ecological setting. Metrics such as a species' adaptive potential and genetic, morphological, and ecological variability can be used to assess representation.

- Redundancy is also assessed at the level of the species and reflects a species' ability to withstand catastrophic events (such as a rare destructive natural event). Redundancy is about spreading the risk of such an event across multiple, resilient populations. As such, redundancy can be measured by the number and distribution of resilient populations across the range of the species.

To evaluate the current and future viability of Arkansas mudalia, we assessed a range of conditions to characterize the species' redundancy, representation, and resiliency (together, the 3

Rs). This report provides a thorough account of biology and natural history and assesses the risk of threats and limiting factors affecting the future viability of the species.

This report includes: (1) a description of Arkansas mudalia resource needs at both individual and population levels (Chapter 1); (2) a characterization of the historical and current distribution of populations across the species' range (Chapter 2); (3) an assessment of factors that contributed to the current and future status of the species and the degree to which various factors influenced viability (Chapter 3); and (4) a synopsis of the factors characterized in earlier chapters as a means of examining the future biological status of the species (Chapter 4). This document is a compilation of the best available scientific information (and associated uncertainties regarding that information) used to assess Arkansas mudalia viability.

Chapter 1 – Life History and Biology

In this chapter, we provide basic biological information about the Arkansas mudalia (*Leptoxis arkansensis*), including its physical environment, taxonomic history and relationships, morphological description, and reproductive and other life history traits. Where life history data is lacking, we used information on other, better-studied species within the genus (*Leptoxis*) and family (Pleuroceridae) as surrogates.

1.1 Taxonomy

L. arkansensis was first described as *Anculosa arkansensis* from the White River near Cotter, Arkansas, and the North Fork White River near Norfork, Arkansas (Hinkley 1915; Figure 3). The genus name *Anculosa* was soon afterwards replaced by the resurrected genus name *Leptoxis* based on expert opinion (Pilsbry 1917).

The currently accepted taxonomy for this species is (ITIS 2016):

Phylum: Mollusca
Class: Gastropoda
Order: Neotaenioglossa
Family: Pleuroceridae
Genus: *Leptoxis*
Species: *arkansensis*

The family Pleuroceridae is a group of small- to medium-sized aquatic snails restricted to North America east of the Rocky Mountains. Pleurocerids are members of the superfamily Cerithioidea, a globally distributed superfamily that includes marine and freshwater groups; pleurocerid snail morphological characteristics include gills located near the front of their body, a spirally coiled shell, and lack of external male reproductive organs or seminal receptacles in females (Kabat and Hershler 1993, Strong and Kohler 2009).

Taxonomy in Pleuroceridae is primarily based on morphological characteristics and geographic ranges; most recognized genera in the family, including *Leptoxis*, seem to be polyphyletic (some species in one genus are more closely related to species in other genera than to other species in their genus) (Brown et al. 2008; Whelan and Strong 2015). Of the approximately 162 currently recognized pleurocerid species, at least 33 (20%) are extinct and eight (5%) are federally listed (Johnson et al. 2013). Four of the thirteen extant (of twenty-two known) *Leptoxis* species are listed as threatened or endangered under the Endangered Species Act; three others are currently under review for listing (Johnson et al. 2013).

1.2 Description

L. arkansensis is globose with a large body whirl in comparison to its shell spire. Adult shell size ranges from 7.9 – 12.2 mm, and color can vary from uniform to banded (Hinkley 1915; Gordon 1987; Wu et al. 1997). It is small and compact compared to sympatric pleurocerid species *Elimia potosiensis* and *Pleurocera acuta* (Hinkley 1915). Its body is dark orange mottled with black and it has a light blue horizontal band around the eyes (Whelan 2013). Pleurocerids are dioecious (separate sexes), and females are often larger than males (Richardson and Sheiring 1994).

1.3 Habitat

L. arkansensis inhabits medium to large-sized rivers in areas of relatively fast current with coarse rocky substrate. Gordon (1987) suggests habitat discrimination based on substrate type, water velocity, and dissolved oxygen levels. Higher respiration rates in *L. arkansensis* (when compared to sympatric species) may limit habitat use, as dissolved oxygen is lower in river edges and backwaters (Gordon 1987).

L. arkansensis generally inhabits mid-channel regions; sympatric species *E. potosiensis* and *P. acuta* tend to inhabit edges (Gordon 1987). In similar rivers outside the range of *L. arkansensis, E. potosiensis* was found in most available habitats, including mid-channel; when sympatric with *P. acuta*, *E. potosiensis* selected for mid-channel, so displacement of *E. potosiensis* to edges within the White River and its tributaries is likely attributable to sympatry with *L. arkansensis* (Gordon 1987).

1.4 Diet

Pleurocerid snails generally eat periphyton (algae, bacteria, and microscopic organisms that grow on hard substrates) and detritus (decaying organic matter). Gordon (1987) performed stomach content analysis and found only periphytal matter in the stomachs of *L. arkansensis*.

Pleurocerids in general have been shown to exhibit faster growth rates when fed periphyton versus detritus (Hawkins et al. 1982) and preferentially may select the former over the latter (Elwood et al. 1981; Gordon 1987). As *L. arkansensis* is primarily found in areas of fast current and coarse substrate, detritus may be less common than periphyton. Periphyton productivity has been associated with growth rates, fecundity, and secondary production (see review in Russel-Hunter 1983). Periphyton is easier to remove by scraping from a hard substrate, and contains higher concentrations of limiting nutrients such as nitrogen than other food sources (Russell-Hunter 1978, Aldridge 1983, Brown 2001).

1.5 Age, Growth, and Population Size Structure

Although no full life cycle data is available for *L. arkansensis*, individuals likely live for two years and are semelparous, reproducing only once before death (Gordon 1987; Whelan 2013). The majority of *Leptoxis* species are found in southern coastal states; semelparity may be more common in more northerly *Leptoxis* species (including *L. arkansensis*) as well as other northernranging pleurocerids (Whelan et al. 2015). There seems to be no appreciable variation in shell shape or characteristics with age or increasing size (Gordon 1987).

Metabolism of *L. arkansensis* individuals tended to increase with temperature until a critical thermal maximum was reached; *L. arkansensis* could not survive more than “very short exposure” to temperatures above 28°C (Gordon 1987). Goodrich (1945) considered 5°C to represent the critical low temperature for sustained activity in pleurocerids. Some species and populations may acclimatize to lower temperatures depending on the thermal history of their local environment (Gordon 1987). At temperatures below a critical thermal minimum, individuals can lose the ability to grip surfaces, become inactive, or die (Gordon 1987).

1.6 Reproduction

Female *Leptoxis* have an egg-laying sinus on the right side of the foot; males lack external sex organs (Burch 1982). *Leptoxis* species lay eggs in one of three patterns: a circular clutch, a line, or single eggs. *L. arkansensis* displays a unique variant of the single egg strategy: females collect the eggs in a clutch near their foot and drag the entire clutch, depositing individual eggs from the clutch onto the substrate (Figure 2; Whelan et al. 2015). *L. arkansensis* lays eggs on the undersides or sides of hard, clean substrates (such as coarse sediment, bedrock, or woody debris without siltation or vegetation) (Whelan et al. 2015). Once egg laying begins, all *Leptoxis* species lay eggs for 60-90 days (Whelan et al. 2015). Eggs are approximately 0.3 mm in diameter (Whelan et al. 2015). In the lab, eggs hatched 14 days from oviposition with over 98% success rate (Whelan et al. 2015).

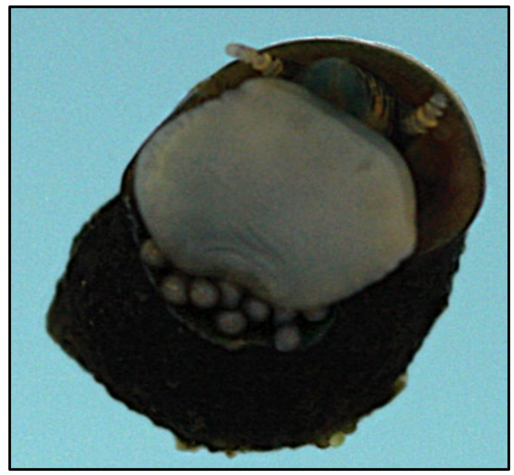

Figure 2. Female *L. arkansensis* with clutch. Figure taken from Whelan et al. (2015)

Reproduction is most likely temperature-mediated with upper/lower thermal bounds controlling time of reproduction, as seen in Whelan et al.’s (2015) breeding study. Under lab conditions, *L. arkansensis* deposited eggs in small tanks with low current at temperatures between 13°C and 27°C (Whelan et al. 2015). In the wild, reproduction primarily occurs from spring through midsummer (Gordon 1987), but while recently hatched snails were most abundant during mid-summer (July –August), juveniles were also found irregularly through December (Gordon 1987). Gordon (1987) suggests possible underestimation of juvenile numbers based on the sampling method and small size of juveniles.

Chapter 2 – Population Needs, Species Needs, and Current Condition

In this chapter, we consider the historical distribution of the Arkansas mudalia, its current distribution, and factors that contributed to the species’ current condition. We first review the distribution of the species. Next, we evaluate species' requisites to consider their relative influence to Arkansas mudalia representation, and redundancy. Through the lens of the 3 Rs, we then estimate the current condition of Arkansas mudalia populations.

2.1 Species Need and Population Needs

L. arkansensis inhabits medium to large-sized rivers in areas of faster current with coarse substrate. In general, greater numbers of *Leptoxis* are associated with increased stream substrate complexity (Stewart and Garcia 2002). Gordon (1987) suggests habitat discrimination, with substrate type as primary determinant and velocity and dissolved oxygen as secondary. Large, hard substrates such as boulder and cobble are more likely to grow phytoplankton and are preferred habitat for foraging (Stewart and Garcia 2002). Additionally, large substrates are stable and likely provide refuge from high velocity flow as well as flood events. The diet of *L. arkansensis* is made up almost solely of periphyton (Gordon 1987), and the habitat parameters must support periphyton growth.

For reproduction, individuals need a hard, clean substrate on which to lay eggs (Whelan et al. 2015). Pleurocerids often display density-dependent breeding under lab conditions (Whelan et al. 2015). If this holds true in the wild, a high enough density of sexually mature adults must be present in the stream reach for reproduction to occur.

Pleurocerid snails have slow and restricted dispersal capabilities (reviewed in Huryn and Denny 1997). Freshwater aquatic snails generally exhibit upstream movement, most likely due to the effect of hydrodynamic drag on the shell (Huryn and Denny 1997). Drag from fast-flowing water can prevent a snail from crawling downstream by causing shell rotation, with the point of the shell pointing downstream, torqueing the foot until the snail faces upstream (Huryn and Denny 1997). *Elimia livescens*, a riffle-inhabiting pleurocerid, generally moves against the water current and maintains positive rheotaxis (faces into the current) (Kappes and Haase 2012). Downstream movement is primarily due to drift from substrate rafting and displacement during high velocity and discharge events such as flooding (Kappes and Haase 2012). *Elimia* species can disperse up to 2.2 m/day, while *Leptoxis carinata* can disperse 0.02 to 0.84 m/day (Huryn and Denny 1997; Stewart 2007; Brown et al. 2008). A three-month long study of free-ranging *Elimia spp*. individuals found that upstream movement ranged between 58 and 200 m, and downstream movement was between 3 and 47 m (Huryn and Denny 1997).

Maximum active upstream movement is likely well under 1.0 km per year for most snails, and the maximum distance at which many species display population mixing seems to be three km (Kappes and Haase 2012). To maintain genetic diversity and reduce the risk of extirpation, it is beneficial for multiple populations to exist close enough together to allow for mixing and recolonization.

2.3 Historical Range and Distribution

The species was originally described from the White River near Cotter, Arkansas, and the lower North Fork White River near Norfork, Arkansas (Hinkley 1915; Table 3 and Figure 3). Early naturalists collected large numbers of *L. arkansensis* at the original collection localities along the mainstem White River and throughout the North Fork White River (Table 3). Although historically it was never collected above the current location of Bull Shoals Dam, based on the recent collections in James River and Beaver Creek, which flow into the White River above Bull Shoals Dam, it is likely that the historical range of this species encompassed the White River headwaters and tributaries to near Batesville, Arkansas (Figure 3).

Arkansas mudalia were recorded from seven sites in the North Fork White River and White River before 1945, but five of these sites were lost due to dam construction. Arkansas mudalia were found in 1915 and 1942 approximately 24 river km downstream of the Bull Shoals Dam location, but none were found at any sites on the mainstem White River in surveys after the dam was constructed (Table 3; Gordon 1982). Similarly, Norfork Lake directly inundated at least one *L. arkansensis* population (see Site 5, Figure 3). However, individuals were found at five sites between 1945 and 1987 in sporadic surveys throughout the North Fork White River watershed above the dam (Figure 3; Table 3). In 1987, Gordon found that *L. arkansensis* was the numerically dominant species at his study site on the North Fork White River near Tecumseh, Missouri, upstream of Norfork Lake, making up 64% of the pleurocerids collected (Gordon 1987).

2.4 Current Range and Distribution

The White River is approximately 1,210 km long with a drainage basin of approximately 72,520 km^2, at least 36,260 km^2 of which is in the upper basin above the confluence with the North Fork White River. There are eight dams along the length of the White River, built between 1913 and 1966. The drainage area of the North Fork White River watershed is 3,597.5 km^2. The construction of Norfork Dam in the early 1940s inundated approximately 52 km of the North Fork White River. Dam releases create areas of cold water and low dissolved oxygen below the dams called tailwaters (Bayless and Vitello 2001). The drastically lowered temperature, lower dissolved oxygen, and presence of snail-eating trout in the tailwaters make it unlikely that *L. arkansensis* could survive and reproduce in any tailwaters. The trout-hosting cold tailwater of Bull Shoals Dam is approximately 148 km long, and the Norfork Dam tailwater covers the entire 8 kilometer length of the river between the dam and confluence with the White River. In total, over 241 km of the main stem White River is classified as tailwater and is no longer suitable habitat for *L. arkansensis*.

Few studies have surveyed for *L. arkansensis* between 2000 and 2017. Individuals were collected from sites in the North Fork White River in 2010 and 2013 (Hayes 2010; Whelan 2013). Surveys on the main stem North Fork White River found *E. potosiensis* was the most common pleurocerid sampled (Hayes 2010), suggesting a decline in *L. arkansensis* relative abundance. *L. arkansensis* were still collected although no population estimates were made (Hayes 2010; Whelan 2013). *L. arkansensis* were also found during a brief survey of a historical Missouri site on the North Fork White River in December 2016 (N. Whelan, personal communication, 2017). In Spring Creek, *L. arkansensis* was found in much higher numbers than *E. potosiensis* (MDNR 2007).

Some stream reaches within the current range in Missouri are classified as Outstanding State Resource Waters, including portions of Bryant Creek, Noblett Creek, North Fork White River, and Spring Creek (MDNR 2017).

Several recent collections of *L. arkansensis* have been made outside of reaches with historical records, although surveys in some small tributaries have found no *L. arkansensis* (N. Whelan, pers. comm. 2017). In 2005, collections of *L. arkansensis* were made at Finley Creek, a tributary of the James River, which converges with the White River at Table Rock Lake, and Beaver Creek, which converges at Bull Shoals Lake (Table 3). A 2008 study of mollusks in the White River and North Fork White River watersheds identified *L. arkansensis* at three new sites in Arkansas (Hayes 2010; Figure 3). Two of these, Otter Creek and Sylamore Creek, have not been modified and have temperature, flow, and substrate suitable for Arkansas mudalia. Two *L. arkansensis* were found during a later search of the Sylamore Creek site (A. Bangs, unpublished data, 2017; Table 3). Otter Creek and Sylamore Creek are likely remnant, isolated populations of *L. arkansensis*. Although both tributaries converge with the North Fork White River and White River tailwaters, the creeks themselves have not been modified. The Finley Creek and Beaver Creek records imply that the species was once spread throughout the White River basin. The low numbers found (Table 3) suggest that they may be small relict populations.

However, the third site from the 2008 study was on the main stem White River within the Bull Shoals tailwater, which is unsuitable habitat. A study in 1982 found only *E. potosiensis* in this section of the White River (Gordon 1982). Additionally, there are no historical records of *L. arkansensis* below the confluence of the North Fork White River. Therefore, is likely that the main stem White River record is instead a globose morph of *E. potosiensis* (D. Hayes, pers. comm. 2017; N. Whelan, pers. comm. 2017).

Recent studies on *E. potosiensis* have demonstrated phenotypic variation in shell length and size that correlated with environmental conditions over only a few hundred meters, with downstream individuals having shorter and rounder shells (Minton et al. 2011). A similar study on a non-Pleurocerid snail species showed development of thicker, shorter, and wider shells in high-flow tanks in a laboratory and in flowing stream environments in the field when compared to no-flow tanks and habitats (Gustafson and Bolek 2015). The globose *Elimia* morphs are difficult to differentiate from *L. arkansensis; L. arkansensis* has a slightly wider aperture and less angular body whirl (Hinkley 1915; D. Hayes, pers. comm. 2017, N. Whelan, pers. comm. 2017).

The majority of *L. arkansensis* collected in 2010 were more closely related genetically to *E. potosiensis* than to *L. arkansensis* individuals collected within and between sites (Hayes 2010); the only individuals that separated out from *E. potosiensis* were collected from Site 7 (Hayes 2010; Figure 3). However, pleurocerid species have been difficult to differentiate by genetic analysis because commonly used mitochondrial markers display a yet unexplained amount of diversity (D. Hayes, pers. comm.; N. Whelan, pers. comm.; Brown et al. 2008; Whelan and Strong 2016). Available data suggest that mitochondrial diversity seen within putative pleurocerid species is not the result of cryptic species being present (Whelan et al. 2015).

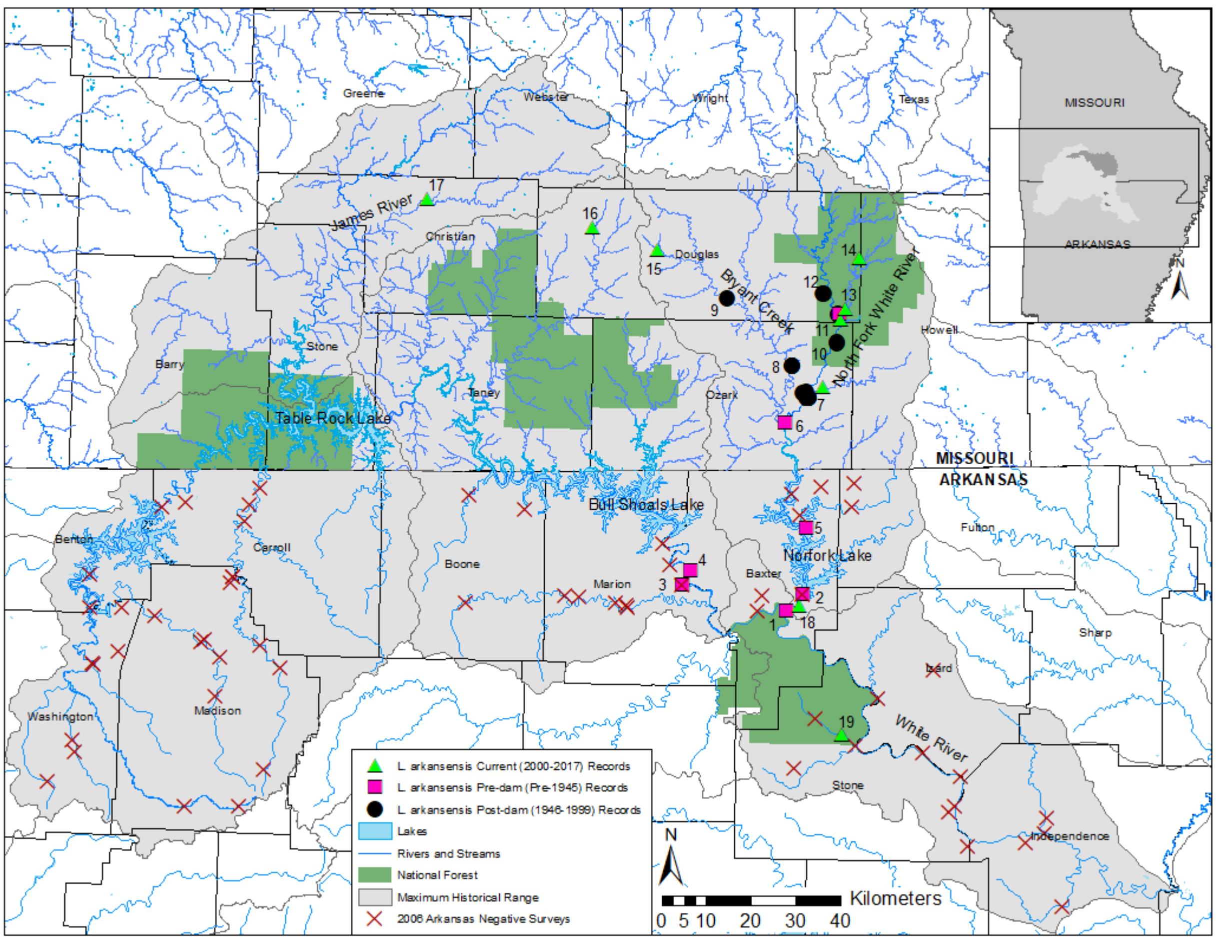

Figure 3: Range map of *Leptoxis arkansensis* showing historical and current collection locations and range in Arkansas and Missouri, USA. Numbers correlate with Site Number in Table 3.

2.5 3 R's Analysis

Lack of knowledge about the original distribution of *L. arkansensis* in the White River and its tributaries coupled with sporadic records and inconsistent sampling methods makes it difficult to estimate range constriction or extent of occupation within the estimated range.

2.5.1 Resiliency

Lack of data regarding demographic measures of the species makes it difficult to evaluate population resiliency. However, we know this species is not highly resilient, as extreme habitat modification and destruction by the dams caused extirpation of all known affected populations. Based on the continued collection of this species at sites within the upper North Fork White River watershed, it seems that populations of *L. arkansensis* are somewhat resilient to natural stochastic events as long as suitable habitat remains present. Anthropogenic impacts in the upper North Fork White River watershed are relatively small and localized; 62% of the watershed is forest/woodland, and under 1% is classified as urban (Miller and Wilkerson 2001). The collection of *L. arkansensis* at Finley Creek suggests populations can persist in areas with moderate levels of anthropogenic impact (James Creek watershed is 63% agricultural, mostly pasture and row cropping, and small dams are located above and below this population). Low numbers collected at that site may indicate a small or decreasing population (Table 3).

2.5.2 Representation

Although it is reasonable to assume that *L. arkansensis* was spread throughout the main stem White River and the North Fork White River, we have less information regarding its distribution in the tributaries. Data suggests that the historic range at minimum encompassed the North Fork White River watershed and the area around its confluence with the White River; the largest range of this snail was most likely the White River and its tributaries downstream to near Batesville, Arkansas (approximately 36,260 km^2). This is approximately where the White River runs from the Ozark Mountains into the Mississippi River Delta, and the habitat would have historically not been appropriate for *L. arkansensis*.

The range of the species has been reduced to the North Fork White River watershed, with a few isolated populations in headwater streams of three other tributaries of the White River (James River, Beaver Creek, and Sylamore Creek), approximately 3,815 km^2 . If the likely maximum range is correct, this constitutes an estimated range reduction of almost 90%.

2.5.3 Redundancy

Within the North Fork White River watershed, there are multiple known populations spread throughout the main stem North Fork River and some tributaries (Fig. 2). A single catastrophic event is unlikely to extirpate all populations within this watershed, and recolonization would likely be possible.

All other known extant sites are presumed to be isolated populations within other watersheds and therefore have low or no redundancy. If no unknown populations exist in these watersheds, or existing populations are separated by distance or impassible habitat, extirpation of the known population would cause a loss of representation for the entire watershed and a sizeable range reduction.

2.6 Site Ranking

As the data regarding the presence of species and population needs on the landscape is sparse, we chose approximate abundance, habitat alteration, the presence of protected land, and isolation as our four parameters to estimate the current condition of each occupied site. As we are uncertain as to the existence of populations between collection sites, each site is ranked with and without the effect of isolation.

Table 1. Matrix for estimating current condition of Arkansas mudalia sites.

Parameter	High	Medium	Low	N/A
Abundance	Recent surveys (2000-present) found >50 individuals	Recent surveys found <50; historical surveys (1946 – 2000) found >50	<50 individuals found 1945-2000	Extirpated: The site no longer has individuals
Habitat	No major alteration; riparian buffer extant and primarily forested	Low level alteration; >~75% forested; majority riparian zone buffered	At least 50% surrounding area cleared/developed; little-no riparian veg.	Extirpated: The habitat for this species no longer exists
Protected Land	On federal or state land	Privately owned land		
Isolation	Post-dam or recent collection site within 3km; no known barriers	Post-dam or recent collection site between 9km and 25km; no known barriers	Post-dam or recent collection site between 9km and 25km; no known barriers	Isolated: Significant barrier(s) between this site and the nearest collection site.

Table 2. Estimated current condition of each Arkansas mudalia site based on four habitat parameters.

Sites	Physical Habitat	Appx. abundance	Land Protection	Isolation	Total w/o isolation	Total
1-6	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated
7	**M**	**M**	**M**	**M**	**Medium**	**Medium**
8	L	M	M	L	Medium	Low
9	M	L	M	L	Medium	Low
10	H	M	H	M	High	Medium
11	**M**	**M**	**H**	**H**	**Medium**	**Medium**
12	H	L	H	M	Medium	Medium
13	**L**	**H**	**H**	**H**	**Medium**	**High**
14	**H**	**M**	**H**	**Isolated**	**High**	**Medium**
15	**L**	**M**	**M**	**L**	**Medium**	**Low**
16	**L**	**H**	**M**	**Isolated**	**Medium**	**Low**
17	**L**	**L**	**M**	**Isolated**	**Low**	**Low**
18	**H**	**L**	**M**	**Isolated**	**Medium**	**Low**
19	**H**	**L**	**H**	**Isolated**	**Medium**	**Medium**

Chapter 3: Future Conditions

The intent of this analysis is to predict the persistence of Arkansas mudalia populations in the future and to inform us of the species viability. Our ability to predict is limited due to a lack of life history and population data and our uncertainty about how Arkansas mudalia populations respond to stressors. Thus, our analysis will be limited to a discussion of future changes in assumed stressors to the species, both the addition of new stressors and changes in the existing stressors. We identified potential stressors and their sources from survey information, literature, reports, discussion with scientific experts, and personal knowledge.

3.1 Habitat Loss

The construction of Norfork Dam in the early 1940s likely inundated a large portion of the original habitat for the species and drastically changed the habitat downstream, including at the type locality. The construction of Bull Shoals Dam in 1951 also modified downstream habitat, and likely affected the species, as many *L. arkansensis* were found in surveys approximately 24 river kilometers downstream of the dam's current location before the dam's construction, but not in later surveys (Gordon 1982). Dam releases have shifted the downstream water temperature to cooler temperatures, spurred the introduction of a cold water fishery that includes predatory rainbow and brown trout, inundated shallow riffle habitat, and lowered dissolved oxygen concentrations (Berger and Kaster 1978; Bayless and Vitello 2001; Brown 2001). Impoundments also reduce the availability of periphyton food below the dam (Lodge and Kelly 1985; Brown and Lydeard 2009; Thorp and Covich 2010).

A few smaller dams are also present within the range of the species. Noblett Dam, located on Noblett Creek, is downstream of a recent *L. arkansensis* collection (Miller and Wilkerson 2001). Three small dams are located on Finley Creek above and below the collection site (Kiner and Vitello 1999). These dams likely provide some barrier to snail movement between upstream and downstream reaches, but don't cause the same scale of habitat destruction and degradation as larger dams.

There are no current plans for large scale water control projects in the North Fork White River watershed, and it is unlikely that any will be developed in the future. This stressor has already reduced the historic range, and existing dams will continue to isolate remaining populations, increase sediment and gravel deposition upstream of reservoirs, and increase exposure of any remaining snails to predatory fish.

Dawt Mill dam, a small dam upstream of Norfork Lake, was removed in February 2017. This dam was near a historical *L. arkansensis* site, and just downstream of a recent collection (Figure 3, sites 6 and 7). Dam removal may allow for recolonization of new or historical habitat and potential increased gene flow if there are still existing populations downstream of the dam location. However, this stream reach is truncated by Norfork Lake and will not provide a significant range recolonization (Figure 3).

3.2 Habitat Degradation

Degradation of water quality and habitat loss is likely the most significant threat to the species' continued survival. As we are fairly certain that *L. arkansensis* is semelparous and has a two year life cycle (Whelan et al. 2015), if reproduction fails or is significantly reduced for more than two years the species is subject to drastic population loss or extirpation from the site. Habitat degradation can also cause habitat fragmentation, which can make gene flow and recolonization of extirpated sites difficult. As *L. arkansensis* rely on clean substrate, low turbidity, and high dissolved oxygen levels, increased sedimentation has the potential to degrade habitat.

Threats include habitat modification from certain types of logging, agriculture (primarily livestock), mining, and various other point and nonpoint pollution discharges (Miller and Wilkerson 2001). Activities can have varying effects on water quality depending on the type of practice, and conservation practices exist that can reduce the negative effects of many of these stressors.

Logging has long been associated with degraded water quality, primarily through increased in-stream sedimentation and turbidity, changes in nutrient cycling, and increased water temperature during and after a logging operation (Swank et al. 2001; Peterman and Semlitsch 2008). Disruption of the ground surface by tree removal, skid trails or roads allows for soil erosion at greater than normal rates; this is often the primary producer of off-site sedimentation (Corbett et al. 1997, Grace 2001). Most states with a commercial timber industry, including Arkansas and Missouri, have created Best Management Practices (BMPs) specific to timber harvest activities to protect water quality; the primary focus of forestry BMPs is to minimize timber harvest effects on water quality and aquatic habitat (Koirala 2009). These BMPs often include a streamside management zone (SMZ): an undisturbed buffer around all waterways that acts as a filter to sediment and slows surface runoff (Bunger 2005). Studies across the eastern United States have demonstrated that timber harvest causes an increase in sediment, discharge, and nutrients, but the implementation of BMPs with SMZs seems to be effective in reducing the effect of the harvest on water quality (Koirala 2009, Peterman and Semlitsch 2009, reviewed in Boggs et al. 2016).

The North Fork White River watershed is primarily rural; pastures and rangeland comprise the second largest percentage of land use in the watershed. This watershed contains some of the primary cattle-producing areas for Missouri, and the density of cattle in this area is predicted to increase (Miller and Wilkerson 2001). Certain practices, primarily unrestricted cattle access to streams and riparian areas, have been identified as a source of nonpoint source pollution; unrestricted cattle cause soil compaction, reduced riparian vegetation, increased in-stream disturbance through increased suspended sediment and associated contaminants, and actively contribute to bank erosion (Owens et al. 1996, Vidon et al. 2008). BMPs to restrict cattle access to streams and riparian areas, including exclusion fencing, off–stream water sources, and seasonal or rotational grazing, have been shown to greatly reduce sedimentation, soil loss, and sediment-bound pollutants such as nitrogen and phosphorus, and allow for revegetation of riparian buffers (Miner et al. 1992, Owens et al. 1996, Sheffeild et al. 1997, Clary 1999). However, large scale implementation of fencing can be costly and difficult (Wilson and Clark 2007), and many landowners are unwilling to follow BMPs and maintain associated structures.

As of 1998, there were 22 permitted gravel mines in the North Fork White River watershed, with three active gravel mines near currently occupied *L. arkansensis* sites (Table 3, site 7; Miller and Wilkerson 2001). Two gravel mines were located in the upper reaches of Beaver Creek in the White River watershed (Bayless and Vitello 2001). Gravel and sand is generally taken from streamside sites, and can have a negative effect on nearby and downstream habitats. The negative effects of gravel mining include channel deepening, sedimentation of downstream habitats, accelerated bank erosion, the formation of a wider and shallower channel, the lowering of the floodplain water table, and channel shift (Brown et al. 1998, Roell 1999). However, correctly applied BMPs may help reduce or eliminate these negative effects downstream of the mine (MDNR 2007).

Four of the nine recently documented populations occur on U.S. Forest Service (USFS) land. In Arkansas, the Ozark National Forest owns approximately 690 km^2 surrounding the Sylamore River (Site 19, Figure 3). In Missouri, the Willow Creek Ranger District of the Mark Twain National Forest covers roughly 22% of the North Fork White River watershed in Missouri, including an area that has maintained Arkansas mudalia for 70 years (Site 11, Figure 3). Habitat modification and degradation is highly unlikely in these areas, as the USFS restricts many of the land practices that can be a threat or, when allowed, follows strict BMPs to reduce the impact of the practice on the environment.

3.3 Disease and Predation

There is no record of disease in Arkansas mudalia. Based on the limited data available, there is little evidence in general for negative population-level effects from disease in freshwater snails.

At least one Leptoxis species is a documented intermediate host for trematode parasites (Hoffman et al. 1985). Trematode-infected snails commonly develop morphological differences such as shell size and shape and sometimes exhibit shifts in behavior (Krist 2000; Lagrue et al. 2007), but there is no evidence that this is currently affecting Arkansas mudalia or will negatively impact the species in the future .

Pleurocerids are consumed by many organisms, including fishes and crayfish (Covich 1977; Brown 2001; Greenwood and Thorp 2001; Krist 2002; Haag and Warren 2006). Experimental evidence supports the conclusion that predators are a source of strong pressure in determining snail diversity and abundance as well as behavior such as habitat choice and foraging behavior (Turner 1997; Weber and Lodge 1990; reviewed in Brown 2001). However, any predation pressures are spread across multiple invertebrate species in Arkansas mudalia habitat, and there is no evidence that predation pressure has changed from historical levels. The introduction of trout in the Bull Shoals tailwater may have combined with habitat modification to extirpate

Arkansas mudalia in the White River, but it is unlikely trout will expand into currently occupied stream reaches.

3.4 Collection

Early scientists collected *L. arkansensis* in large numbers but this species has not been the focus of many collection activities beyond that for localized scientific studies (Table 3). There is no known collection for the pet trade. It is unlikely that current collection pressure is large enough to affect remaining populations.

3.5 Catastrophe

A catastrophic event is generally defined as a temporally and spatially discrete devastating event, such as a rare natural disaster or an incident covering multiple populations. As of 2017, no large-scale catastrophic events have been recorded affecting waterways in the assumed range of the Arkansas mudalia. The Missouri Department of Conservation (MDC) tracks and investigates fish kill and water pollution events throughout the state. Overall, the number of fish kill/pollution incidents recorded by the MDC peaked in the mid to late 1990s and has declined since (O'Hearn and Martin 2012). Generally, the investigation includes water chemistry screening and a record of the number and species of fish killed; they do not track other aquatic organisms. The majority of incidents recorded between 2006 and 2013 within the range of Arkansas mudalia were fish die-offs in lakes due to high temperatures and low dissolved oxygen. Arkansas mudalia are not expected to be found in lotic environments.

In 2010, there is a record of a fish kill event in Bryant Creek, Douglas County, Missouri; the cause of the event and the number of animals killed was not determined by MDC investigators. While there are records of Arkansas mudalia in Bryant Creek, it is unlikely this event was large enough to affect more than the immediate event site and as such cannot be categorized as a catastrophic event. Similarly, in 2012, 200 fish were killed by high temperatures during spawning in the James River. This record is downstream of any known Arkansas mudalia sites and the increased temperature unlikely to have affected the entire river segment (Zweig 2008; O'Hearn and Martin 2012; O'Hearn and Martin 2014). Of 11 pollution records in the 1990's, only one caused fish death and none affected more than the immediate stream reach (Miller and Wilkerson 2001).

3.6 Climate Change and Shifts in Water Regime

The terms "climate" and "climate change" are defined by the Intergovernmental Panel on Climate Change (IPCC). The term "climate" refers to the mean and variability of different types of weather conditions over time, with 30 years being a typical period for such measurements (IPCC 2013a, p. 1,450). Thus, the term "climate change" [or changing climate conditions] refers to a change in the mean or variability of one or more measures of climate (for example, temperature or precipitation) that persists for an extended period, whether the change is due to natural variability or human activity (IPCC 2013a, p. 1,450).

All freshwater systems are considered vulnerable to climate change because of the combination of climate-dependent water temperature and habitat availability and existing anthropogenic stressors combined with the limited dispersal ability of many aquatic species (Woodward et al. 2010, p 2093). The specific effect of climate change on aquatic species such as *L. arkansensis* is difficult to predict because of the potential synergies between components of climate change and other stressors (Woodward et al. 2010).

A conservative climate change prediction model predicts that the current range of *L. arkansensis* will show an average 1.2°C temperature increase by 2040 when compared to recent (1985-2006) temperature measurements, which is consistent with the predicted minimum warming of 1°C over the next 50 years (Moss et al. 2008; NCAR GIS Program 2012).

Air and surface water temperatures are correlated. Average air temperatures are predicted to increase in the future and surface water will follow this trend; groundwater temperatures will increase after a lag time, depending on aquifer dimensions (Meisner et al. 1988; Stefan and Preud'homme 1993; Karl et al. 2009; Kurylyk et al. 2014). As the North Fork White River watershed geography is primarily dolomite and sandstone, karst features such as losing streams are common (285 kilometers of losing streams) and many of the streams are spring fed (Miller and Wilkerson 2001). Groundwater discharge, primarily through springs, helps create cooler microhabitats in streams that can provide refugia for species when water temperatures rise (Davis et al. 2013). Cold-water inputs like those from springs may help moderate the influence of air temperature on surface water temperature in near future scenarios (Davis et al. 2013, p 1978; Luce et al. 2014).

Increased water temperatures will alter distributions of aquatic organisms; species' thermal limits will cause shifts or reductions in suitable habitat (Eaton and Scheller 1996; Rieman et al. 2007). Higher water temperatures generally result in lower dissolved oxygen in surface waters which could also restrict available *L. arkansensis* habitat (Covich et al. 1997). Environmental temperature also influences morphological and physiological traits in ectothermic animals (e.g. aquatic invertebrates) including metabolic rate, reproduction, growth, and fecundity (Ficke et al. 2007; Rypel 2009; Whelan et al. 2015). Above an upper thermal limit (approximately 28°C for *L. arkansensis*), physiological function breaks down and death can occur (Magnuson 1979; Gordon 1987, Ficke et al. 2007).

Climate change is also expected to change the timing and quantity of stream flows, and anthropogenic use is likely to exacerbate these effects. Increases in the frequency of severe droughts and storm events are predicted (Karl et al. 2009). During droughts, surface waters will have less surface input, and groundwater recharge of surface streams will decline due to the reduced rainfall. Water withdrawals for human use will put additional strain on ground and surface waters (Covich et al. 1997). Low stream flows are associated with faster water warming in response to high air temperatures (Poole and Berman 2001). Drying and hypoxia associated with high temperature and low dissolved oxygen lower diversity and cause die-offs of gastropod populations (Lodge and Kelly 1985; Lodge et al. 1987). Storm events can cause habitat destruction and shifting in waterways through scouring and debris, and high flow events can wash aquatic invertebrates downstream. Human response to unpredictable rainfall is often to build water control structures, which radically alter natural hydrologic variability and destroy and modify habitat (Poff and Allan 1995; Olden et al. 2006)

Because of their short life span, pleurocerids can be affected by sporadic shifts in natural phenomena, including shifts in climate and stream drainage patterns, as well as human actions (Goudreau et al. 1993; Neves et al. 1997; Angelo et al. 2002; Lydeard et al. 2004). As discussed in Section 2, any change to a population's habitat that causes a lowered recruitment or recruitment failure could extirpate that population. Small or isolated patches of habitat are more vulnerable to extirpation (Rieman et al. 2007; as a species with low vagility, natural reestablishment of extirpated populations is unlikely unless surviving populations are in close proximity.

Table 3. Museum records and published data for *Leptoxis arkansensis*. Numbers correspond to site number on map (Figure 3). Cat # is the museum accession number, when available (USNM: Smithsonian Department of Invertebrate Zoology, UM: University of Michigan – Museum of Zoology, Malacology: Harvard Museum of Comparative Zoology, UFID: Florida Museum of Natural History, FMNH: The Field Museum, ANSP: The Academy of Natural Sciences of Drexel, BMSM: Bailey-Matthews National Shell Museum, LM: Landes Museum – Germany, UCM: University of Colorado Museum

Site No	Collector	Year	Locality	Cat #	# collected
1	A. Hinkley	1914	North Fork White River		82
2	A. Hinkley	1914	North Fork White River	USNM 271764	30
3	A. Hinkley	1914	White River		"very few"
13	L. Hubricht	1935	Spring Creek	UM 176126, 128753	N/A
6	L. Hubricht	1942	North Fork River		164
4	L. Hubricht	1942	White River	UM 176124, 159883	235
5	L. Hubricht	1942	North Fork White River	UM 176125, 159881	69
11	A. Leonard	1948	North Fork River	Malacology 166971	10
12	A. Leonard	1948	North Fork River	Malacology 166972	15
9	A. Leonard	1948	Bryant Creek	Malacology 166979	15
7	H. Kemper	1969	North Fork River	UFID 486311	6
7	F. Shilling	1969	North Fork River	FMNH 350650	6
7	F. Shilling	1969	North Fork River	FMNH 350628	7
7	F. Shilling	1969	North Fork River	FMNH 350632	19
7	F. Shilling	1969	North Fork River	ANSP 448146	3
7	F. Shilling	1969	North Fork River	BMSM 111616	2
7	F. Shilling	1970	North Fork River	FMNH 350629	N/A
10	F. Shilling	1970	North Fork River	FMNH 350630	N/A
7	H. Kemper	1971	North Fork River	LM 6606455	N/A
8	F. Shilling	1979	Bryant Creek	FMNH 350631	N/A
8	F. Shilling	1980	Bryant Creek	FMNH 350644	N/A
7	M. Gordon	1982	North Fork River		N/A
8	R. Oesch	1982	Bryant Creek	UCM 31802	312
7	R. Oesch	1982	North Fork River	UCM 31805	210
10	R. Oesch	1982	North Fork River	UCM 32129	135
11	R. Oesch	1983	North Fork River	UCM 31822	11
12	R. Oesch	1983	North Fork River	UCM 31825	1
7	R. Oesch	1983	North Fork River	UCM 31814	260

Table 3 continued.

Site No.	Collector	Year	Locality	Cat #	# collected
7	M. Gordon	1984	North Fork River	UCM 40142	600
8	R. Oesch	1984	Bryant Creek	UCM 32754	49
15	W. Mabee	2005	Hunter Creek		21
17	W. Mabee	2005	Finley Creek		6
7	W. Mabee	2005	Spring Creek		1
16	W. Mabee	2005	Beaver Creek		113
16	W. Mabee	2005	Beaver Creek		21
11	D. Hayes	2006	Spring Creek		3
14	D. Hayes	2006	Noblett Creek		3
18	D. Hayes	2006	Otter Creek		1
19	D. Hayes	2006	N. Sylamore Creek		4
13	MDNR	2006	Spring Creek		153
13	MDNR	2006	Spring Creek		162
13	MDNR	2007	Spring Creek		22
13	MDNR	2007	Spring Creek		>93
13	MDNR	2007	Spring Creek		20
13	MDNR	2007	Spring Creek		>25
13	N. Whelan	2010	Spring Creek	USNM 1249588	50
19	A. Bangs	2017	N. Sylamore Creek		2

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