

Species Status Assessment for Three Cave Amphipods from Virginia and West Virginia

Cooper's cave amphipod (*Stygobromus cooperi*)
Minute cave amphipod (*Stygobromus parvus*)
Morrison's cave amphipod (*Stygobromus morrisoni*)



Stygobromus morrisoni

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Executive Summary

Minute cave amphipod (*Stygobromus parvus*), Cooper’s cave amphipod (*S. cooperi*), and Morrison’s cave amphipod (*S. morrisoni*) are groundwater amphipods that are highly specialized for subterranean karst habitat characterized by relatively stable physiochemical conditions compared to surface environments and limited or patchily distributed food resources. Due to the absence of light and primary producers in subterranean environments, these species are likely detritivores or omnivores that feed on organic matter (*i.e.*, dead plant and animal material) originating from the surface. While groundwater amphipods are commonly thought to be K-selected species characterized by delayed maturity, small population size, and low reproductive rates, specific demographic and life history parameters for these species are unavailable.

The three species of *Stygobromus* being considered are restricted to Virginia and West Virginia, with highly limited distributions (Figure 2). Available data includes amphipod occurrences that cannot be reliably used to infer current population condition. Due to this uncertainty, an expert knowledge elicitation workshop following the Sheffield Elicitation Framework was organized to obtain a balanced scientific assessment of how populations may respond to current and projected levels of major stressors. A threats analysis was conducted for each locality based on available land use data, which was used as the basis for expert judgments on the probability of persistence of each meta-population over four generations (roughly 10–20 years). While persistence alone is not sufficient to consider a species viable, expert judgments implicitly considered viability in the sense that higher probabilities reflect greater current viability and/or lower threat magnitudes. Because data on genetic connectivity between localities are not available, this report assumes that each locality represents a distinct meta-population.

Current Conditions Summary Table

Species	Number of Localities	Range Extent (km ²)
<i>S. cooperi</i>	1	27
<i>S. morrisoni</i>	9	2,266
<i>S. parvus</i>	8	1,467

The experts had low confidence in persistence for the single *S. cooperi* population (known from only three individuals), reflected by both the low median probability of persistence (Table 7) and large degree of uncertainty in judgments (Figure 5). Low confidence in persistence stemmed from the high number of developed areas within the region and an anticipated increase in visitation rates due to changes in cave ownership (Table 8). Conversely, expert judgments for *S. parvus* localities generally suggest high confidence in persistence despite considerable uncertainty in estimates for several meta-populations. The greatest threat to persistence for most *S. parvus* populations relates to forest management and timber harvest practices by landowners. Uncertainty in the probability of persistence was generally much higher for populations of *S. morrisoni*, based on suspected differences in habitat use and variation in the characteristics of occupied caves. Differences in local geology, including depth and size of the cave and susceptibility to flooding, were viewed as primary factors influencing the likelihood of persistence. The proximity to development and roads, intensity of agricultural practices, and levels of cave visitation represent the greatest threats to *S. morrisoni* populations (Table 8).

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1 Introduction

This Species Status Assessment (SSA) summarizes the ecological needs and extinction risk for three species of subterranean aquatic amphipods in Virginia and West Virginia: Cooper's cave amphipod (*Stygobromus cooperi*), Minute cave amphipod (*Stygobromus parvus*), and Morrison's cave amphipod (*Stygobromus morrisoni*). All analyses follow the SSA framework, focusing on the conservation biology principles of resilience, redundancy, and representation as they apply to the species' ecology (section 2), current conditions (section 3), and future conditions (section 4). Additional details on the SSA Framework can be found in USFWS (2016, entire) and Smith *et al.* (2018, entire).

The U.S. Fish and Wildlife Service (Service) is responsible for identifying those species in need of protection under the Endangered Species Act of 1973, as amended (ESA). The Service was petitioned to list 404 aquatic, riparian, and wetland species, including the three cave amphipod species, as endangered or threatened under the ESA on April 20, 2010 by the Center for Biological Diversity, Alabama River Alliance, Clinch Coalition, Dogwood Alliance, Gulf Restoration Network, Tennessee Forests Council, West Virginia Highlands Conservancy, Tierra Curry, and Noah Greenwald. In September 2011 the Service found that the petition presented substantial scientific or commercial information indicating the listing of these three species may be warranted (76 FR 59836-59862). The Service will make a determination on whether these three *Stygobromus spp.* warrant protections under the ESA, and this report serves as a compilation of the best available information on the species' biological status in support of these decisions. Importantly, any decisions regarding the legal classification of these species will be made separately, after reviewing this document and all relevant laws, regulations, and policies. The results of the decisions will be announced in the Federal Register, with appropriate opportunities for public input.

1.1 Species taxonomy

All three species in the present assessment are groundwater crustaceans in the genus *Stygobromus*, with *S. cooperi* and *S. morrisoni* belonging to the *emarginatus* group and *S. parvus* belonging to the *ephemerus* group (Holsinger 1967, pp. 28-33; 1969, pp. 22-25; 1978, pp. 8, 20, 46). The recognized taxonomy is shown in Table 1. These species all have morphological characteristics typical of subterranean species, including lack of eyes and body pigmentation. Species identification requires assessment of morphometrics under microscope by trained professionals (*e.g.*, relative size of appendages, number of spines or setae). Detailed descriptions of the distinguishing characteristics for each species can be found in Holsinger (1978, pp. 8, 20, 46) and references therein.

It has been suggested that the northern-most occurrence of *S. morrisoni* in Dyers Cave in West Virginia may represent a distinct species or sub-species (Holsinger 1978, p. 10; Fong *et al.*

2007, p. 80), as this locality occurs in a region of karst that is disjunct from the remainder of the species' known range (Figure 2). Similarly, *S. morrisoni* individuals collected from Mountain Grove Saltpetre Cave in Virginia display morphological differences from other localities that warrant further genetic study (see Elicitation Record, p. 45). Cryptic diversity is likely widespread in groundwater amphipods due to strong morphological similarities of species occupying subterranean habitats (e.g., Trontelj *et al.* 2009, entire). Genetic studies are required to better delineate taxonomic boundaries within these species; however, in the absence of such data the present assessment follows recognized taxonomy based on morphology and assumes all *S. morrisoni* localities represent a single species. Future assessments should carefully consider new genetic data as they become available.

Table 1. Taxonomy for three *Stygobromus* spp. based on Holsinger (1978, pp. 8, 20, 46) and references therein.

Taxonomic Level	Cooper's cave amphipod	Minute cave amphipod	Morrison's cave amphipod
Kingdom	Animalia	Animalia	Animalia
Phylum	Arthropoda	Arthropoda	Arthropoda
Class	Malacostraca	Malacostraca	Malacostraca
Order	Amphipoda	Amphipoda	Amphipoda
Family	Crangonyctidae	Crangonyctidae	Crangonyctidae
Genus	<i>Stygobromus</i>	<i>Stygobromus</i>	<i>Stygobromus</i>
Group	emarginatus	ephemerus	emarginatus
Species	<i>Stygobromus cooperi</i>	<i>Stygobromus parvus</i>	<i>Stygobromus morrisoni</i>

1.2 Overview of analysis

Available data include amphipod occurrences that cannot be reliably used to infer current population condition, or temporal trends in population size and extent of the occupied range. Due to this uncertainty, an expert knowledge elicitation (EKE) workshop was organized to obtain a balanced scientific assessment of how populations of these three *Stygobromus* spp. may respond to current and projected levels of major stressors.

These *Stygobromus* spp. were assessed using a common analysis and combined into a single SSA report because all three species are distributed in the same region, are highly specialized for subterranean habitats within karstic areas, face common threats to persistence, have similar data availability, and are on similar ESA assessment timelines. Additional details on the similarities and differences between species (e.g., differences in microhabitat use) are provided in section 2 *Ecological Needs*. While a common elicitation framework and expert panel

was used, all expert judgments, analyses, and results discussed below were applied to each species individually and species were not assumed to have similar responses to major stressors.

2 Ecological Needs

All three species are highly specialized for subterranean karst habitat characterized by relatively stable physiochemical conditions compared to surface environments (Culver and Pipan 2019, p. 3) and limited or patchily distributed food resources (Gibert and Deharveng 2002, p. 479). Due to the absence of light and primary producers in subterranean environments, many stygobionts (*i.e.*, organisms living in groundwater habitats) are detritivores or omnivores that rely on organic matter inputs from the surface (Gibert and Deharveng 2002, pp. 478-479). While stygobionts are commonly thought to be K-selected species characterized by delayed maturity, small population size, and low reproductive rates (Dickson and Holsinger 1981, p. 2), specific demographic and life history parameters for *S. parvus*, *S. cooperi*, and *S. morrisoni* are generally unavailable. Known life history and habitat characteristics are summarized in Table 2, many of which have been assumed based on closely related taxa.

Table 2. Life history and habitat characteristics of three *Stygobromus* species.

Life History Element	<i>S. parvus</i>	<i>S. cooperi</i>	<i>S. morrisoni</i>	References
Max lifespan (years)	8–10	8–10	8–10	(Assumed; Dickson and Holsinger 1981, p. 41)
Age at maturity (years)	1	1	1	Assumed; Fasulo (2005)
Length at maturity (mm)		2.3	2.3	(Holsinger 1978, p. 6)
Max length (mm)	3.0 (male) 4.2 (female)	6.0	6.0 (male) 8.0 (female)	(Holsinger 1978, pp. 9, 20; Lewis 2001, p. 4)
Gestation (weeks)	1–3	1–3	1–3	Assumed
Habitat	epikarst; mud-bottom, drip, and seep pools	epikarst; drip pools	small gravel-bottom stream; mud-bottom lake	(Holsinger 1978, pp. 10, 42; Pipan <i>et al.</i> 2010, p. 749)

While all three species can be considered groundwater habitat specialists, important differences in microhabitat use may impact species' vulnerability to common threats. *Stygobromus parvus* and *S. cooperi* are epikarstic species, predominantly occupying water percolating through the uppermost layer of karst at the rock-soil interface. This perched aquifer occurs in the vadose zone, or the area above the permanent groundwater table (Pipan and Culver 2007b, p. 265; 2013, entire). Because epikarst occurs just below the surface, these habitats are often characterized by greater organic matter inputs and environmental variation compared to deeper subterranean habitats (Culver *et al.* 2010, pp. 68-69) and are likely more susceptible to environmental degradation on the surface (Pipan *et al.* 2010, entire). While *S. parvus* and *S. cooperi* are often collected in drip pools within caves, these areas may not represent primary habitat and are likely operating as sink populations that are highly dependent on immigration

from the epikarst (Pipan *et al.* 2010, entire). There is greater uncertainty around the microhabitat use of *S. morrisoni*. Several experts involved in the EKE assumed *S. morrisoni* is primarily a stream species based on known collection sites (Table 2) and because cave stream specialists tend to have larger body sizes compared to epikarst species (e.g., Culver *et al.* 2010, p. 70); however, all experts agreed additional research is needed on specific habitat requirements for this species. While the potential threats to persistence are similar across all three species and can be described by a common conceptual model (Figure 1), the relative impacts of various stressors may differ between both microhabitats and species. Therefore, expert judgments were provided separately for each species (see Section 4 – Future Conditions).

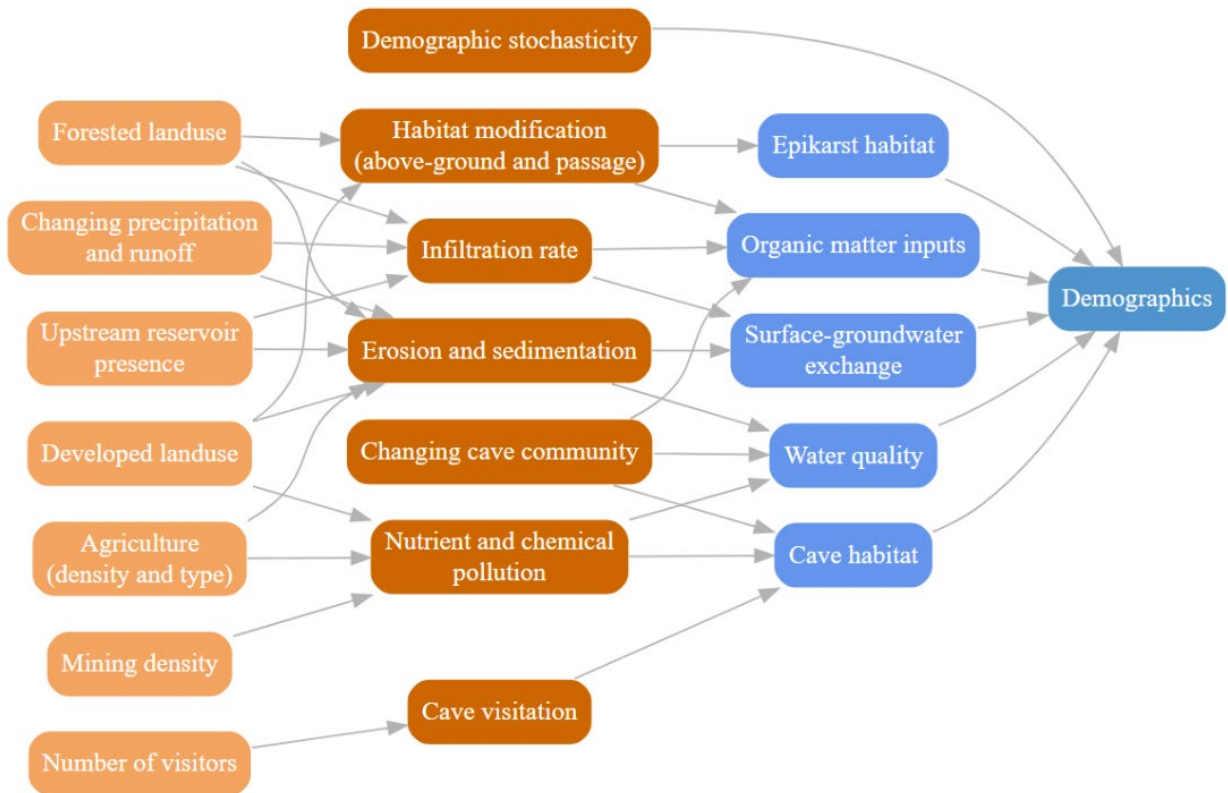


Figure 1. Conceptual model of factors impacting species viability, with ecological needs shown in light blue and stressors and stressor proxies shown in dark orange and light orange, respectively.

3 Current Conditions

3.1 Distribution

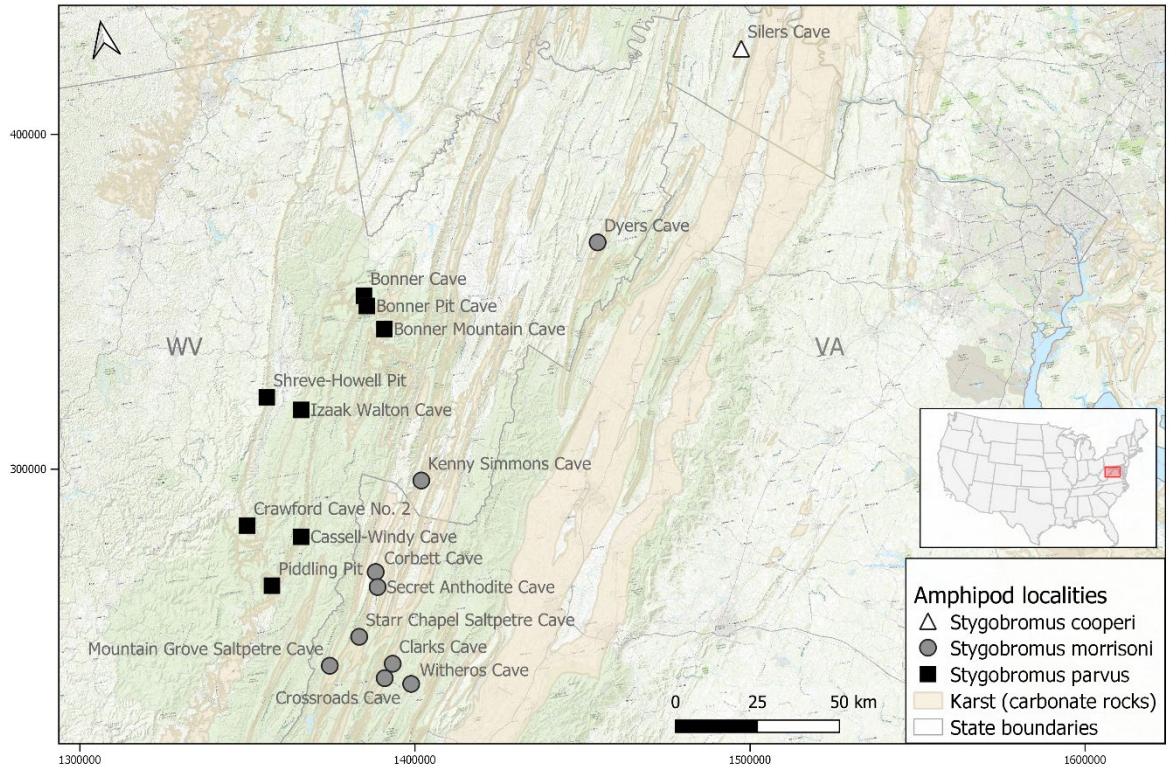


Figure 2. Known localities for three *Stygobromus* spp. in relation to exposed karst regions.

The three species of *Stygobromus* being considered are restricted to portions of Virginia and West Virginia (Figure 2; Lewis 2001, entire; Fong *et al.* 2007, pp. 79-84; Holsinger *et al.* 2013, pp. 44-45), with an extent of occurrence of 1,467 square kilometers (km²) for *S. parvus* and 2,266 km² for *S. morrisoni*. Extent of occurrence was estimated as the minimum convex hull around known localities (i.e., minimum perimeter). *Stygobromus cooperi* is a single site endemic with an extremely limited distribution, occurring in a region with only 27 km² of exposed karst isolated from other karst formations. Sampling of stygobionts is generally limited and fine-scale distributions of all three species are uncertain; however, Christman *et al.* (2016, entire) compiled over 11,000 records of cave species spanning the Appalachian region and found no records of these three species in caves outside of WV or VA. Data from European stygobionts suggest that species ranges > 200 km are extremely rare (Trontelj *et al.* 2009, entire) and nearly half (44%) of US species are known from a single county (Culver *et al.* 2000, p. 391). This suggests that the known localities provide a reasonable estimate of the species' extent and that *S. parvus* and *S. morrisoni* may occupy a large range relative to other stygobionts (although still highly restricted).

3.2 Population structure – resilience and redundancy

No direct data is available to estimate population size or structure of the three focal species, making current population- and species-level resilience unknown. Surveys for these species are frequently conducted opportunistically, or as part of reviews documenting broad patterns of diversity in cave species through previously published records, museum specimens, and natural heritage databases (Fong *et al.* 2007, entire; Holsinger *et al.* 2013, entire). Details on sampling effort and the number of individuals collected are frequently unavailable (Table 3), and no studies have estimated abundances using established quantitative methods for sampling epikarst (Pipan *et al.* 2010, pp. 749-750).

Stygobromus cooperi is known from only three specimens in a single location of isolated karst (Figure 2, Table 3), and discussions during the EKE suggest this species is consistently encountered at low densities (see Elicitation Record, p. 32). Holsinger (1978, p. 10) stated that additional populations of *S. morrisoni* likely remain to be discovered between presently known localities; yet, simultaneously expressed uncertainty whether disjunct northern localities represent a distinct species or subspecies. Mark-recapture studies of the closely related *S. emarginatus* (a non-focal species) in a 350-meter (m) stream section in Organ Cave, WV revealed densities around 10/m and a population estimate around 3,500, suggesting that not all range-restricted stygobionts are numerically rare (Knapp and Fong 1999, entire).

Because data on genetic connectivity between localities are not available, this report assumes that each locality represents a distinct meta-population (Table 3), with *S. morrisoni* currently known from 9 localities, *S. cooperi* from a single locality, and *S. parvus* from 8 localities. Data from epikarst copepods that occupy similar habitats suggest that populations generally extend less than 1km along a cave passage (Pipan and Culver 2007a, pp. 819-820) and genetic differentiation or meta-population structure can be detectable at scales as small as tens of meters (Sbordoni *et al.* 2000, entire). The minimum nearest neighbor distance between known localities was 3.1 km and 4.3 km for *S. parvus* and *S. morrisoni*, respectively, but values ranged up to 88 km. It is important to note that karst areas between known localities have not been adequately sampled and the true extent of each meta-population is a major source of uncertainty, impacting estimates of the number of populations, the potential for genetic connectivity between localities, and our understanding of both current representation and redundancy for these species.

Table 3. Known localities with available collection and site information.

Species	Representative Unit	Locality	Number ⁺	Year	Ownership [†]	Reference [*]
<i>S. morrisoni</i>	Northern	Dyers Cave	1	1966	Private	Holsinger (1978); Fong <i>et al.</i> (2007); WVDNR
			6	2006		
	Eastern	Witheros Cave	14	1967	Private	Holsinger <i>et al.</i> (2013) T. Malabad (2020) <i>pers. com.</i>
			20	2014		
Central	Crossroads Cave	2	2014	NGO	Holsinger <i>et al.</i> (2013); T. Malabad (2020) <i>pers. com.</i> Holsinger <i>et al.</i> (2013)	
	Clarks Cave			Private		

Species	Representative Unit	Locality	Number ⁺	Year	Ownership [†]	Reference [*]
	Western	Starr Chapel Saltpetre Cave			Federal	Holsinger et al. (2013)
		Mountain Grove Saltpetre Cave	1	2000	Federal	Holsinger et al. (2013); T. Malabad (2020) <i>pers. com.</i>
		Corbett Cave			Private	Holsinger et al. (2013)
		Secret Anthodite Cave			Private	Holsinger et al. (2013)
		Kenny Simmons Cave	1	1966	Private	Fong et al. (2007); Holsinger (1978)
<i>S. cooperi</i>	Single site endemic	Silers Cave	2	1967	Private/NGO	Fong et al. (2007); Pipan et al. (2010)
			1	2006		
<i>S. parvus</i>	Eastern	Bonner Cave	12	1992	Private	Fong et al. (2007); WVDNR
		Bonner Mountain Cave			Private	Fong et al. (2007)
		Bonner Pit Cave	12	1992	Private	Feller (1992) unpublished; Lewis (2001)
		Cassell-Windy Cave	1	1969	Private	Fong et al. (2007); Lewis (2001)
		Piddling Pit	4	1972	NGO	Fong et al. (2007);
			4	1990		WVNR
				2005		
	Central	Izaak Walton Cave	2	2005	NGO	Fong et al. (2007); WVDNR
	Western	Crawford Cave No. 2		1969	Private	Fong et al. (2007); Lewis (2001)
		Shreve-Howell Pit	2	2001	Corporation	Fong et al. (2007); WVDNR

⁺Number of individuals collected or observed

[†]NGO refers to non-governmental organization, including non-profit conservation, caving, or hunting and fishing groups

^{*}Page numbers excluded from table for brevity, please see text for complete references.

3.3 Representative units

Stygobromus cooperi is a single site endemic with inherently low representation. While the extent of the meta-population is unknown, the immediate region contains only 27 km² of exposed karst that is likely isolated from other nearby karst formations, suggesting that the ability to adapt to environmental changes through dispersal is limited. The amount of genetic diversity is unknown, but it is worth noting that the emarginatus group that contains *S. cooperi* and *S. parvus* is characterized by very little morphological diversity (Holsinger 1978, p. 6). *Stygobromus morrisoni* populations all occur within Siluro-Devonian karst, but discussions with the expert panel suggested that the eastern, central, and western belts may form meaningful representative units based on low probability of dispersal between these regions (Figure 3). The northern most population occurs in a separate Siluro-Devonian karst belt. *Stygobromus parvus* populations all occur within a contiguous region of karst formed within the Mississippian Greenbrier outcrop, but can similarly be described as occupying an eastern, central, and western belt (Figure 3). It is important to note that all three species occur in highly specialized habitat

within a small geographic area, suggesting that potential to adapt to regional changes in climate or other similarly broad threats may be limited.

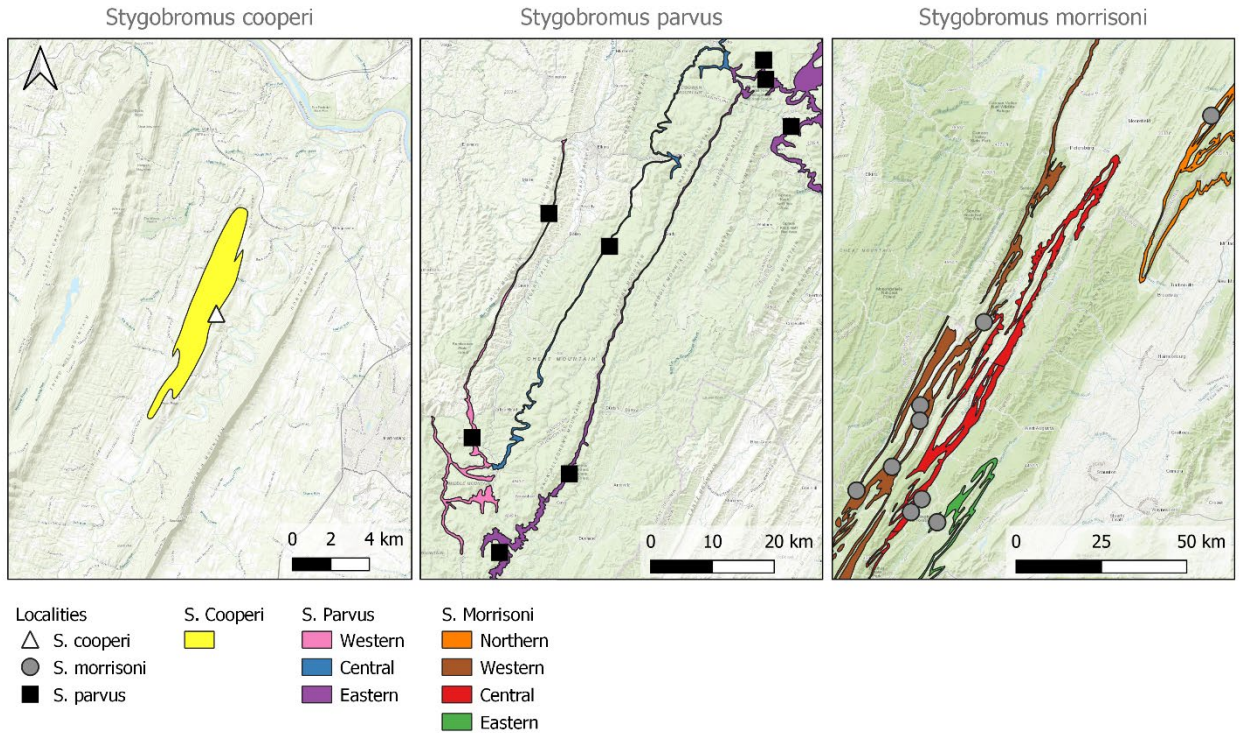


Figure 3. Representative units for three *Stygobromus* spp. Units are based on the orientation and connections between exposed karst regions from the Weary and Doctor (2014) US karst map. Please note that not all karst areas are shown in order to highlight representative units.

3.4 Threats to species persistence

The broad categories of threats to cave and karst biota are well documented, and include high sensitivity to groundwater contamination by sediments and toxic compounds, disruption of food supply due to deforestation, and direct modification of habitats and hydrology due to cave visitation and urban development of karst areas (e.g., Culver *et al.* 2000, pp. 387, 392-396; Pipan *et al.* 2010, entire). See Figure 1 for conceptual diagram. For example, *Stygobromus mackini* (a closely related non-focal species) have shown occurrence patterns consistent with negative impacts of groundwater pollution by septic systems in Banner Cave, VA (Simon and Buikema 1997, entire) and toxic pollutant spills represent one of the primary threats to many karst species (Loop and White 2001, entire; Pipan *et al.* 2010, entire). Elsewhere in the United States, low dissolved oxygen as a result of microbial breakdown of organic matter from wastewater contamination was implicated in the extirpation of the Illinois cave amphipod from a previously occupied cave stream system (Panno *et al.* 2006).

Pumping of groundwater aquifers and wells to support development and other land uses (e.g., agriculture) can alter the natural flow and can reduce the flows to cave and karst conduits (Baker and Genty 1998) on which stygobionts depend. For example, aquifer overuse is a primary threat to the Peck's Cave amphipod in Texas (Elliott 2000). Data and information are lacking to indicate water quantity threatens *S. cooperi*, *S. parvus*, or *S. morrisoni*.

Agricultural practices that involve clearing natural vegetation, either for crop cultivation or through grazing by domesticated herd animals, disturb natural vegetation cover and can alter water budgets in karst systems. Tillage disturbs soils, leading to greater rates of erosion and subsequent increases in sediment moving into the subsurface. Agricultural chemicals such as fertilizers, herbicides and insecticides that are spread on karst lands infiltrate into epikarst and subsequently into underlying karst aquifers. Additionally, animal waste products enter karst hydrological systems and artificially alter subterranean nutrient balances and contribute to contamination (Earle 2021). Overall data and information are lacking to indicate agricultural practices threaten *S. cooperi*, *S. parvus*, or *S. morrisoni*.

Cave visitation by humans causes degradation of cave ecosystems (Buchanan et al. 2022). Development and expansion of trails in caves, damage to cave surfaces, and repeated foot traffic cause sediment compaction, which can alter or destroy cave niches and prevent proper mineral deposition (Toomey 2009). Data and information are not available to indicate cave visitation threatens *S. cooperi*, *S. parvus*, or *S. morrisoni*.

An analysis of the current threats to each population was conducted as part of the expert elicitation process, and is described in detail in sections 4.1 – Methods – Expert Knowledge Elicitation and 7.1 – Site narratives used in EKE workshop. The magnitude of various stressors that *Stygobromus* populations can withstand, however, represents a critical source of uncertainty in the assessment process. Data from the Edwards Aquifer region of TX suggest that the 10–15% impervious cover threshold for degradation of biological communities in surface waters (Paul and Meyer 2001, entire; Walsh *et al.* 2005, entire; Schueler *et al.* 2009, entire) represents a reasonable starting point for estimating impacts to subterranean species in the absence of site- or karst-specific information (Veni 1999, entire). Similar estimates for how the other stressors identified in Figure 1 may impact *Stygobromus* species (spp.) resilience are lacking.

The appropriate spatial extent in which to consider threats to population resilience represents another major source of uncertainty. We are not aware of direct dye-tracing studies from the identified caves that could aid delineation of groundwater basins and potential influence zones. While the boundaries of groundwater basins frequently deviate from surface basins, impacts to surface waters in karst areas also impact groundwater quality. For example, cave streams in WV show elevated nitrate and pesticide levels in agricultural areas (Boyer and Pasquarell 1995; Pasquarell and Boyer 1996). Protection of surface areas is critical for the conservation of subterranean fauna, particularly for epikarst specialists such as *S. parvus* and *S. cooperi* (Culver *et al.* 2000, pp. 387, 392-396; Pipan *et al.* 2010, entire).

The uncertainties listed above severely limit our ability to estimate the relative impacts of various threats on species' conditions using an empirical approach. Because the SSA framework seeks to characterize the current and future conditions by explicitly considering species' responses to potential stressors (Smith *et al.* 2018, entire) and few empirical data are available on

species' historical or current condition, this assessment must rely on expert knowledge to evaluate uncertainty in how threats may impact populations of these three *Stygobromus* spp.

4 Future Conditions

4.1 Methods – Expert Knowledge Elicitation

Due to the limited data available to assess species' current conditions, an expert knowledge elicitation (EKE) workshop was used to estimate the uncertainty in species' future viability. While it is always preferable to use empirical data for extinction risk assessments (e.g., Smith *et al.* 2018, pp. 307-308), many at-risk species lack sufficient demographic data for traditional assessment methods and alternative approaches are required to provide timely support for conservation decision making. The use of structured protocols to elicit expert knowledge in support of conservation and management decisions is rapidly increasing (Martin *et al.* 2012, entire; Drescher *et al.* 2013, entire), including recent applications towards assessing extinction risk of birds (McBride *et al.* 2012, entire) and koalas (Adams-Hosking *et al.* 2016, entire), among others. While several protocols exist for eliciting and combining expert judgments in a scientifically rigorous and transparent manner, all contain methods for capturing uncertainty within individual judgments, recording differences of opinion between experts, and minimizing the influence of common cognitive biases (O'Hagan 2019, entire). This analysis uses the Sheffield Elicitation Framework (SHELF), which differs from other leading protocols in its behavioral approach to synthesizing individual expert judgments into a fully specified probability distribution for an unknown quantity of interest (Gosling 2018, entire; O'Hagan 2019, pp. 73-81; Oakley and O'Hagan 2019, entire).

A critical step in an EKE is identifying and recruiting the appropriate expert panel, which typically contains between 4–8 participants in the SHELF protocol (O'Hagan 2019, p. 74). The use of multiple experts provides decision makers with a diversity of perspectives and helps reduce the risk of overconfidence in judgments by any single expert. Potential experts were identified based on a combination of past experience sampling the species, peer-reviewed publications on the ecology and biogeography of the genus *Stygobromus*, and demonstrated experience with conservation and management of cave and karst biota. Out of fourteen experts initially contacted, seven were available for full participation (Table 4). The expert panel included both regional and international experts on *Stygobromus* spp., as well as the geology, hydrology, and management of karst habitats more generally. Several of the experts (D. Fong, D. Culver, W. Orndorff) are co-authors on the authoritative references on the cave and karst fauna of Virginia and West Virginia (Fong *et al.* 2007, entire; Holsinger *et al.* 2013, entire). All panelists have extensive experience with cave biota and karst ecosystems in the central Appalachians, and most have direct experience sampling the specific localities considered in this assessment. Experts were provided training in quantifying personal beliefs using materials provided with the SHELF protocol (Oakley and O'Hagan 2019, entire), and practiced using an example quantity of interest (the probability that the maximum age of *S. cooperi* is greater than 6 years) before providing judgments in support of this SSA.

Table 4. Expert panelists involved in elicitation workshop. Please see Elicitation Record, pp. 2-3 for full credentials and declarations of interests.

Expert	Affiliation
Dr. David Culver	Professor Emeritus of Environmental Science, American University
Dr. Matthew Niemiller	Assistant Professor of Ecology, University of Alabama Huntsville
Wil Orndorff	Karst Protection Coordinator, Virginia Department of Conservation and Recreation
Dr. Daniel Fong	Associate Professor of Biology, American University
Daniel Nolfi	Karst Species Expert, U.S. Fish and Wildlife Service, Chubbuck, ID
Daniel Feller	Western Regional Ecologist, Maryland Department of Natural Resources
Jeff Hajenga	Wildlife Biologist II, Cave and Karst Project Leader, West Virginia Division of Natural Resources

Data are available to estimate levels of several major threats using proxy variables (Table 5), with the missing quantities of interest being species’ responses to various stressor levels. Experts discussed multiple approaches for structuring the elicited quantity and determined that estimating the probability of persistence based on the empirical habitat conditions for each locality was most tractable. Specifically, future conditions were assessed as the probability of persistence of each meta-population (*i.e.*, locality) over four generations (roughly 10–20 years). The use of four generations reflects standard practices in extinction risk assessments while accounting for uncertainty in generation length. For example, several of the criteria for the International Union for the Conservation of Nature’s Red List of Threatened Species assess changes over the longer of 10 years or three generations (IUCN 2019, entire). Because so little is known about current population conditions, no attempt was made to further classify a populations’ future status beyond persistence or extirpation. While persistence alone is not sufficient to consider a species viable, it is important to note that expert judgments on the probability of persistence implicitly consider viability. In addition to reflecting the magnitude of threats, a higher probability of persistence over time may reflect an expectation of increased current viability compared to lower probabilities of persistence.

Table 5. Quantification of stressor proxies for expert knowledge elicitation

Stressor Proxy	Measure	Stressors	Data source
Developed land use	% in upstream watershed	Habitat modification Erosion and sedimentation	(Hill <i>et al.</i> 2016; NLCD 2016; Sohl <i>et al.</i> 2018, all sources entire)
Agricultural land use (crop or pasture)	% in upstream watershed	Nutrient and chemical pollution Erosion and sedimentation	(Hill <i>et al.</i> 2016; NLCD 2016; Sohl <i>et al.</i> 2018, all sources entire)
Animal agriculture	# of animal feeding operations (per county)	Nutrient and chemical pollution Erosion and sedimentation	(Hill <i>et al.</i> 2016, entire)
Dams/reservoirs	# dams in upstream watershed	Groundwater infiltration rate Erosion and sedimentation	(USACE 2020, entire)

Stressor Proxy	Measure	Stressors	Data source
Changing precipitation	Change in annual average for region	Groundwater infiltration rate Erosion and sedimentation	(Abatzoglou 2013, entire)
Mining density	# mines in upstream watershed	Nutrient and chemical pollution	(EIA 2020, entire)
Oil and gas proximity	Within/outside of shale play	Nutrient and chemical pollution	(EIA 2020, entire)
TMDL or 303(d) status	Impaired streams in watershed	Nutrient and chemical pollution	(EPA 2020, entire)
	Qualitative, as available	Cave visitation	Expert discussion
	Qualitative, as available	Changing cave community	Expert discussion
	Qualitative, as available	Cave management/ownership	Expert discussion

An evidence dossier compiling available information on historical and current conditions, as well as individual site narratives providing visual and numeric summaries of past, current, and projected stressor proxies, were used as the basis for expert judgements. Information on threat proxies was displayed at several spatial scales due to experts' beliefs that the appropriate scale depends on the specific threat being assessed (see section 7.1 – Site narratives used in EKE). At the smallest spatial extent, the catchment area of individual epikarst drips are generally less than a few hundred square meters (Pipan and Culver 2013, p. 216). Therefore, a 1 km² closeup of each locality showing aerial imagery from 2019 (US National Agriculture Imagery Program) was used for assessing current land use in the immediate vicinity. Based on data from epikarst copepods (Pipan *et al.* 2010, p. 753), a 1 km buffer around sampling localities was assumed to represent the potential area occupied by each meta-population. Local catchments intersecting this buffer and their upstream watersheds represent other potentially relevant scales, as surface water can act as a vector for contaminants moving both downstream and laterally through karst environments. Aerial imagery was shown at the local catchment scale. Land-use statistics were quantified at the upstream watershed scale in 2006 and 2016 based on National Landcover Data (NLCD 2016, entire) and projected to 2030 based on the Intergovernmental Panel on Climate Change emission scenarios A1B, A2, B1, and B2 (Sohl *et al.* 2018, entire). Descriptions of the four emissions scenarios considered are provided in Table 6. Experts were also provided regional land-use projections out to 2040 due to uncertainty in generation time (*e.g.*, Figure 4), as well as regional projections in precipitation based on multiple climate models (Abatzoglou 2013, entire). Surface catchments were defined based on the US National Hydrography Plus (NHDPlus Version 2) dataset. The largest spatial extent provided a 2016 land-use model (NLCD 2016, entire) and the locations of mining operations (EIA 2020, entire), dams (USACE 2020, entire), and impaired surface waters (EPA 2020, entire) at least 10 km away from known localities due to high uncertainty in subsurface movement of water through karst environments and the possibility for meta-population dynamics between surrounding karst regions not directly sampled.

Table 6. Intergovernmental Panel on Climate Change emission scenario descriptions. Scenarios were used as the basis for land use projections, which in turn informed expert judgements on species' probabilities of persistence.

Scenario	Description
A1B	A future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The major underlying theme is convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. This scenario represents a balance across fossil-fuel intensive and non-fossil energy sources.
A2	A very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than other scenarios.
B1	A convergent world with the same global population trend as A1B, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
B2	A world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in B1 and A1B. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

The elicitation workshop was carried out remotely using a series of 2-hour video conferencing calls (8 hours total) between June 9 and July 2, 2020. For each locality, experts were first provided a summary of the current conditions and threats assessment to reduce the availability bias. During the individual judgment round, experts provided private judgments for the probability that the meta-population surrounding the locality would persist over 4 generations using the quartile method. This approach begins by specifying an upper and lower plausible limit to counter overconfidence and anchoring effects (O'Hagan 2019, p. 75). The median value is then estimated by dividing the plausible limits into two equally probable parts following the bisection method (Raiffa 1968, pp. 161-168). This bisection procedure is then repeated to specify an upper quartile and lower quartile using the previously specified median value and plausible limits. Judgments were submitted via an online form and probability distributions were fit by minimizing the sum of squared differences between elicited and fitted probabilities along the cumulative distribution function using the SHELF package in R (Oakley 2019, entire). Certain populations were assessed simultaneously due to similarities in observed land use identified through k-means clustering and their geographic proximity within connected regions of karst (*e.g.*, Bonner Mountain Cave and Bonner Pit Cave).

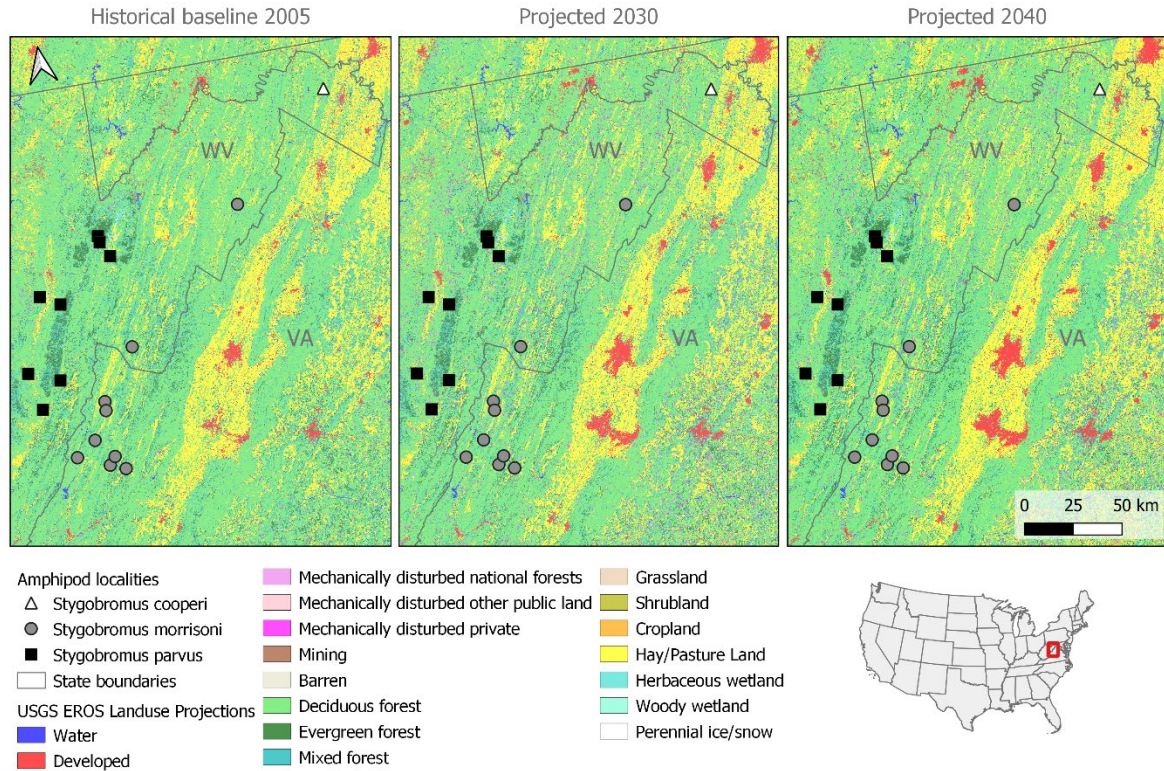


Figure 4. Regional land use projections under the A1B emissions scenario based on Sohl et al. (2018, entire). During the EKE, experts were provided summaries of the A1B, A2, B1, and B2 land use projections within the upstream watersheds of each locality.

Experts were then led through a facilitated group discussion where they provided the reasoning for their judgments, including which stressors were of greatest concern and which factors generated the most uncertainty. During the group judgment round, experts were asked to provide new quartiles from the perspective of a Rational Impartial Observer (RIO) who had listened to the group discussion and understood their arguments (O'Hagan 2019, pp. 77-78). Due to concerns over potential dominance or halo effects within the group (*i.e.*, a tendency to conform to beliefs of a dominant or senior expert) combined with the remote nature of the workshop, each expert privately provided a RIO judgment using the same procedure described above, which were then used to facilitate selection of the final RIO quartiles. This slight modification of the SHELF protocol required each expert to provide twice as many judgments, but ensured that no single expert dominated selection of the group quartiles. Finally, a scaled beta probability distribution was fit to the final RIO judgments to represent the collective uncertainty in the probability of persistence.

4.2 Results – Probability of Population Persistence

A detailed description of the entire EKE is provided in the supplemental Elicitation Record. A summary of the main results is presented here, including individual judgements, final group distributions, and highlights from the group discussion round for each quantity of interest.

The experts had low confidence in persistence for the single *S. cooperi* population, reflected by both the low median value (Table 7) and large degree of uncertainty in estimates (Figure 5). The low confidence in persistence stemmed from the high number of developed areas within the region and an anticipated increase in visitation rates due to recent changes in cave ownership (Table 8). The geologic characteristics of this locality constrain the potential area the metapopulation could occupy, resulting in a high risk of extirpation from stochastic events. While population estimates are not available, sampling experience suggests *S. cooperi* is consistently collected at lower densities than other *Stygobromus* spp. in the region and that even moderate increases in threats could have severe consequences for the population (Elicitation Record, p. 32). The higher median probability of persistence provided by expert F (Figure 5) reflects experience from other regions where epikarst *Stygobromus* spp. were among the last taxa to persist in impacted caves; however, all experts agreed that this locality had the lowest probability of persistence among assessed caves as reflected by the lower 90% credible interval of 0.19 for the final group judgment.

Table 7. Summary statistics for the probability of persistence for the meta-population surrounding each locality. See Figures 2–4 for complete distributions and individual expert judgments. Confidence in persistence was classified based on the $P(x > 0.5)$ as follows: very low < 0.5 , low $0.5 - 0.7$, medium $0.7 - 0.9$, high > 0.9 . CI stands for Credible Interval.

Species	Representative Unit	Localities	Median	90% CI	$P(x > 0.5)$	Confidence in persistence
<i>S. cooperi</i>	Single site	Silers Cave	0.48	0.19 – 0.77	0.47	Very low
<i>S. morrisoni</i>	Northern	Dyers Cave	0.60	0.33 – 0.83	0.71	Medium
		Witheros Cave	0.76	0.46 – 0.95	0.92	High
		Central	Clarks Cave	0.55	0.27 – 0.78	0.61
	Western	Crossroads Cave	0.60	0.35 – 0.83	0.74	Medium
		Kenny Simmons Cave	0.47	0.21 – 0.71	0.44	Very low
		Corbett Cave	0.67	0.37 – 0.90	0.81	Medium
		Secret Anthodite Cave	0.67	0.37 – 0.90	0.81	Medium
		Mountain Grove Saltpetre Cave	0.73	0.46 – 0.91	0.92	High
		Starr Chapel Saltpetre Cave	0.73	0.46 – 0.91	0.92	High
<i>S. parvus</i>	Eastern	Bonner Cave	0.76	0.48 – 0.94	0.93	High
		Bonner Mountain Cave	0.72	0.44 – 0.90	0.91	High
		Bonner Pit Cave	0.72	0.44 – 0.90	0.91	High
		Cassell-Windy Cave	0.73	0.37 – 0.96	0.85	Medium
		Piddling Pit	0.81	0.58 – 0.94	0.99	High
	Central	Izaak Walton Cave	0.78	0.49 – 0.94	0.95	High
	Western	Shreve-Howell Pit	0.67	0.34 – 0.91	0.78	Medium
		Crawford Cave No. 2	0.71	0.32 – 0.95	0.80	Medium

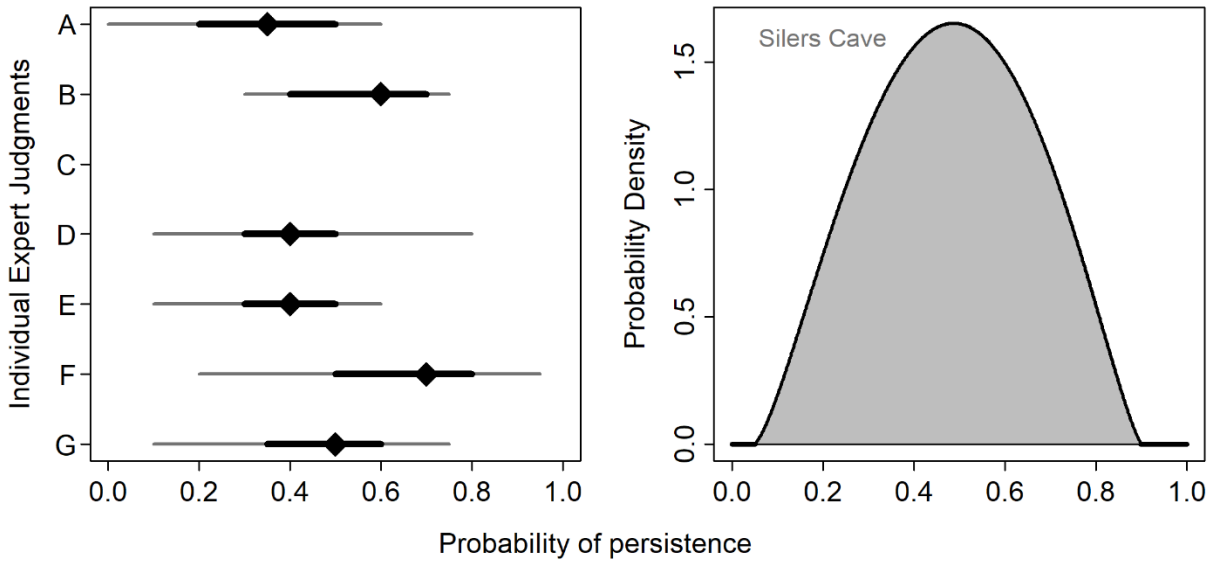


Figure 5. Expert judgments on the probability of persistence for the single known *S. cooperi* locality. The left panel shows individual expert judgments for the median (symbol), 50% credible interval (thick black line), and plausible limits (thin grey line). Right panel shows the final probability distribution from the group judgment round. Note that C was unable to provide judgments for this locality due to video conference connectivity issues, but agreed that the final distribution captures the risk and uncertainty for this locality.

The expected risk to persistence varied widely among localities for *S. morrisoni* (Table 7, Figure 6) based primarily on differences in land ownership and agricultural intensity. Expert judgments suggest that three out of the nine known localities could be characterized as having high confidence in persistence, while two localities face much greater risks to persistence (Table 7). For example, the estimates for both Mountain Grove and Starr Chapel Saltpetre Caves suggest these localities are likely to persist despite uncertainty in current conditions. The lack of information on historical conditions at these sites were assumed to reflect sampling deficiencies rather than the historic or current condition of the populations. In contrast, Kenny Simmons Cave had among the lowest confidence in persistence due to both the lack of available survey data and proximity to high intensity animal agriculture. Importantly, the projected risk is not distributed evenly across representative units for *S. morrisoni*, with three of the populations with the greatest risk comprising all known occurrences within the northern (Dyers Cave) and central karst belts (Clarks and Crossroads Caves). All three localities have high levels of uncertainty in persistence reflected by wide confidence intervals and median estimates of the probability of persistence between 0.55 and 0.6 (Table 7), suggesting a future risk of lost representation throughout the range.

Table 8. Primary factors identified for each locality as impacting expert judgments of risk and uncertainty.

Species	Localities	Primary factors
<i>S. cooperi</i>	Silers Cave	Proximity to development; projected increase in cave visitation; risk of stochastic events; demographic stochasticity from potentially low density
<i>S. morrisoni</i>	Dyers Cave	Proximity to highway and potential development; risk of stochastic pollutant spills from highway
	Kenny Simmons Cave	High intensity animal agriculture; low flow within cave suggests pollutants may concentrate; current status unknown
	Corbett Cave	Current status unknown; surface stream impairments suggest agricultural impacts; history of cave visitation
	Secret Anthodite Cave	Current status unknown; surface stream impairments suggest agricultural impacts
	Mountain Grove Saltpetre Cave	National Forest land ownership; low visitation due to gated cave; current status unknown
	Starr Chapel Saltpetre Cave	National Forest land ownership; low visitation due to gated cave; current status unknown
	Clarks Cave	High visitation rates; cave subject to flooding and surface contaminants; current status unknown
	Crossroads Cave	High current and projected visitation; proximity to road and risk of stochastic spills/runoff; potentially large catchment area in agricultural landscape
	Witheros Cave	Cave recently sampled; high current and projected forest cover; extent of meta-population unknown
<i>S. parvus</i>	Bonner Cave	High current and projected forest cover; extent of meta-population unknown
	Bonner Mountain Cave	High agricultural land use
	Bonner Pit Cave	High agricultural land use
	Shreve-Howell Pit	Logging; land ownership by private companies; proximity to development
	Izaak Walton Cave	High current and projected forest cover; land ownership by non-profit organization; logging
	Crawford Cave No. 2	Limestone mining; high agricultural land use
	Cassell-Windy Cave	High current and projected forest cover; current status unknown; proximity to impaired watershed
	Piddling Pit	Land ownership by conservation organization; history of occurrence; remote cave requiring permission to access

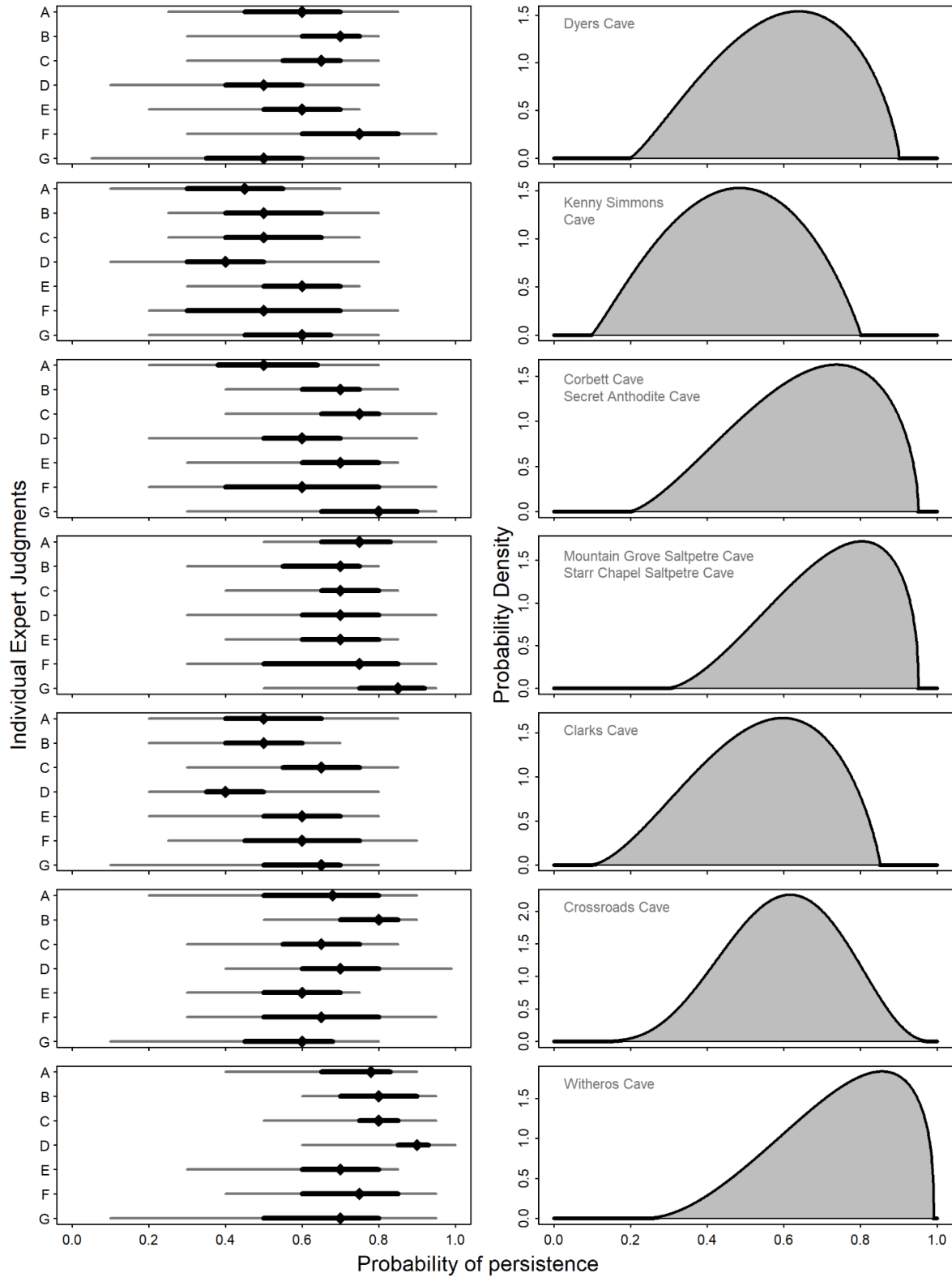


Figure 6. Expert judgments on the probability of persistence for *S. morrisoni* localities. The left panel shows individual expert judgments for the median (symbol), 50% credible interval (thick black line), and plausible limits (thin grey line). Right panel shows the final probability distributions from the group judgment round.

Expert judgments generally expressed high confidence in future persistence for *S. parvus* populations (Table 7, Figure 7). Indeed, the Piddling Pit meta-population has the highest confidence in persistence among any locality assessed, with 90% credible intervals ranging from 0.58 – 0.94 based primarily on land ownership by a conservation organization and restricted cave access. While several localities are surrounded by mostly intact forests, threats from agricultural land use and mining are present within the species' range and contribute to differences in uncertainty between localities. For example, the presence of past limestone mining and agriculture in the vicinity of Crawford Cave No. 2 led experts to judge that the probability of persistence could credibly be as low as 0.32 despite a high median value. Lower 90% credible intervals were similarly low for Shreve-Howell Pit and Cassell-Windy Cave. These uncertainties are critical to consider when assessing potential risk. Logging, mining, and agriculture have occurred in the region historically, and observations of the species within the last 30 years were taken as evidence that populations can persist amidst historical levels of disturbance. During group discussions, however, experts frequently pointed to differences in contemporary agricultural practices, such as the increase in large-scale poultry farming, the application of poultry manure as fertilizers, and use of industrial herbicides and pesticides. Other species in the genus *Stygobromus* have been negatively impacted by concentrated waste products in septic systems in VA (Simon and Buikema 1997, entire), and decreased certainty in estimates for several *S. parvus* populations reflected concern that similar effects could arise from increased animal agriculture. The possibility for emerging threats such as disease and an unknown likelihood of stochastic events also contributed to uncertainty in estimates and should be considered when assessing species' future viability.

The two localities with the lowest median values and lowest certainty (Crawford Cave No. 2 and Shreve Howell Pit) are the only known localities within the western representative unit for *S. parvus*, suggesting that the greatest risk for loss of future representation occurs within the western portion of the species range. While confidence in persistence for the Izaak Walton Cave population was high, this is the only known locality within the central representative unit (Figure 3).

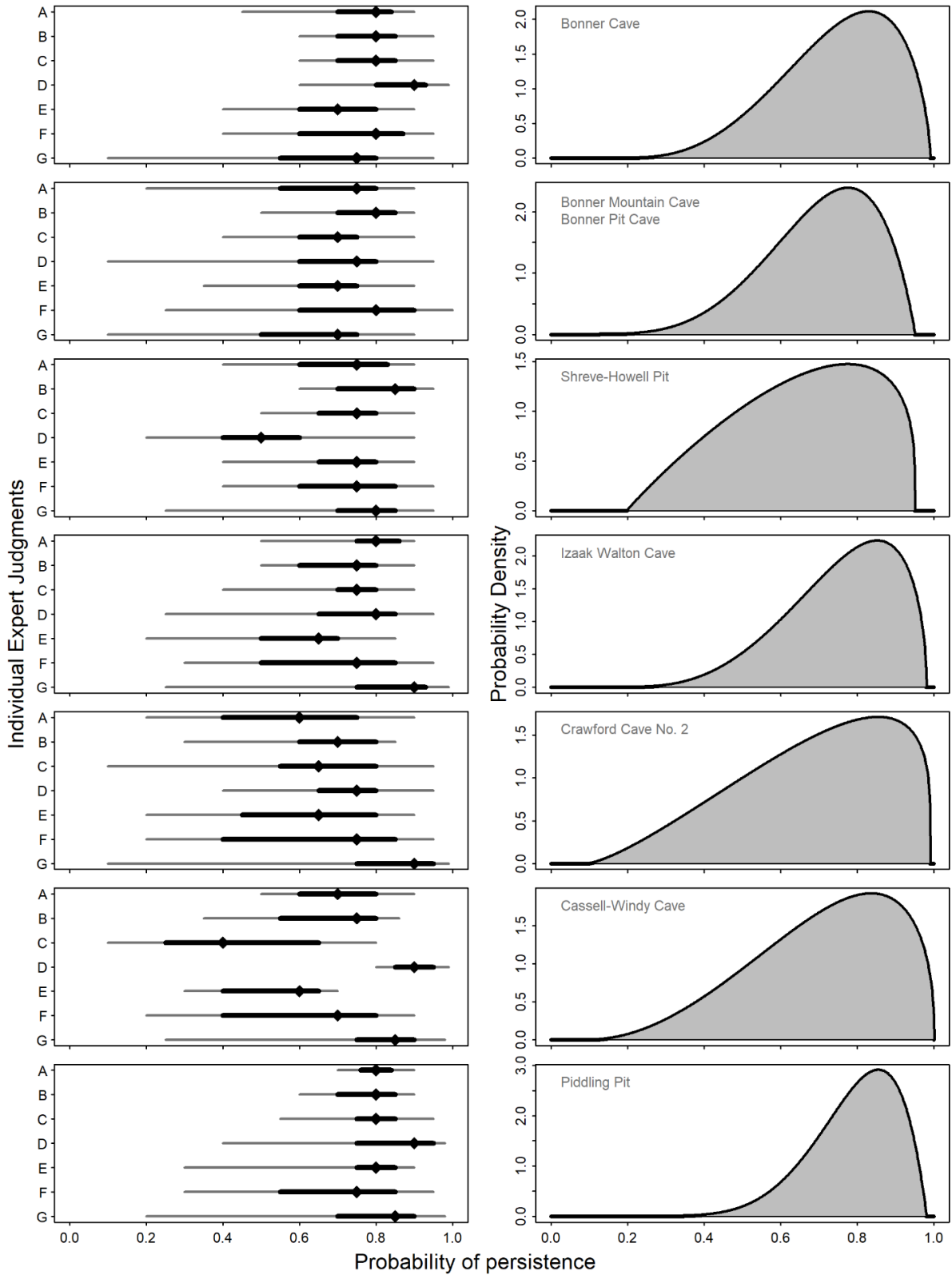


Figure 7. Expert judgments on the probability of persistence for *S. parvus* localities. The left panel shows individual expert judgments for the median (symbol), 50% credible interval (thick black line), and plausible limits (thin grey line). Right panel shows the final probability distributions from the group judgment round.

5 Synthesis and Conclusions

5.1 *Restricted range and habitat specialization*

All three species are highly specialized for subterranean karst habitat and limited to small geographic ranges, consistent with the restricted ranges seen in many cave and karst specialists (Culver *et al.* 2000, entire; Pipan *et al.* 2010, p. 748). These characteristics suggest that all three species are inherently susceptible to stochastic events, as well as potential regional stressors such as impacts from climate change or disease outbreak due to limited potential for long-distance dispersal. This risk is compounded for the single known meta-population of *S. cooperi*, which lacks any known redundancy and has an unknown level of current resilience. Persistence of these species depends on the availability of intact karst habitat and adequate groundwater quality, which can be particularly sensitive to contamination due to the heterogenous structure of karst (Notenboom *et al.* 1994, pp. 477-504; Doerflinger *et al.* 1999, entire; Culver *et al.* 2000, pp. 393-394; Loop and White 2001, entire). Long-term viability of all three species requires protecting not only areas of known occurrence, but the unsampled karst regions between known localities that maintain connectivity and the potential for recolonization following localized stochastic events (Pipan *et al.* 2010, pp. 753-754).

5.2 *Risk of local extirpation*

While uncertainty exists in the estimated risk of extirpation for all populations, expert judgments provided useful information on the magnitude and variation in uncertainty that can facilitate decision making. For example, the inherently high risk of extinction for narrowly endemic species is compounded by the fact that the single *S. cooperi* meta-population was judged to have the lowest confidence in persistence of any locality assessed (Table 7, Figure 5). This reflected expert judgements that proximity to development was among the greatest threats to these species, including associated increases in cave visitation, surface alteration, and increased risk of pollution and contaminants.

Expert judgments for *S. parvus* localities generally suggest high confidence in persistence despite considerable uncertainty in estimates for several meta-populations. The greatest threat to persistence for most *S. parvus* populations relates to forest management and timber harvest practices by landowners.

Uncertainty in the probability of persistence was generally much higher for populations of *S. morrisoni*, based on suspected differences in habitat use and variation in the characteristics of occupied caves. Unlike *S. cooperi* and *S. parvus*, *S. morrisoni* is not thought to be an epikarst specialist and may rely more on cave stream and pool habitats. Differences in local geology, including depth and size of the cave and susceptibility to flooding, were viewed as primary factors influencing the likelihood of persistence. The proximity to development and roads,

intensity of agricultural practices, and levels of cave visitation represent the greatest threats to *S. morrisoni* populations (Table 8); however, the current and projected impacts of these threats on persistence is less clear compared to the epikarst species analyzed. In addition, the potential risk is unevenly distributed across representative units, with the central and northern populations perceived to have a much greater risk of extirpation compared to the western and eastern populations.

5.3 Key uncertainties

Available empirical data for this status assessment are limited, resulting in key uncertainties that must be considered when interpreting results of the EKE. It has been suggested that the northern-most occurrence of *S. morrisoni* in Dyers Cave, WV may represent a distinct species (Holsinger 1978, p. 10; Fong *et al.* 2007, p. 80). Similarly, *S. morrisoni* individuals collected from Mountain Grove Saltpetre Cave in Virginia display morphological differences from other localities that warrant further genetic study (see Elicitation Record, p. 45). Cryptic diversity is likely widespread in groundwater amphipods due to strong morphological convergence within subterranean habitats (e.g., Trontelj *et al.* 2009, entire). The potential for cryptic diversity within *S. morrisoni* impacts our understanding of both redundancy and representation for this species, as well as the true number of species being considered within this SSA report.

The extent and current status of each meta-population represent another critical source of uncertainty (see Elicitation Record, p. 61). Limited collection information for many localities provide experts with no way to assess resilience beyond presence-absence, and lack of recent surveys at many sites suggest that we cannot be completely confident that all identified populations currently persist. Uncertainty in the below-ground movement of water through karst impacted experts' ability to assess the relevant spatial scale to consider for the various threats. We are not aware of direct dye-tracing studies that could aid delineation of groundwater flow around known localities, and detailed information on the geology of each cave and the surrounding epikarst would greatly improve this assessment. Combined, these factors make it difficult for experts to assess the magnitude of various stressors that *Stygobromus* populations can withstand.

5.4 Existing conservation measures

Conservation measures directly benefiting these species are limited. None of the species are listed at the state level; however, all three are recognized as species of greatest conservation need throughout their respective ranges in West Virginia and/or Virginia (VDGIF 2015, appendix A; WVDNR 2015, p. 467). The single *S. cooperi* locality does not occur on federal land, and no existing conservation measures protecting this locality are known.

While two *S. morrisoni* populations (Witheros and Clarks Caves) may be afforded some protection based on efforts to conserve hibernating Indiana bat (*Myotis sodalis*) populations, cave access is only restricted during winter months and summer visitation rates are high in Clarks Cave. Restricting cave access does little to protect epikarst environments from changes in surface land use or risk of water-borne contaminants. This is reflected in the median probability of persistence of 0.55 for the Clarks Cave meta-population. Mountain Grove and Starr Chapel Saltpetre Caves within the George Washington and Jefferson National Forest are the only populations of *S. morrisoni* on federal land, and high confidence in persistence for these localities was based predominantly on management practices by the National Forest for Indiana bats (GWJNF 2014, entire).

S. parvus is recognized as a Forest Service Region 9 regional forester's sensitive species (Shawn Cochran 2020, personal communication). One population of *S. parvus* is beneath land currently protected by The Nature Conservancy, which heavily impacted experts' confidence in persistence for that locality. Access to Izaak Walton Cave is also restricted during the Indiana bat hibernation period. None of the localities have been reported in caves located on lands administered by the Monongahela National Forest, and the localities near the proclamation boundary are unlikely to be hydrologically connected to managed lands (Shawn Cochran 2020, personal communication).

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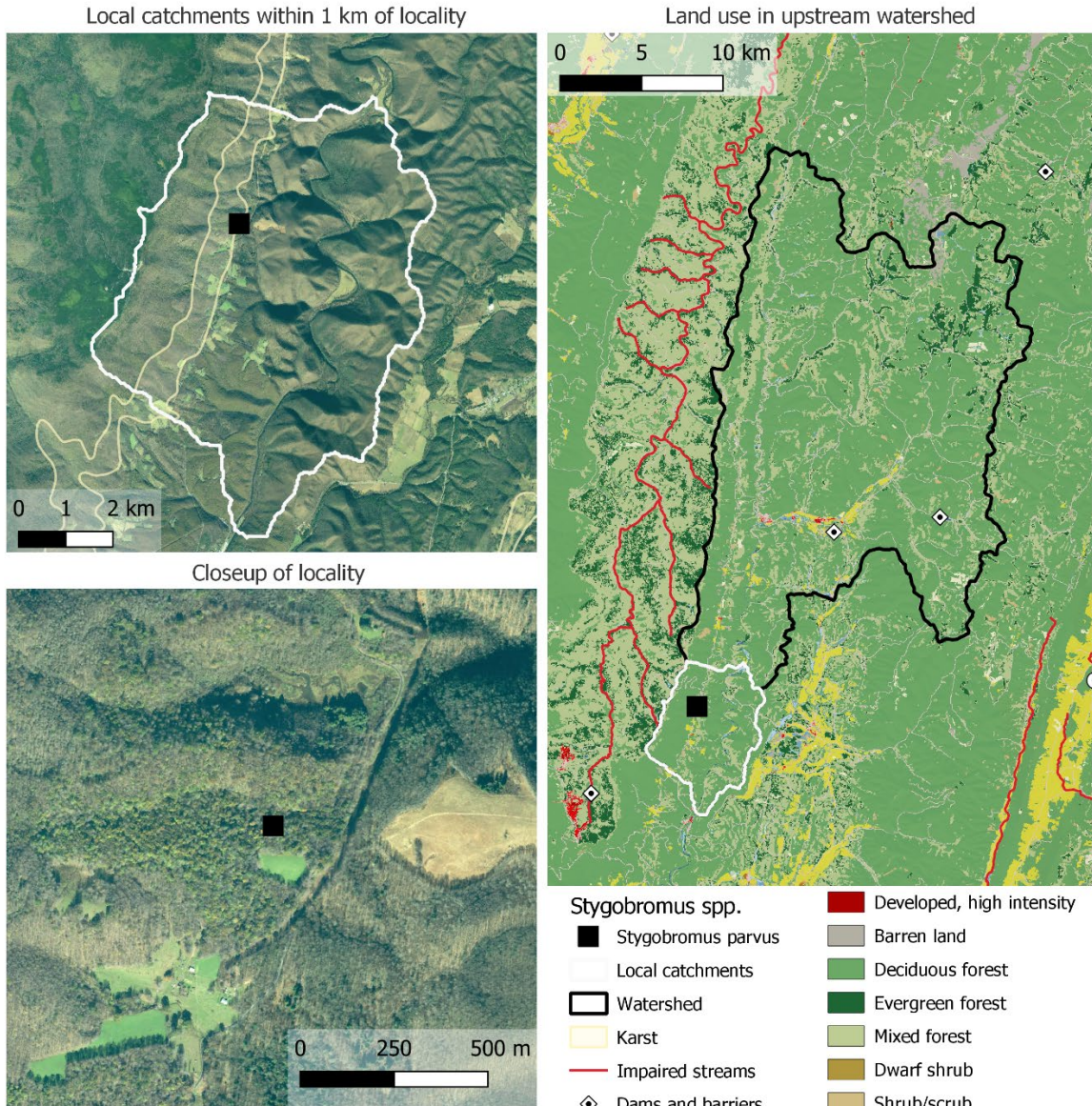
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7 Appendix

7.1 Site narratives used in EKE workshop

Stygobromus parvus - Cassell-Windy Cave

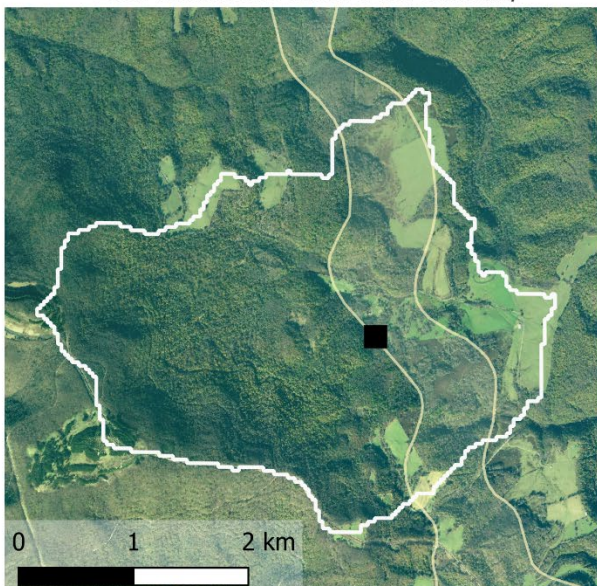


	2006	2016	Projected 2030
Percent developed:	3	4	3
Percent pasture:	1	1	1-3
Percent crop:	0	0	0
Percent forested:	94	93	90-94

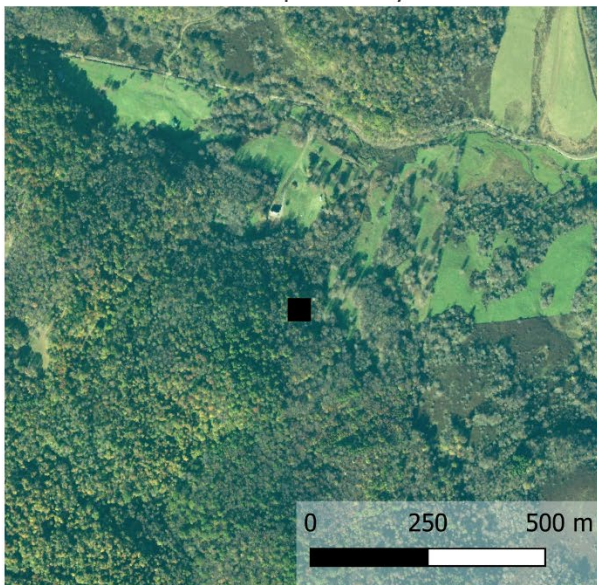
Within shale play: Yes
 Number mines: 0 CAFOs per county (2007): 0
 Number dams: 2 Stream impairment: none listed in watershed

Stygobromus parvus - Crawford Cave No. 2

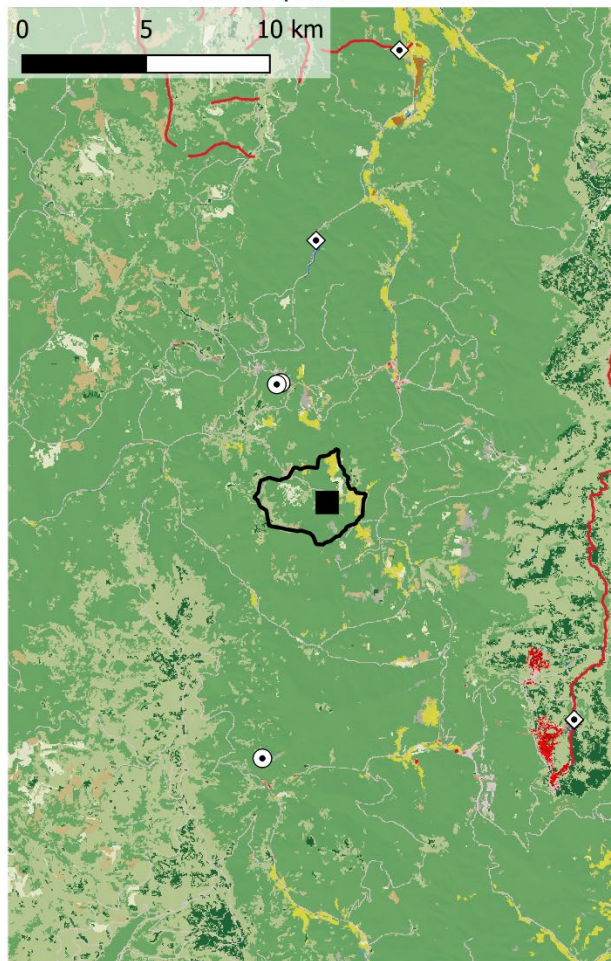
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- Stygobromus spp.**
- Stygobromus parvus
 - Local catchments
 - Watershed
 - Karst
 - Impaired streams
 - ◇ Dams and barriers
 - ⊙ Mines
- NLCD 2016**
- Open water
 - Developed, open space
 - Developed, low intensity
 - Developed, med intensity
 - Developed, high intensity
 - Barren land
 - Deciduous forest
 - Evergreen forest
 - Mixed forest
 - Dwarf shrub
 - Shrub/scrub
 - Grassland
 - Pasture/Hay
 - Cultivated crops
 - Woody wetlands
 - Herbaceous Wetlands

	2006	2016	Projected 2030
Percent developed:	2	1	2
Percent pasture:	2	7	1-2
Percent crop:	9	0	7-9
Percent forested:	82	83	79-83

Within shale play: Yes

Number mines: 0

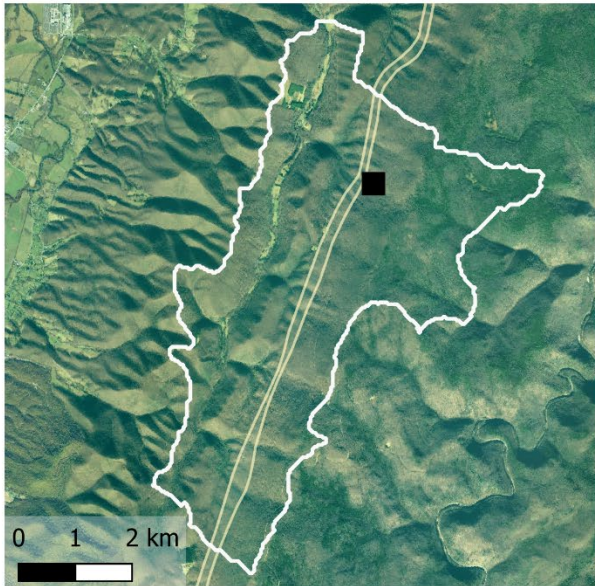
Number dams: 0

CAFOs per county (2007): 0

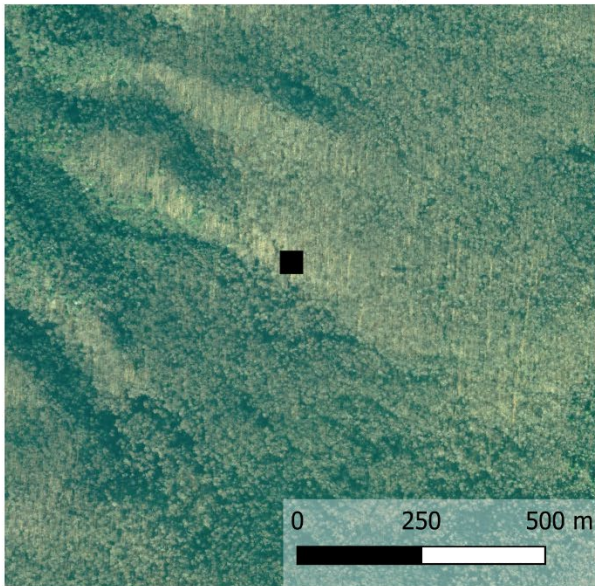
Stream impairment: none listed in watershed

Stygobromus parvus - Izaak Walton Cave

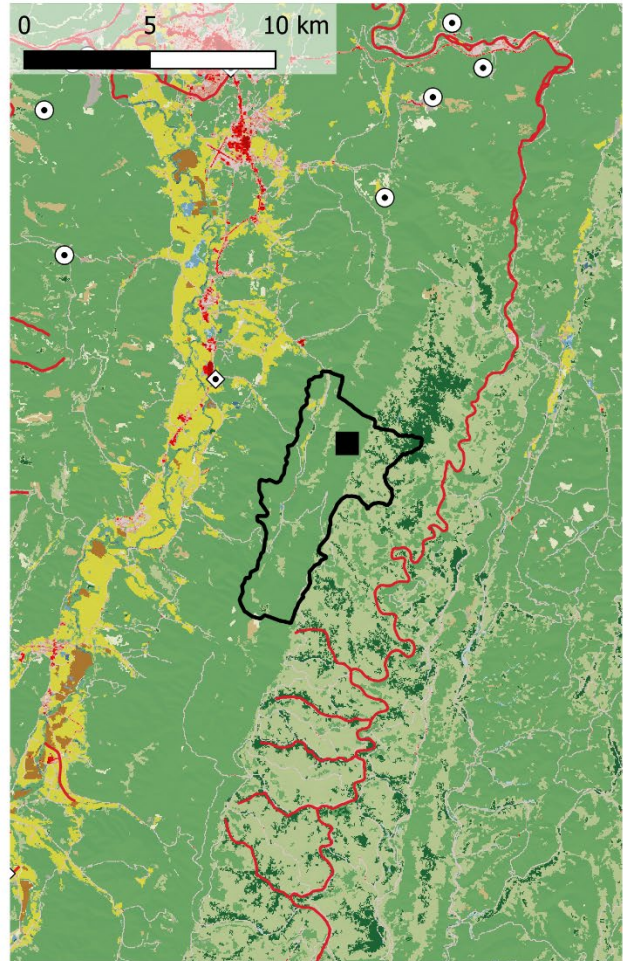
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- Stygobromus spp.**
- *Stygobromus parvus*
 - Local catchments
 - Watershed
 - Karst
 - Impaired streams
 - ◇ Dams and barriers
 - ⊙ Mines
- NLCD 2016**
- Developed, high intensity
 - Barren land
 - Deciduous forest
 - Evergreen forest
 - Mixed forest
 - Dwarf shrub
 - Shrub/scrub
 - Grassland
 - Pasture/Hay
 - Cultivated crops
 - Woody wetlands
 - Herbaceous Wetlands
 - Developed, open space
 - Developed, low intensity
 - Developed, med intensity

	2006	2016	Projected 2030
Percent developed:	1	1	1
Percent pasture:	0	0	0
Percent crop:	0	0	0
Percent forested:	99	99	96-99

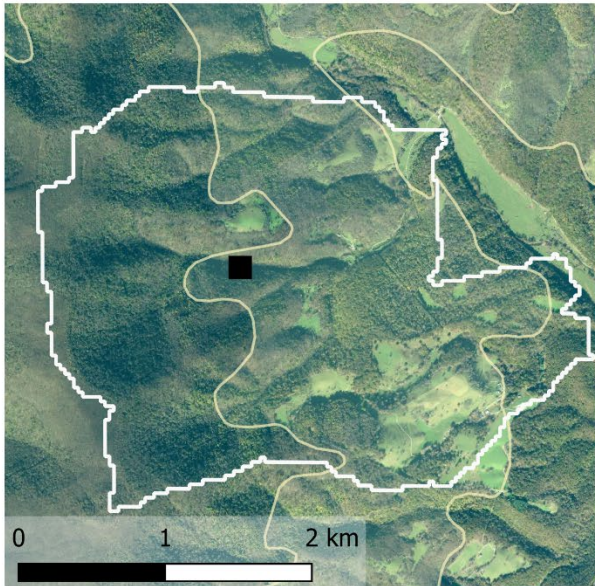
Within shale play: Yes

Number mines: 0 CAFOs per county (2007): 0

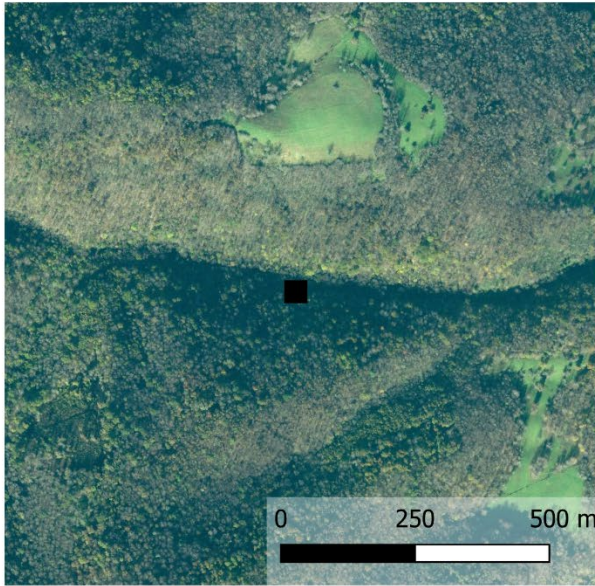
Number dams: 0 Stream impairment: none listed in watershed

Stylobromus parvus - Piddling Pit

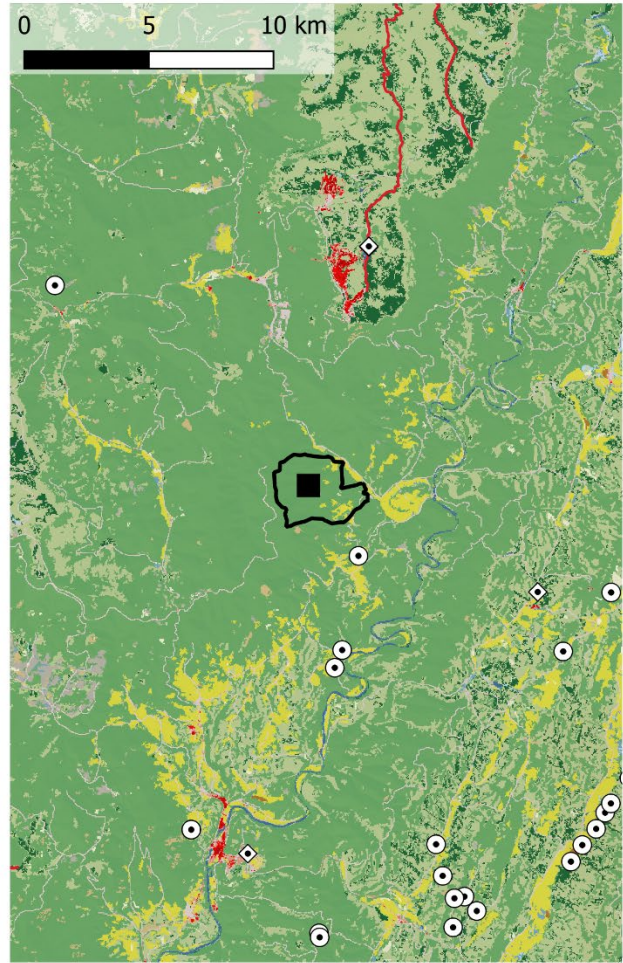
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- Stylobromus spp.**
- Stylobromus parvus
 - Local catchments
 - Watershed
 - Karst
 - Impaired streams
 - ◇ Dams and barriers
 - ⊙ Mines
- NLCD 2016**
- Open water
 - Developed, open space
 - Developed, low intensity
 - Developed, med intensity
 - Developed, high intensity
 - Barren land
 - Deciduous forest
 - Evergreen forest
 - Mixed forest
 - Dwarf shrub
 - Shrub/scrub
 - Grassland
 - Pasture/Hay
 - Cultivated crops
 - Woody wetlands
 - Herbaceous Wetlands

	2006	2016	Projected 2030
Percent developed:	1	0	1
Percent pasture:	6	7	2-5
Percent crop:	1	0	1
Percent forested:	91	92	87-94

Within shale play: Yes

Number mines: 0

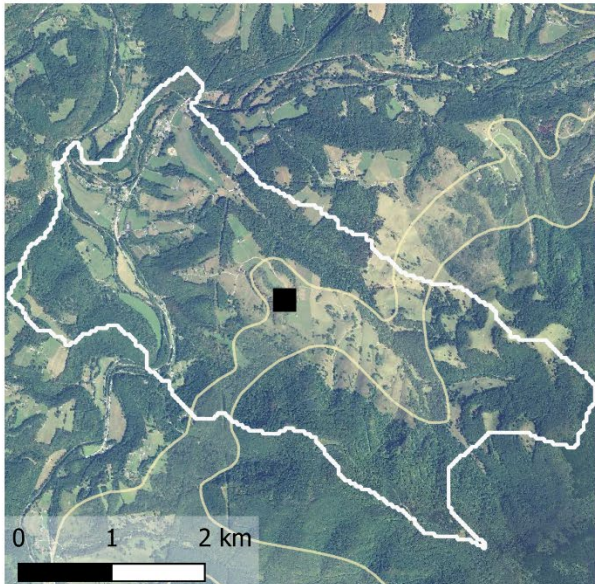
Number dams: 0

CAFOs per county (2007): 0

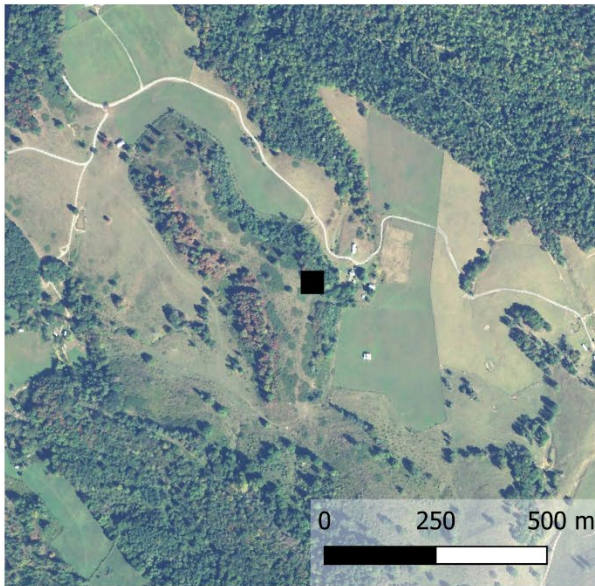
Stream impairment: none listed in watershed

Stygobromus parvus - Bonner Mountain Cave

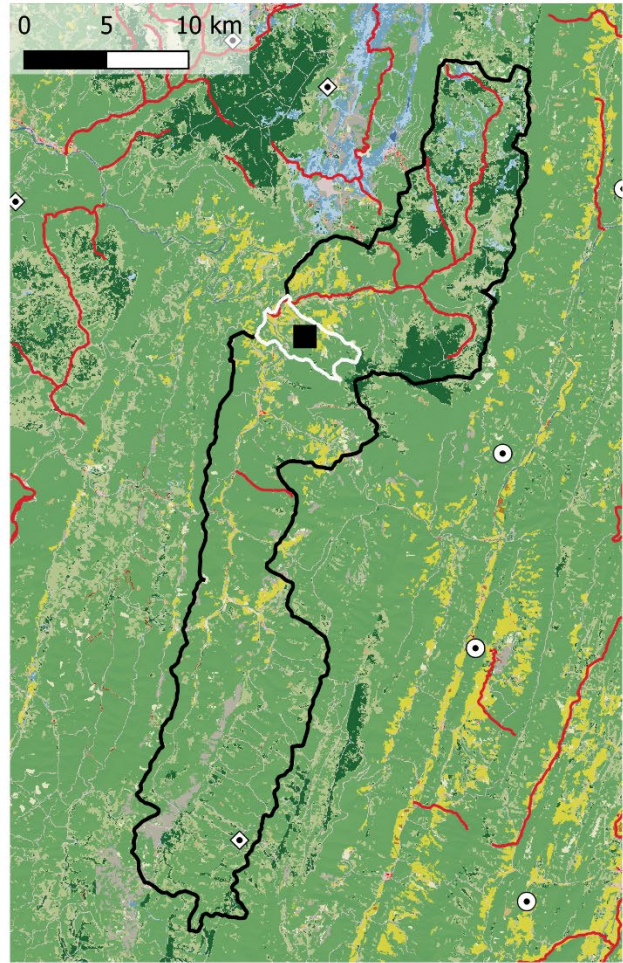
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- Stygobromus spp.**
- Stygobromus parvus
 - Local catchments
 - Watershed
 - Karst
 - Impaired streams
 - ◇ Dams and barriers
 - ⊙ Mines
- NLCD 2016**
- Open water
 - Developed, open space
 - Developed, low intensity
 - Developed, med intensity
 - Developed, high intensity
 - Barren land
 - Deciduous forest
 - Evergreen forest
 - Mixed forest
 - Dwarf shrub
 - Shrub/scrub
 - Grassland
 - Pasture/Hay
 - Cultivated crops
 - Woody wetlands
 - Herbaceous Wetlands

	2006	2016	Projected 2030
Percent developed:	2	3	2
Percent pasture:	10	7	9-12
Percent crop:	0	0	0
Percent forested:	86	85	82-86

Within shale play: Yes

Number mines: 0

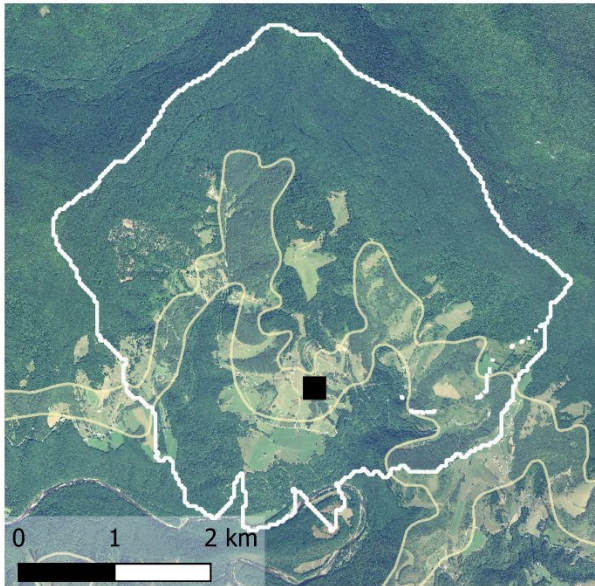
Number dams: 1

CAFOs per county (2007): 0

Stream impairment: pH/Acidity/Caustic Conditions

Stygobromus parvus - Bonner Pit Cave

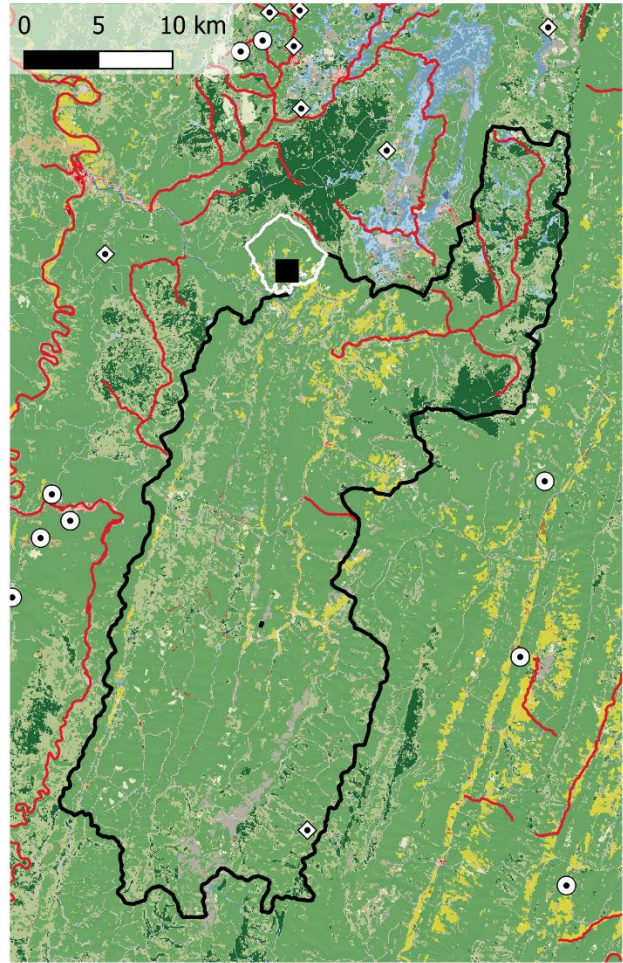
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- Stygobromus spp.**
- Stygobromus parvus
 - Local catchments
 - ▭ Watershed
 - ◻ Karst
 - Impaired streams
 - ◇ Dams and barriers
 - ⊙ Mines
- NLCD 2016**
- Open water
 - Developed, open space
 - Developed, low intensity
 - Developed, med intensity
 - Developed, high intensity
 - Barren land
 - Deciduous forest
 - Evergreen forest
 - Mixed forest
 - Dwarf shrub
 - Shrub/scrub
 - Grassland
 - Pasture/Hay
 - Cultivated crops
 - Woody wetlands
 - Herbaceous Wetlands

	2006	2016	Projected 2030
Percent developed:	3	3	3
Percent pasture:	6	6	5-7
Percent crop:	0	0	0
Percent forested:	89	87	86-89

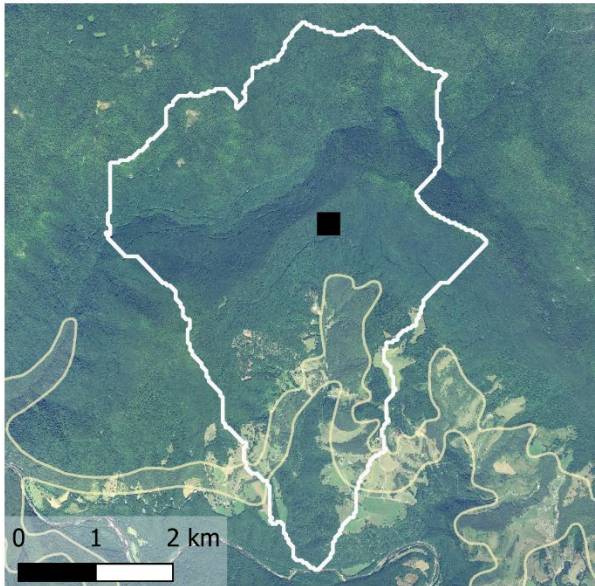
Within shale play: Yes

Number mines: 0 CAFOs per county (2007): 0

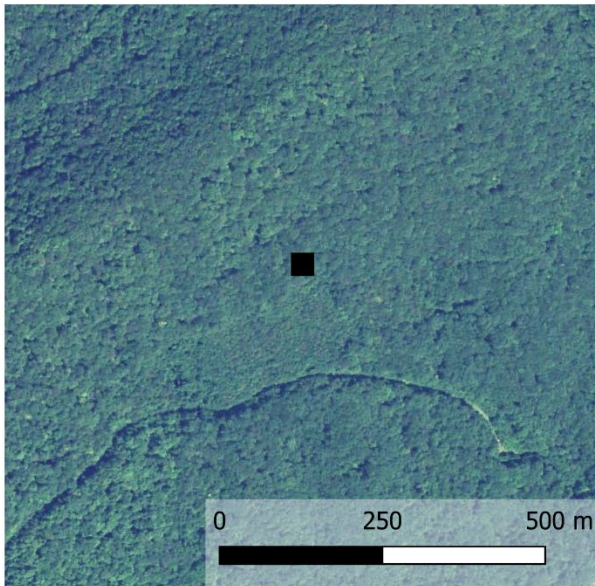
Number dams: 1 Stream impairment: pH/Acidity/Caustic Conditions; impaired biota - benthic inverts.

Stygobromus parvus - Bonner Cave

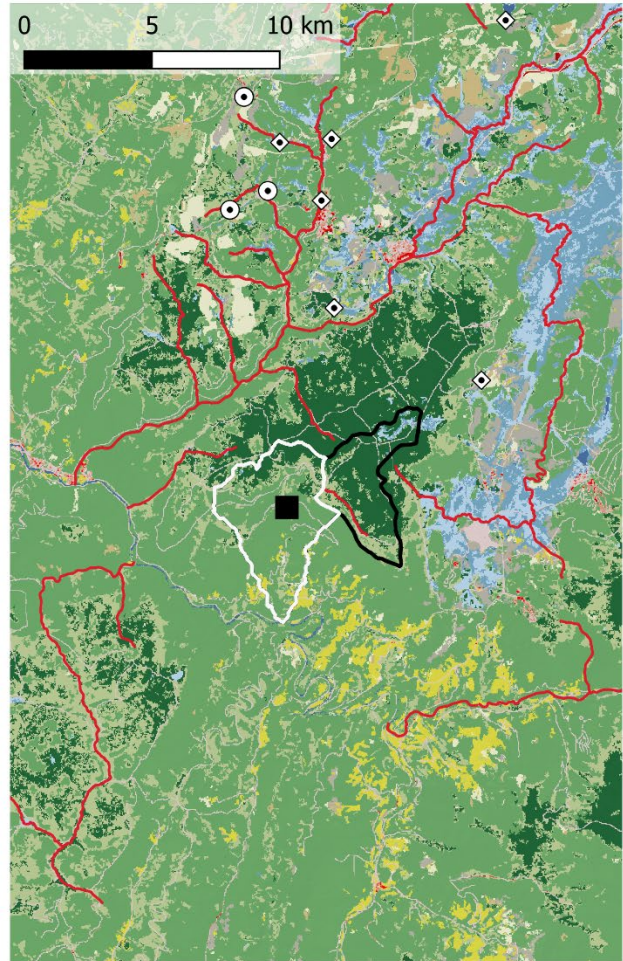
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



	2006	2016	Projected 2030
Percent developed:	3	5	3
Percent pasture:	2	2	2
Percent crop:	0	0	0
Percent forested:	95	91	94-95

Within shale play: Yes

Number mines: 0

Number dams: 0

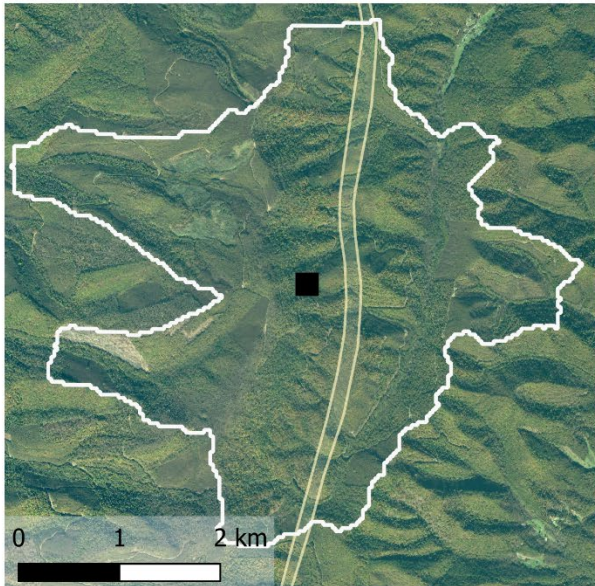
CAFOs per county (2007): 0

Stream impairment: pH/Acidity/Caustic Conditions

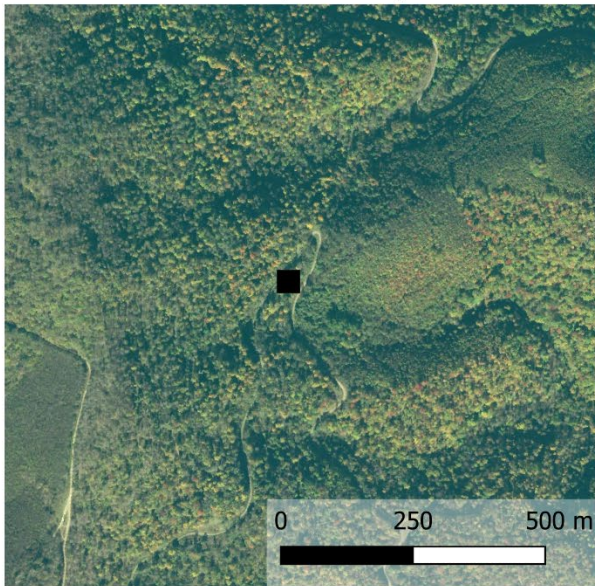
- Stygobromus spp.**
- Stygobromus parvus
 - Local catchments
 - Watershed
 - Karst
 - Impaired streams
 - ◇ Dams and barriers
 - Mines
- NLCD 2016**
- Open water
 - Developed, open space
 - Developed, low intensity
 - Developed, med intensity
 - Developed, high intensity
 - Barren land
 - Deciduous forest
 - Evergreen forest
 - Mixed forest
 - Dwarf shrub
 - Shrub/scrub
 - Grassland
 - Pasture/Hay
 - Cultivated crops
 - Woody wetlands
 - Herbaceous Wetlands

Stygobromus parvus - Shreve-Howell Pit

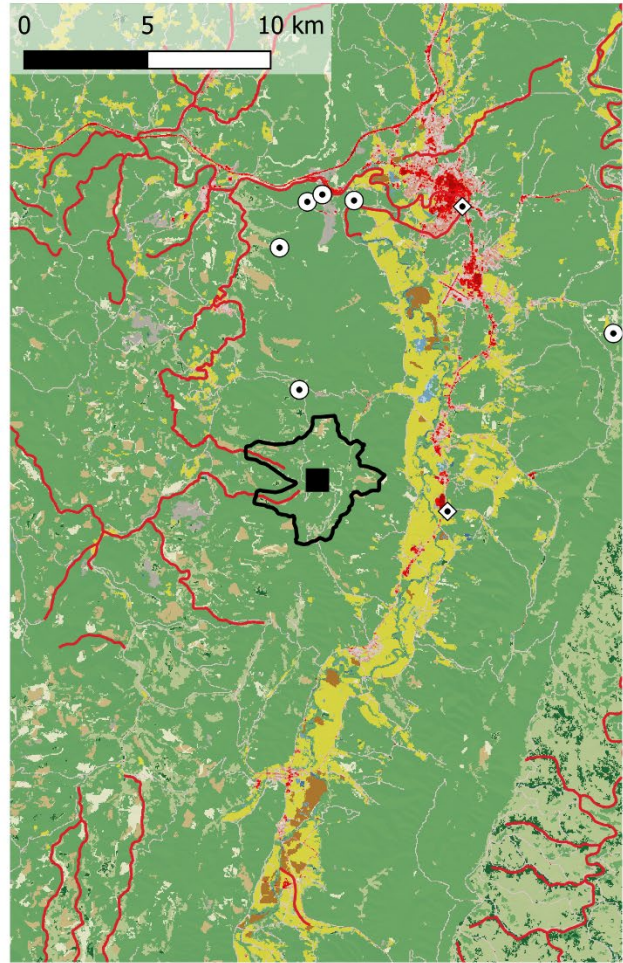
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- Stygobromus spp.**
- Stygobromus parvus
 - Local catchments
 - Watershed
 - Karst
 - Impaired streams
 - ◇ Dams and barriers
 - ⊙ Mines
- NLCD 2016**
- Open water
 - Developed, open space
 - Developed, low intensity
 - Developed, med intensity
 - Developed, high intensity
 - Barren land
 - Deciduous forest
 - Evergreen forest
 - Mixed forest
 - Dwarf shrub
 - Shrub/scrub
 - Grassland
 - Pasture/Hay
 - Cultivated crops
 - Woody wetlands
 - Herbaceous Wetlands

	2006	2016	Projected 2030
Percent developed:	1	2	1
Percent pasture:	0	0	0
Percent crop:	0	0	0
Percent forested:	98	88	93-100

Within shale play: Yes

Number mines: 0

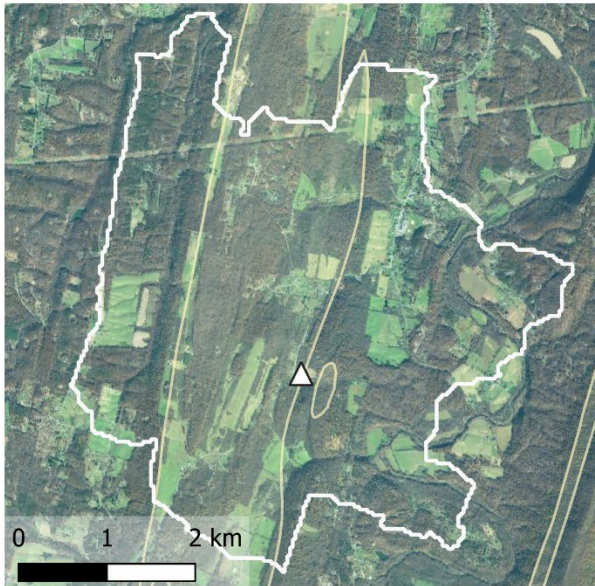
Number dams: 0

CAFOs per county (2007): 0

Stream impairment: Metals (Aluminum, Iron, Manganese); pH/Acidity/Caustic Conditions

Stygobromus cooperi - Silers Cave

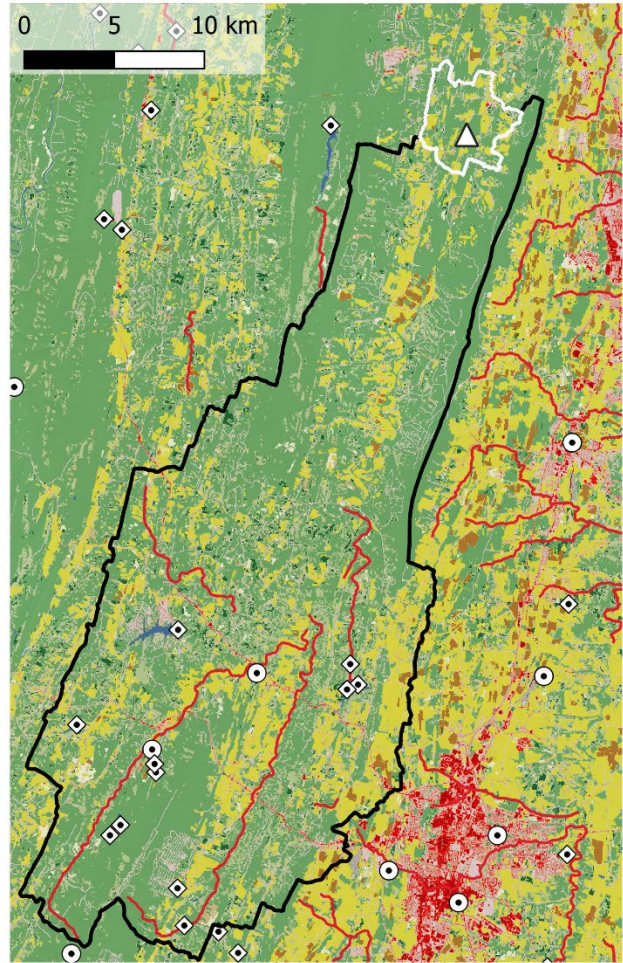
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- Stygobromus spp.**
- △ Stygobromus cooperi
 - Local catchments
 - Watershed
 - Karst
 - Impaired streams
 - Dams and barriers
 - Mines
- NLCD 2016**
- Open water
 - Developed, open space
 - Developed, low intensity
 - Developed, med intensity
 - Developed, high intensity
 - Barren land
 - Deciduous forest
 - Evergreen forest
 - Mixed forest
 - Dwarf shrub
 - Shrub/scrub
 - Grassland
 - Pasture/Hay
 - Cultivated crops
 - Woody wetlands
 - Herbaceous Wetlands

	2006	2016	Projected 2030
Percent developed:	6	7	6
Percent pasture:	18	18	18-26
Percent crop:	2	0	2-3
Percent forested:	74	73	64-74

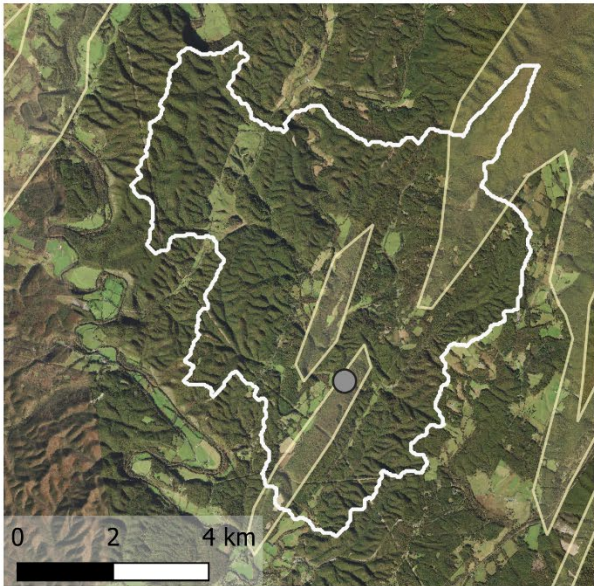
Within shale play: No
 Number mines: 2
 Number dams: 13

CAFOs per county (2007): 0

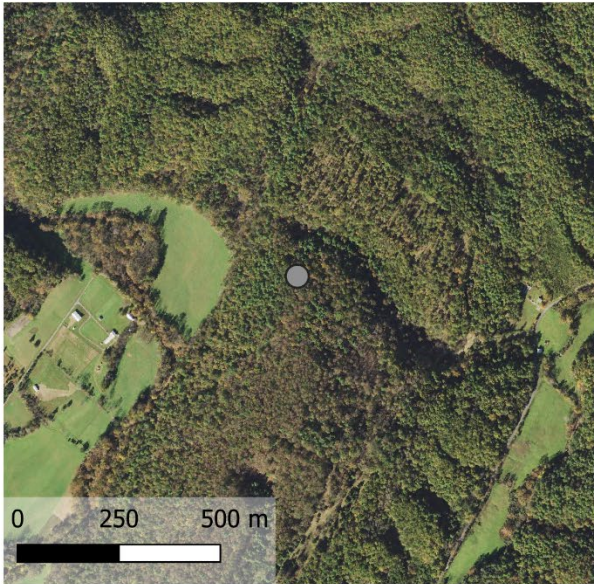
Stream impairment: Pathogens (E. coli, fecal coliform, bacteria); impaired benthic inverts.

Stygobromus morrisoni - Witheros Cave

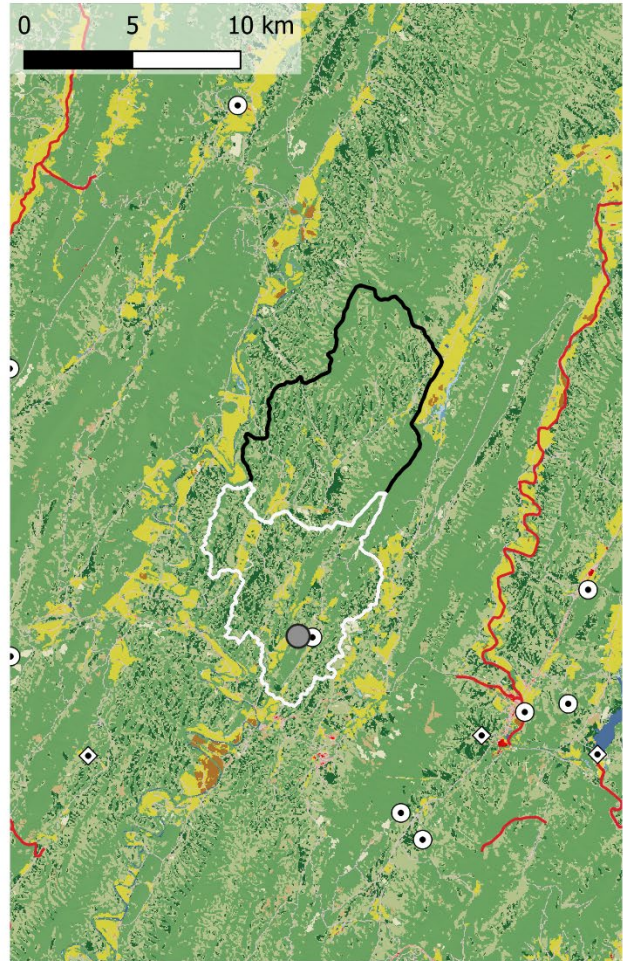
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- | | |
|----------------------------|--|
| Stygobromus spp. | ■ Developed, high intensity |
| ● Stygobromus morrisoni | ■ Barren land |
| ○ Local catchments | ■ Deciduous forest |
| □ Watershed | ■ Evergreen forest |
| ■ Karst | ■ Mixed forest |
| — Impaired streams | ■ Dwarf shrub |
| ◇ Dams and barriers | ■ Shrub/scrub |
| ⊙ Mines | ■ Grassland |
| NLCD 2016 | ■ Pasture/Hay |
| ■ Open water | ■ Cultivated crops |
| ■ Developed, open space | ■ Woody wetlands |
| ■ Developed, low intensity | ■ Herbaceous Wetlands |
| ■ Developed, med intensity | |

	2006	2016	Projected 2030
Percent developed:	3	3	3
Percent pasture:	5	5	4-9
Percent crop:	0	0	0
Percent forested:	92	91	85-92

Within shale play: No

Number mines: 1

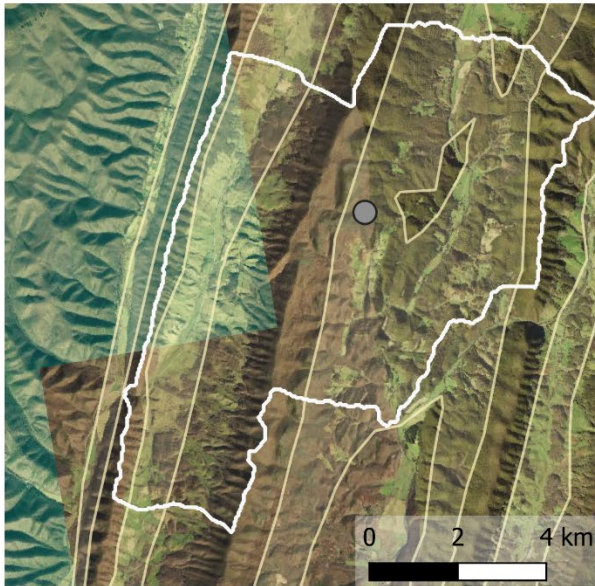
Number dams: 0

CAFOs per county (2007): 19

Stream impairment: none listed in watershed

Stygobromus morrisoni - Corbett Cave

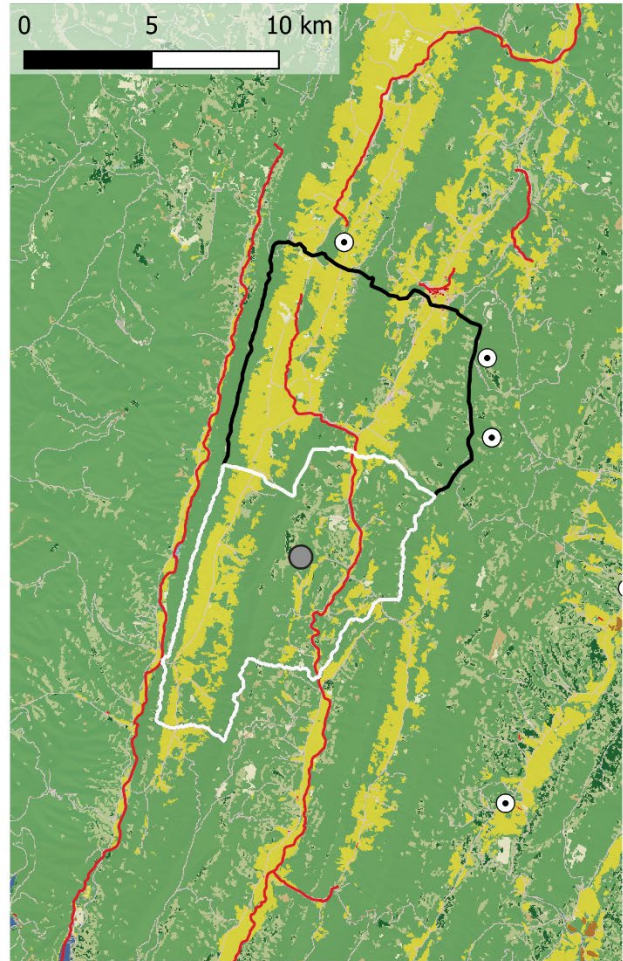
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- Stygobromus morrisoni
- Local catchments
- Watershed
- Karst
- Impaired streams
- Dams and barriers
- Mines
- Developed, high intensity
- Barren land
- Deciduous forest
- Evergreen forest
- Mixed forest
- Dwarf shrub
- Shrub/scrub
- Grassland
- Pasture/Hay
- Open water
- Cultivated crops
- Woody wetlands
- Herbaceous Wetlands
- Developed, open space
- Developed, low intensity
- Developed, med intensity

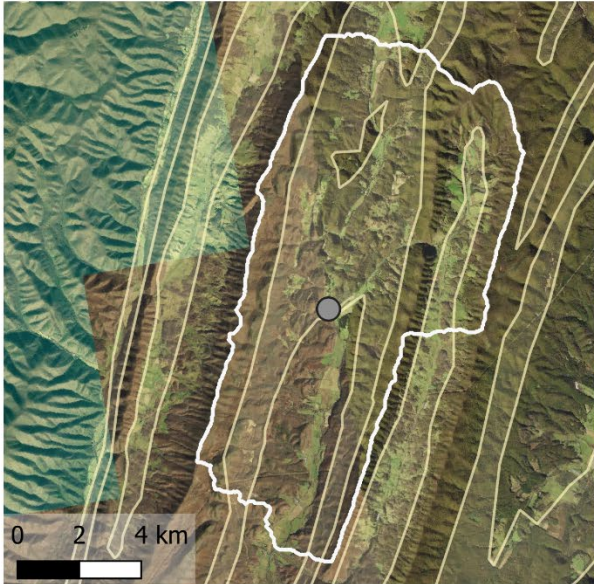
	2006	2016	Projected 2030
Percent developed:	4	3	4
Percent pasture:	33	33	24-36
Percent crop:	0	0	0
Percent forested:	62	64	55-69

Within shale play: No
 Number mines: 0
 Number dams: 0

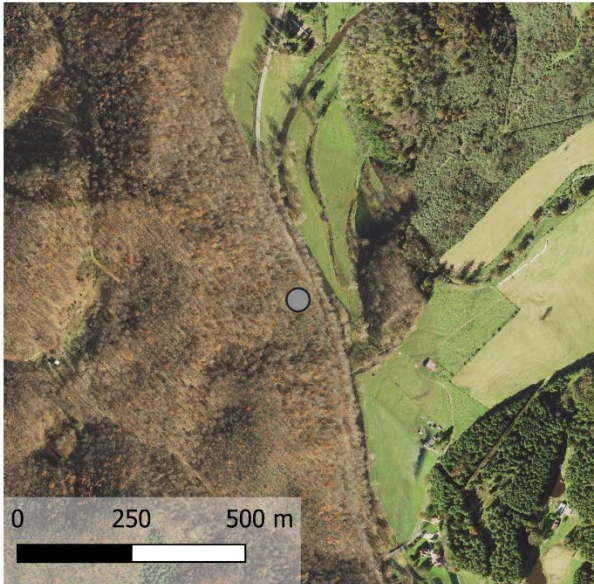
CAFOs per county (2007): 1
 Stream impairment: Pathogens (E. coli)

Stygobromus morrisoni - Secret Anthodite Cave

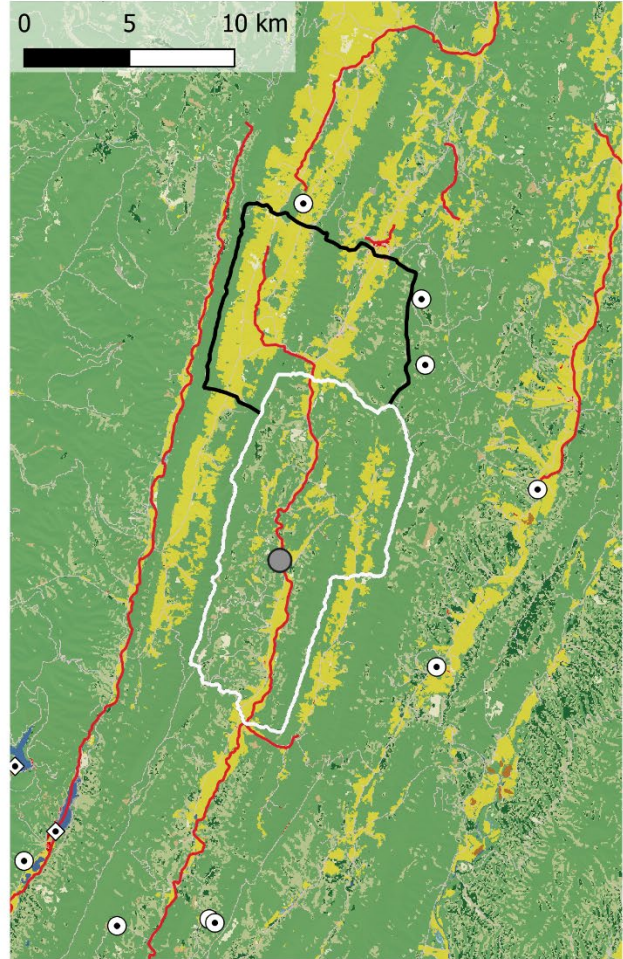
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



	2006	2016	Projected 2030
Percent developed:	4	3	4
Percent pasture:	24	25	17-28
Percent crop:	1	0	1
Percent forested:	71	71	63-75

Within shale play: Yes

Number mines: 0

Number dams: 0

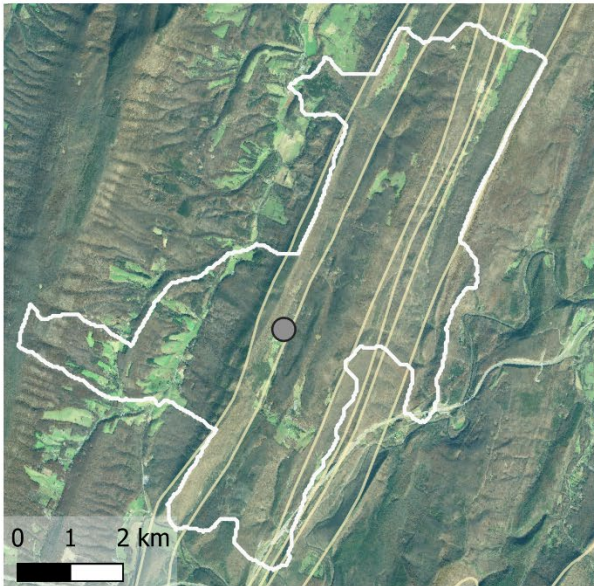
CAFOs per county (2007): 1

Stream impairment: Pathogens (E. coli)

- Stygobromus spp.**
- Stygobromus morrisoni
- Local catchments
- Watershed
- Karst
- Impaired streams
- ◇ Dams and barriers
- ⊙ Mines
- NLCD 2016**
- Open water
- Developed, open space
- Developed, low intensity
- Developed, med intensity
- Developed, high intensity
- Barren land
- Deciduous forest
- Evergreen forest
- Mixed forest
- Dwarf shrub
- Shrub/scrub
- Grassland
- Pasture/Hay
- Cultivated crops
- Woody wetlands
- Herbaceous Wetlands

Stygobromus morrisoni - Dyers Cave

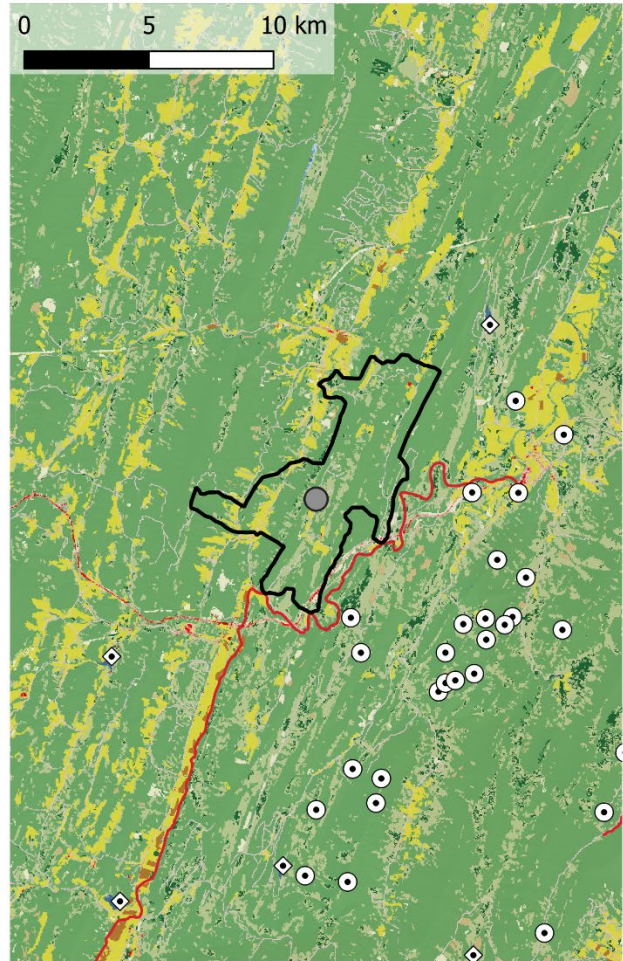
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- Stygobromus spp.**
- Stygobromus morrisoni
 - Local catchments
 - Watershed
 - Karst
 - Impaired streams
 - ◇ Dams and barriers
 - ⊙ Mines
- NLCD 2016**
- Open water
 - Developed, open space
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 - Evergreen forest
 - Mixed forest
 - Dwarf shrub
 - Shrub/scrub
 - Grassland
 - Pasture/Hay
 - Cultivated crops
 - Woody wetlands
 - Herbaceous Wetlands

	2006	2016	Projected 2030
Percent developed:	4	4	4
Percent pasture:	7	7	7-14
Percent crop:	0	0	0
Percent forested:	88	87	81-87

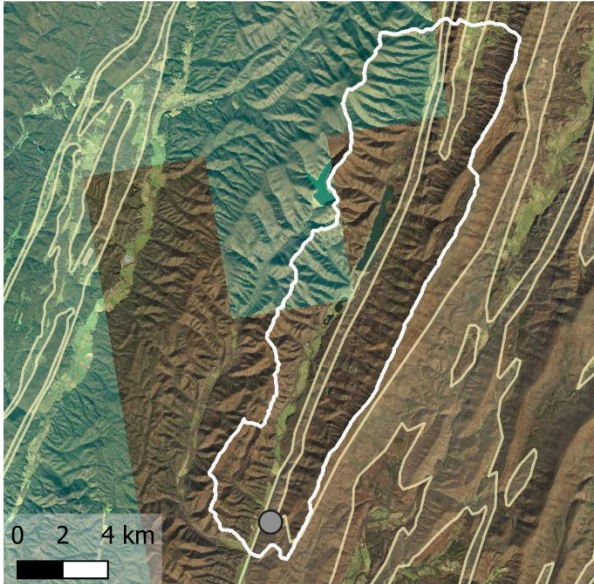
Within shale play: No
 Number mines: 0
 Number dams: 0

CAFOs per county (2007): 34

Stream impairment: Pathogens (fecal coliform)

Stygobromus morrisoni - Mountain Grove Salt Petre Cave

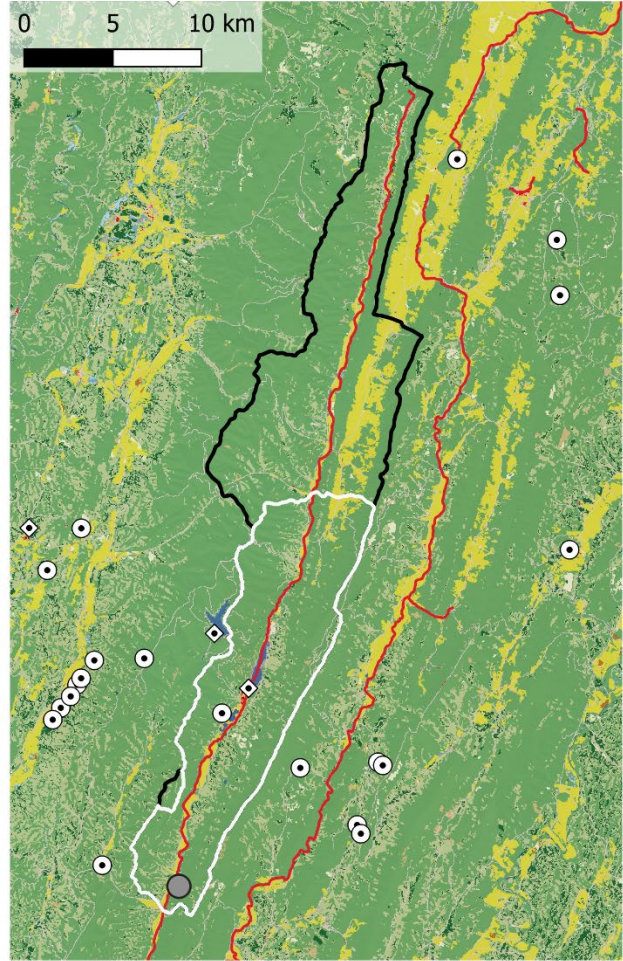
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



	2006	2016	Projected 2030
Percent developed:	3	2	3
Percent pasture:	6	6	4-7
Percent crop:	0	0	0
Percent forested:	91	91	88-92

Within shale play: Yes

Number mines: 1

Number dams: 1

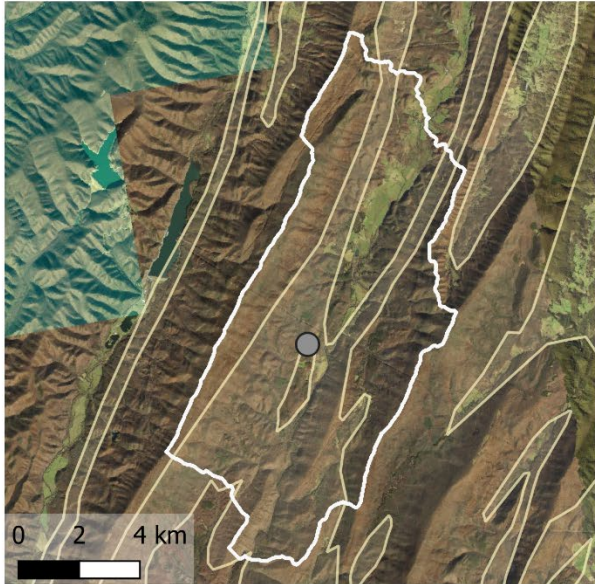
CAFOs per county (2007): 19

Stream impairment: Temperature; pathogens (E. coli)

- Stygobromus spp.**
- Stygobromus morrisoni
- Local catchments
- Watershed
- Karst
- Impaired streams
- ◇ Dams and barriers
- ⊙ Mines
- NLCD 2016**
- Open water
- Developed, open space
- Developed, low intensity
- Developed, med intensity
- Developed, high intensity
- Barren land
- Deciduous forest
- Evergreen forest
- Mixed forest
- Dwarf shrub
- Shrub/scrub
- Grassland
- Pasture/Hay
- Cultivated crops
- Woody wetlands
- Herbaceous Wetlands

Stygobromus morrisoni - Starr Chapel Salt Petre Cave

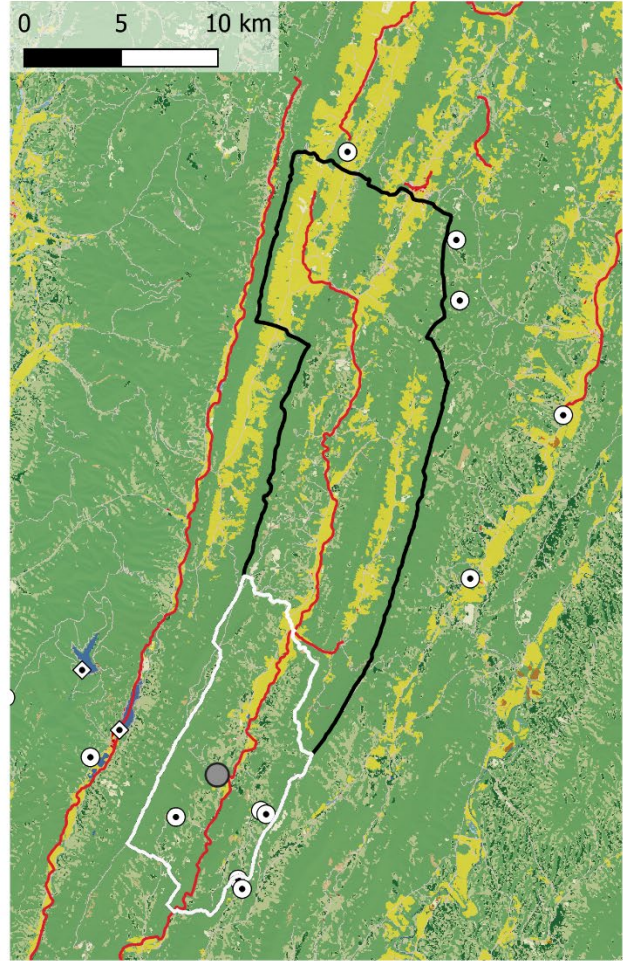
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



	2006	2016	Projected 2030
Percent developed:	4	3	4
Percent pasture:	17	18	12-20
Percent crop:	0	0	0
Percent forested:	78	78	72-81

Within shale play: No
 Number mines: 3
 Number dams: 0

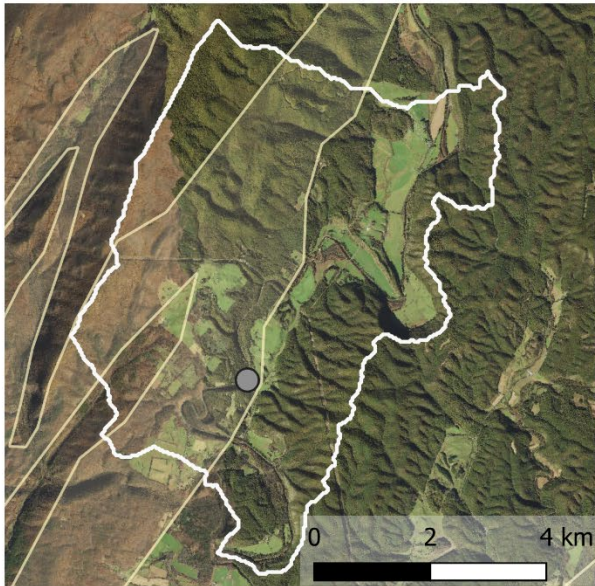
CAFOs per county (2007): 19

Stream impairment: Temperature; Pathogens (E. coli)

- Stygobromus spp.**
- Stygobromus morrisoni
 - Local catchments
 - Watershed
 - Karst
 - Impaired streams
 - ◇ Dams and barriers
 - ⊙ Mines
- NLCD 2016**
- Open water
 - Developed, open space
 - Developed, low intensity
 - Developed, med intensity
 - Developed, high intensity
 - Barren land
 - Deciduous forest
 - Evergreen forest
 - Mixed forest
 - Dwarf shrub
 - Shrub/scrub
 - Grassland
 - Pasture/Hay
 - Cultivated crops
 - Woody wetlands
 - Herbaceous Wetlands

Stygobromus morrisoni - Clarks Cave

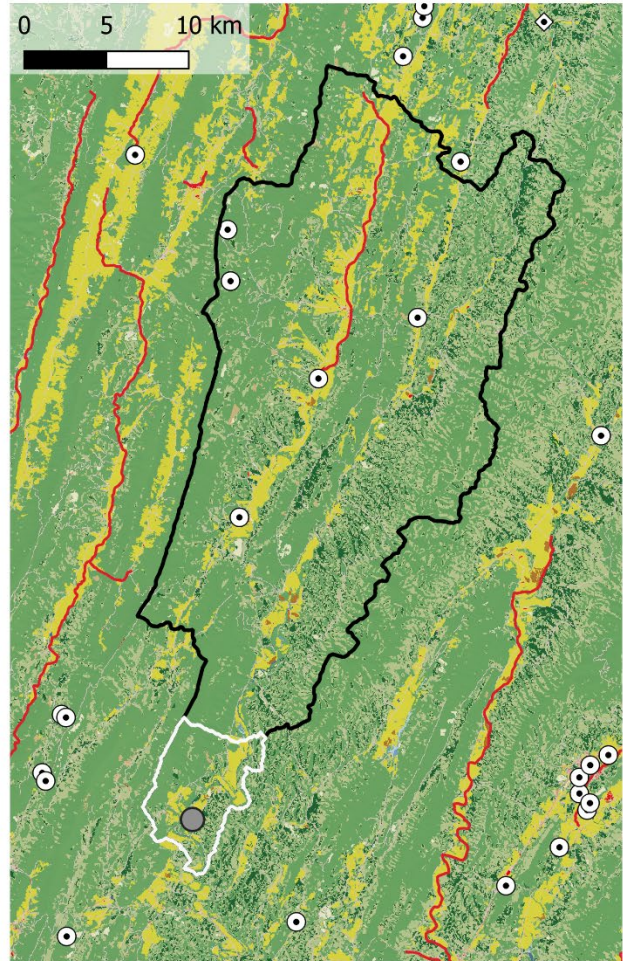
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- | | |
|--------------------------|---------------------------|
| Stygobromus spp. | Developed, high intensity |
| Stygobromus morrisoni | Barren land |
| Local catchments | Deciduous forest |
| Watershed | Evergreen forest |
| Karst | Mixed forest |
| Impaired streams | Dwarf shrub |
| Dams and barriers | Shrub/scrub |
| Mines | Grassland |
| NLCD 2016 | Pasture/Hay |
| Open water | Cultivated crops |
| Developed, open space | Woody wetlands |
| Developed, low intensity | Herbaceous Wetlands |
| Developed, med intensity | |

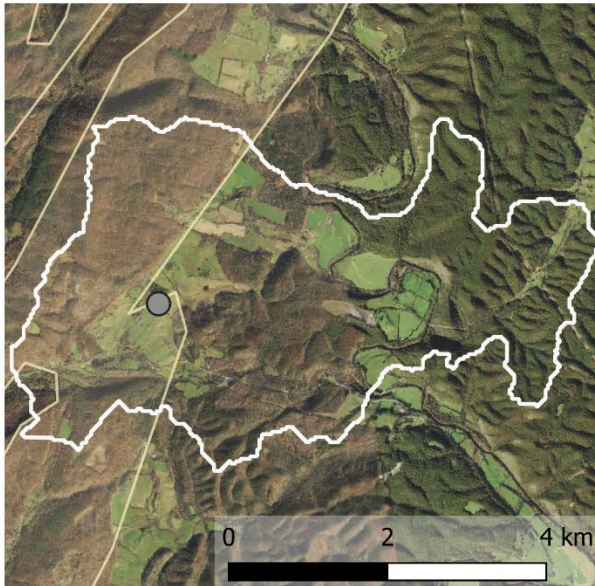
	2006	2016	Projected 2030
Percent developed:	3	3	3
Percent pasture:	11	11	9-16
Percent crop:	0	0	0
Percent forested:	85	85	78-86

Within shale play: No
 Number mines: 7
 Number dams: 0

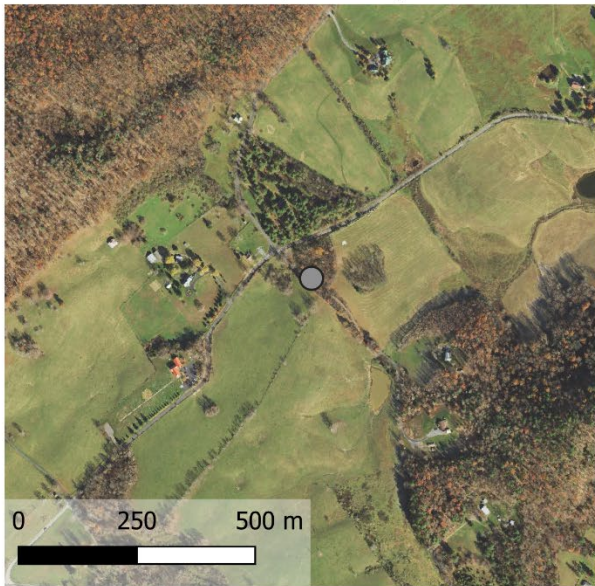
CAFOs per county (2007): 19
 Stream impairment: pathogens (E. coli)

Stygobromus morrisoni - Crossroads Cave

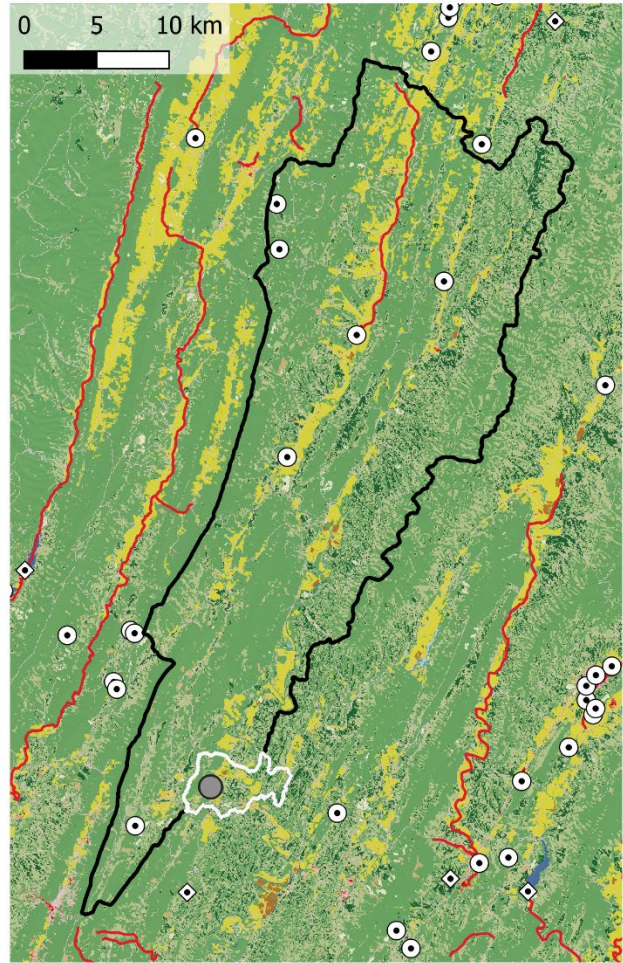
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- Stygobromus spp.**
- Stygobromus morrisoni
 - Local catchments
 - Watershed
 - Karst
 - Impaired streams
 - ◇ Dams and barriers
 - ⊙ Mines
- NLCD 2016**
- Open water
 - Developed, open space
 - Developed, low intensity
 - Developed, med intensity
 - Developed, high intensity
 - Barren land
 - Deciduous forest
 - Evergreen forest
 - Mixed forest
 - Dwarf shrub
 - Shrub/scrub
 - Grassland
 - Pasture/Hay
 - Cultivated crops
 - Woody wetlands
 - Herbaceous Wetlands

	2006	2016	Projected 2030
Percent developed:	4	4	4
Percent pasture:	8	7	6-13
Percent crop:	0	0	0
Percent forested:	88	87	81-89

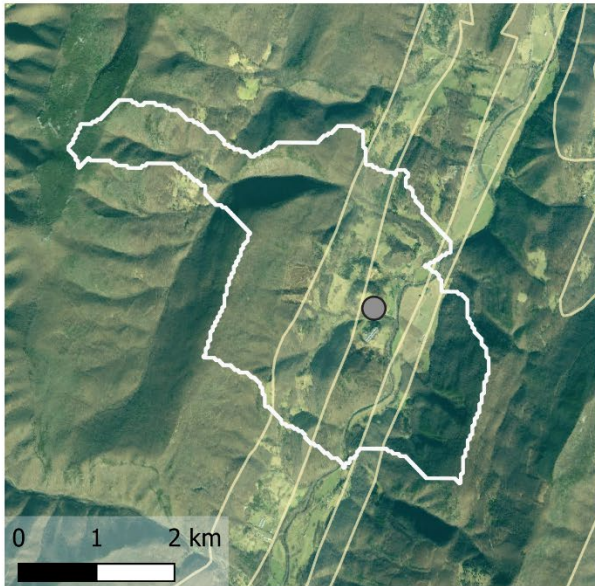
Within shale play: No
 Number mines: 8
 Number dams: 0

CAFOs per county (2007): 19

Stream impairment: Pathogens (E. coli)

Stygobromus morrisoni - Kenny Simmons Cave

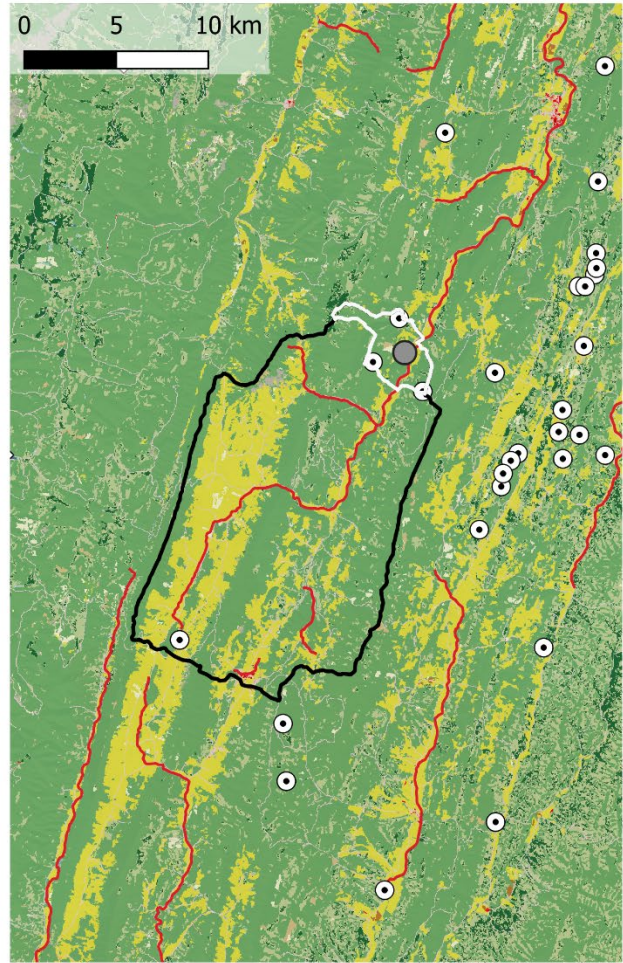
Local catchments within 1 km of locality



Closeup of locality



Land use in upstream watershed



- Stygobromus spp.**
- Stygobromus morrisoni
- Local catchments
- Watershed
- Karst
- Impaired streams
- ◇ Dams and barriers
- ⊙ Mines
- NLCD 2016**
- Open water
- Developed, open space
- Developed, low intensity
- Developed, med intensity
- Developed, high intensity
- Barren land
- Deciduous forest
- Evergreen forest
- Mixed forest
- Dwarf shrub
- Shrub/scrub
- Grassland
- Pasture/Hay
- Cultivated crops
- Woody wetlands
- Herbaceous Wetlands

	2006	2016	Projected 2030
Percent developed:	3	2	3
Percent pasture:	18	17	9-22
Percent crop:	0	0	0
Percent forested:	79	80	77-87

Within shale play: No
 Number mines: 5
 Number dams: 0

CAFOs per county (2007): 18

Stream impairment: Pathogens (E. coli, fecal coliform); Polychlorinated biphenyls (PCBs)

7.2 Supplemental tables

Table 9. Parameter estimates for scaled Beta distributions fit to expert judgments. Distributions were fit by minimizing the sum of squared differences between elicited and fitted probabilities along the cumulative distribution function using the SHELF protocol, and were scaled to the identified interval (Limits).

Species	Localities	Limits	α	β
<i>Stygobromus cooperi</i>	Silers Cave	0.05 - 0.90	2.41	2.33
<i>Stygobromus morrisoni</i>	Dyers Cave	0.20 - 0.90	2.25	1.74
	Kenny Simmons Cave	0.10 - 0.80	2.15	1.94
	Corbett Cave	0.20 - 0.95	2.46	1.57
	Secret Anthodite Cave	0.20 - 0.95	2.46	1.57
	Mountain Grove Saltpetre Cave	0.30 - 0.95	2.61	1.47
	Starr Chapel Saltpetre Cave	0.30 - 0.95	2.61	1.47
	Clarks Cave	0.10 - 0.85	2.63	1.83
	Crossroads Cave	0.10 - 0.99	4.62	3.61
	Witheros Cave	0.25 - 0.99	2.77	1.39
<i>Stygobromus parvus</i>	Bonner Cave	0.20 - 0.99	3.74	1.69
	Bonner Mountain Cave	0.10 - 0.95	4.75	1.96
	Bonner Pit Cave	0.10 - 0.95	4.75	1.96
	Shreve-Howell Pit	0.20 - 0.95	1.97	1.29
	Izaak Walton Cave	0.20 - 0.98	3.83	1.55
	Crawford Cave No. 2	0.10 - 0.99	2.34	1.24
	Cassell-Windy Cave	0.10 - 1.00	3.02	1.45
	Piddling Pit	0.20 - 0.98	6.24	2.00