Salamander Use of Karst Sinkholes in Montgomery County, Virginia

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Abstract - To better understand salamander-habitat relationships in karst sinkholes, we surveyed 25 sinkholes and three upland control sites at the Selu Conservancy (Montgomery County, VA) in the spring and summer of 2008. At each site, we measured 26 habitat parameters (e.g., number/decomposition stage of downed logs and snags, soil moisture, soil temperature, canopy coverage, leaf-litter depth). With these data, we questioned if sinkholes supported higher salamander densities than non-sinkhole habitats, if salamander densities changed throughout the spring and summer months in response to changes in soil temperature and soil moisture, and which microhabitat measures were most strongly correlated with average salamander densities. In seven rounds of surveys, we captured 292 *Plethodon cinereus* (Eastern Red-backed Salamanders) and 223 *Plethodon glutinosus* (Northern Slimy Salamanders). Although we found that capture success did vary among rounds, we found no significant differences in salamander densities between sinkholes and upland sites. We discovered a weak positive relationship between total captures per round and percent soil moisture. Non-metric multidimensional scaling ordination suggested that capture success for both species was markedly lower in sinkholes in and surrounded by early successional habitats than those within a forest matrix. Indirect indicators of soil fertility (e.g., percent organic matter, bryophyte cover, litter depth) were correlated to salamander capture success. Our study serves as a springboard for an ongoing project that examines patterns in salamander genetic diversity across a wider range of sinkholes with varying historical land-use patterns.

Introduction

Karst sinkholes in southwestern Virginia are small (typically <1 ha) depressions in the landscape resulting from the gradual dissolution of subsurface limestone or other water-soluble carbonate bedrock material (Kastning 2003, Woodward and Hoffman 1991). The rate of such dissolution depends greatly on natural (water table levels, rainfall) and anthropogenic (various types of human disturbance) factors. Oftentimes, sinkholes are the avenue by which surface water pools and then seeps into the groundwater table (Hubbard 2007).

Kastning (2003) mapped and described the topography and geology of 41 karst sinkholes located on Radford University's Selu Conservancy in Montgomery County, VA (156 ha; Fig. 1). Her work emphasized the importance of these habitats on a regional basis and the stresses they encounter due to their placement on "weak zones," which make them highly susceptible to groundwater pollution and surface instability (Kastning 2003).

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Although these karst sinkholes on the Selu Conservancy have been thoroughly described from a topographic and geologic perspective (Kastning 2003), little is known about the biotic communities of these unique habitats. Furthermore, as the forested sections of this tract (ca. 120 ha) are relatively protected (restricted public access, hiking trails maintained to limit erosion; Kastning 2003), biotic surveys of these habitats will provide important baseline data for future research investigating salamander use of regional sinkholes subject to differing anthropogenic land-use histories. Given their life-history characteristics and suspected habitat preferences from preliminary upland forest and forest sinkhole surveys in 2007 (K. Francl, unpubl. data), we deemed salamanders as an appropriate choice for assessing the ecological value of these isolated landscape features (karst sinkholes). Two species captured in sinkholes in 2007—*Plethodon cinereus* Green (Eastern Red-backed Salamander) and the *Plethodon glutinosus* Green (Northern Slimy Salamander)—were the focus of this investigation. These two species are capable of traversing forested landscapes and moving among sinkholes, yet their small home-range size (both average <15 m^2; Kleeberger and Werner 1982, Merchant 1972) shows them capable of living exclusively within even the smallest of recognized sinkhole habitats at the Conservancy (34 m^2; Table 1).

We questioned whether biotic or abiotic factors (or a combination of the two) were attracting Red-backed and Slimy Salamanders to these sinkhole habitats. Previous studies in southwestern Virginia (Giles County) in non-sinkhole upland forest habitats found that both Slimy and Red-backed Salamander abundances were positively related to increased cover (rocks, downed logs) and increased soil moisture (Grover 1998, Marsh and

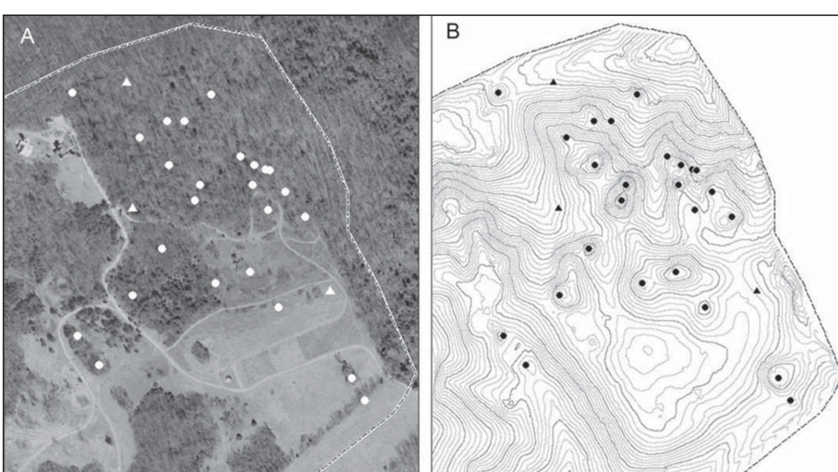

Figure 1. (A) Aerial photograph (2002; Aerial Imagery, Commonwealth of Virginia) showing field and forest habitats and locations of survey sites within the boundaries of the Selu Conservancy, Montgomery County, VA. (B) Topographic map (1-m contours; Kastning 2003) showing locations of sinkhole (circles) and upland (triangles) survey sites within the boundaries of the Conservancy.

Beckman 2004). Higher soil temperature also was linked to greater captures (ergo, inferred abundances) of Red-backed Salamanders (Grover 1996).

From these recognized salamander preferences, we sought to determine: 1) if sinkholes supported higher salamander densities than non-sinkhole habitats 2) if salamander densities changed throughout the spring and summer months in response to changes in soil temperature and soil moisture and 3) which microhabitat measures were most strongly correlated with average salamander densities. We expected higher salamander densities (restricted to surface activity as estimated through capture success) in sinkhole sites as compared to non-sinkhole sites, given that sinkholes pool water and that soil moisture would therefore be greater at these sites. We expected both species to respond positively to increases in soil temperature and soil moisture. Finally, we expected that habitat cover availability (e.g., percent cover of rocks, snag, and log density) would be positively related to salamander capture success.

Table 1. Sinkhole (n = 25) and non-sinkhole upland (n = 3) sites surveyed for salamanders in spring and summer 2008 at Radford University's Selu Conservancy (Montgomery County, VA). UTM (NAD83, Zone 16N) northing and easting values listed for each site. Also listed is area of sinkhole, plus number of minutes each site was surveyed per round (based on area calculation).

	UTM Northing	UTM Easting	Area (m^2)	Minutes surveyed
Baby	539742	4104904	34	1.6
Big Field	539707	4104752	1732	83.1
Brambles	539531	4104717	1658	79.6
East Ridgecrest	539748	4104897	74	3.5
Elbow	539717	4104928	326	15.7
Entrance	539888	4104570	1276	61.3
Fallen Logs	539575	4104785	652	31.3
Fenceline	539911	4104543	123	5.9
Frog Pond	539761	4104885	704	33.8
Hole-in-the-Wall	539642	4105034	534	25.6
Lower Valley	539560	4104919	1135	54.5
Marshy	539803	4104845	1073	51.5
North Loop	539717	4104884	972	46.7
North Ridgecrest	539569	4104990	1486	71.3
Oak Leaf	539607	4104985	1567	75.2
Quad-North	539633	4104888	1125	54.0
Quad-South	539618	4104855	1463	70.2
Rockpile Burn Field	539755	4104696	316	15.2
South Loop	539734	4104855	241	11.6
Subtle	539530	4104963	733	35.2
Tiny	539694	4104939	39	1.9
Upper Valley	539418	4105031	1276	61.2
Valley Train	539438	4104631	789	37.9
Valley Train 2	539475	4104587	261	12.5
West Field	539655	4104734	1047	50.3
Upland 1	539760	4104785	900	43.2
Upland 2	539500	4104850	900	43.2
Upland 3	539450	4105050	900	43.2

Methods

Site description

Radford University's Selu Conservancy tract is a 156-ha natural area in Montgomery County, VA (Fig. 1). Historically, much of this site was cleared for agriculture through the 1960s (Leftwich 1992). Today, much of the eastern half of the Conservancy (the focus of this study) lies in 50–60-year-old second-growth forest, dominated by *Quercus* spp. (oak), *Liriodendron tulipifera* L. (Tulip Poplar), *Fraxinus americana* L. (White Ash), and hickories (esp. *Carya ovata* [Mill.] K. Koch [Shagbark Hickory]and *C. alba* [L.] Nutt. ex Ell. [Mockernut Hickory]). About 4 ha are maintained through prescribed burning or mowing as early successional native grassland; three sinkholes occur within this area (Fig. 1).

We selected 25 sinkholes (size range = 34–1732 m^2) mapped by Kastning (2003) (Table 1). Three upland sites (area = 900 m^2, the average size of the surveyed sinkholes) also were selected—one in the fire-maintained field, and two in upland mature, closed-canopy forests.

Salamander surveys

We surveyed each of the 25 sinkholes seven times from February to July, 2008, at approximately 3-week intervals. The three upland sinkholes were added after the completion of the first round, and were therefore surveyed six times (March to July, 2008). We conducted these hand-capture surveys on days in which the temperature met or exceeded those seasonal minimums set by the Virginia Frog and Toad Calling Survey (Garrett 2002) and lacked heavy rain. Ambient temperature was measured with a Kestrel 3000 pocket weather meter (Nielsen Kellerman, Boothwyn, PA).

We surveyed sites for time periods based on the estimated total area (maximum length x maximum width; calculated area of an ellipse to account for circular and oblong-shaped sinkholes) of the sinkhole (Table 1; Francl 2005), so that effort-per-square-meter (4.8 minutes per 100-m^2) did not differ across sites. All searches focused on the overturning of logs, rocks, and boulders, as well as examinations of snags and leaf litter in a non-destructive manner.

All captured salamanders were identified, weighed, and measured (total length, snout–vent length). Additionally, ca. 3 mm of each salamander's tail was clipped and transferred to vials containing 70% ethanol. These tails will be utilized in on-going salamander genetics research (R. Sheehy, Radford University, Radford, VA, pers. comm.). The clips also served as a method to note recaptures within the same season. After measuring and clipping, individual salamanders were released near the point of capture within the surveyed sinkhole. All methods were approved by the Radford University Animal Care and Use Committee (Protocol #FY08-007).

Habitat measures

We measured 26 habitat and environmental variables at each site. Variables measured in January/February 2008 included: sinkhole or upland survey area (described above); the number of upright snags (diameter at breast height [1.37 m; DBH] > 5 cm) and downed logs (length > 2 m, diameter > 5 cm; Francl 2005) per plot; snag and log DBH and respective stage of decomposition (utilized averages per site; Maser et al. 1979); number of exposed boulders (>15 cm) per sinkhole; spring (pre-leaf-out) and summer canopy cover (using a concave spherical densiometer; measured in four cardinal directions from center of sinkhole); average leaf-litter depth (average of 20 measures randomly placed within each sinkhole); average slope (measured in four cardinal directions from center of sinkhole with a clinometer).

Vegetation and associated habitat variables were assessed in June and July 2008, in sample plots ranging in size from 36–400 m^2. Plot sizes were established to most closely approximate the size of each sinkhole, with a maximum plot size of 400 m^2. Within each plot, the percentage ground area covered by each vascular plant species was estimated, as well as total ground, shrub layer, and canopy cover. For all woody stems reaching or exceeding 1.37 m (breast height), plot basal area and density were determined. In addition, bryophyte, decaying wood, and leaf-litter cover were estimated. Range pole measures in each plot were used to calculate the Levins index of vertical diversity (Levins 1968) and total vegetation volume (TVV, Mills et al. 1989). Five replicate measures of photosynthetically active radiation (PAR, LI-250A quantum sensor light meter, LI-COR, Lincoln, NE) and percent soil moisture (Kel Instruments, Inc., Wyckoff, NJ) were taken from each plot to characterize canopy light penetration and moisture availability. Composite soil samples from the upper 10 cm were collected from each plot and used in laboratory determinations of pH (glass-electrode method; Oakton Double Junction pHTestr 20, Oakton Instruments, Vernon Hills, IL) and percent organic matter (dry ash method; Shepard et al. 1993).

Furthermore, each time we surveyed for salamanders, we measured soil temperature and percent soil moisture at five random points within the sinkhole. These five measures were averaged and compared to round-by-round salamander captures-per-unit-effort.

Statistical analyses

Trends across rounds were examined with a repeated measures ANOVA to determine if captures varied by round and between sinkhole and non-sinkhole sites; however, because non-sinkhole sites were not surveyed in round 1, only rounds 2 through 7 were statistically analyzed. We then utilized a repeated measures mixed regression to examine additional trends in all seven rounds (SAS 9.1, SAS Institute, Cary, NC). We utilized soil moisture, soil temperature, and the interaction between the two to examine site-by-site trends between these measures and the average number of salamanders captured per square meter searched.

Non-metric multidimensional scaling (NMS) ordination was used to examine salamander capture success relative to stand and site characteristics across sample plots. NMS is an indirect ordination technique, assessing relationships among sample plots based on species composition and abundance. This ordination method differs from other commonly used techniques (e.g., DCA, PCA) in being non-parametric and iterative, using ranked distances to arrange sample plots along a number of axes determined by a minimal stress configuration. NMS has been shown to perform well with ecological data that tend to be non-normal and contain numerous zero entries (Minchin 1987). Mean number of salamander captures by species and total salamander captures at each of the 28 sample sites were analyzed using the global NMS procedure performed by PC-ORD for Windows (version 5.14; MjM Software, Gleneden Beach, OR). Following ordination analysis, stand and environmental variables were correlated with NMS axis scores to identify habitat variables most strongly influencing salamander capture success (Pearson product-moment correlations, PC-ORD for Windows).

Results

Across seven rounds of surveys, we captured 515 salamanders: 223 Slimy Salamanders from 22 sites, and 292 Red-backed Salamanders from 23 sites. In 26 of the 28 sites, we captured at least one salamander during the survey period. The two remaining sites (East Ridgecrest [a forested sinkhole] and Upland 1 [a non-sinkhole grassland control]) had no salamander captures.

Salamander capture success (hereafter, defined as salamanders captured per m^2) per round varied significantly among rounds 2–7 ($F = 7.786$, df = 5, $P < 0.001$), but the difference in capture success between sinkholes and non-sinkholes was not significant ($F = 2.238$, df = 1, $P = 0.147$) (Fig. 2).

When examining the temporal influence of soil moisture and soil temperature on the salamander capture success, we found mixed results. When examined separately, neither salamander species showed any significant

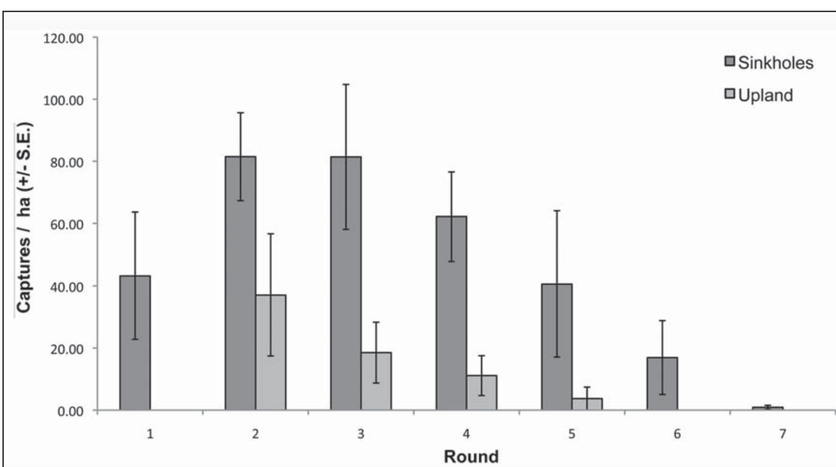

Figure 2. Average number of salamander captures per hectare per round (± standard error) for 25 sinkhole (dark grey) and 3 non-sinkhole (light grey) sites (non-sinkholes not surveyed in round 1). Statistical analyses revealed significant differences among rounds 2–7 ($F = 7.786$, df = 5, $P < 0.001$), but not between sinkholes and non-sinkholes ($F = 2.238$, df = 1, $P = 0.147$).

relationship between capture success and soil temperature or moisture (Table 2). However, when examining both salamanders collectively, we found a weak ($P = 0.051$) relationship between soil moisture and salamander captures (Table 2).

The NMS ordination was best fit by a two-axis solution, as determined by a Monte Carlo randomization test ($P < 0.05$) and NMS scree plot. The first two NMS axes accounted for 95.1% of the variability in the data (axis 1 = 87.5%, axis 2 = 7.5%; final stress = 2.38; final instability <0.001; 82 iterations). To accommodate statistical assumptions of ordination analysis, the two survey sites lacking salamander captures were excluded from the NMS ordination.

Slimy and Red-backed Salamanders showed similar habitat preferences, based on NMS ordination results. Capture success for both species showed strong positive correlations with NMS axis 1 (Red-backed Salamanders, r = 0.75, *P. glutinosus, r* = 0.67) and negative correlations with axis 2 (Slimy Salamanders, r = -0.44, Slimy Salamanders, r = -0.90). Thus, the greatest numbers of captures per square meter occurred in survey sites positioned high on NMS axis 1 and low on axis 2 (Table 3, Fig. 3). Both salamander species showed markedly higher numbers of captures in forested sinkholes than in early successional (field) sinkholes or upland sites (Fig. 3). Note that abundance (mean number of captures per round) of Slimy Salamanders was similar across nearly all forested sinkholes, whereas trends for Red-backed Salamanders were influenced by greater abundance in a single forested sinkhole site (Fig. 3).

Following ordination analysis, habitat variables were correlated with NMS axis scores to identify the variables most strongly influencing salamander capture success (Table 3). The variables correlated with the greater capture successes found in forested sinkholes (i.e., positively correlated with axis 1 and negatively correlated with axis 2) were leaf-litter depth, bryophyte cover, tree canopy cover, soil organic matter, and number of standing snags (Table 3, Fig. 4). Surveys in upland controls and field sites

Table 2. Results from repeated measures mixed regressions, examining salamander capture success (for each species separately, plus all captures combined) as the dependent variable and soil temperature and moisture (and their interaction) as predictive variables.

	Num df	Den df	*F*	*P*
Eastern Red-backed Salamander				
Soil temperature	1	161	0.16	0.694
Soil moisture	1	161	1.92	0.168
Soil temperature * soil moisture	1	161	0.90	0.344
Northern Slimy Salamander				
Soil temperature	1	161	0.57	0.453
Soil moisture	1	161	2.12	0.147
Soil temperature * soil moisture	1	161	1.27	0.261
Both species				
Soil temperature	1	161	0.56	0.456
Soil moisture	1	161	3.87	0.051
Soil temperature * soil moisture	1	161	2.02	0.158

had poor capture success. These low numbers of salamander capture success were associated with greater TVV, higher sinkhole area, and higher spring canopy cover (i.e., fields and thickets with tall grasses and shrubs persisting in late winter and early spring; Table 3, Fig. 4).

Discussion

Our results indicated that salamander populations in sinkholes did not markedly differ from our three upland control sites. We attribute this trend to the immense variability in sinkhole microhabitat features, combined with a lack of captures at one of our three upland control sites (that resulted in our removing it from some analyses). The remaining upland sites were both forested habitats with similar microhabitat features as other forested sinkhole sites.

However, the lack of salamanders in a field habitat lends credence to our assumption that landscape-level habitat designations (whether the

Table 3. Pearson product moment correlations between NMS axis scores for each sample site and salamander capture success or quantitative habitat variables.

Variable	*r* Axis 1	*r* Axis 2
Salamander capture success		
Total salamander	0.84	-0.66
Plethodon cinereus	0.75	-0.44
Plethodon glutinosus	0.67	-0.90
Habitat variables		
Total vegetation volume (TVV)	-0.55	0.63
Sinkhole area (m^2)	-0.45	0.57
Spring canopy cover (%)	-0.28	0.43
Boulder (no./sinkhole)	-0.24	0.02
Photosynthetically active radiation (µmol/sec/m^2)	-0.19	0.19
Decaying log cover (%)	-0.18	0.24
Boulder cover (%)	-0.13	-0.29
Logs (no./ m^2)	-0.12	-0.29
Snags (no./ m^2)	0.04	-0.40
Total ground layer cover (%)	0.11	0.31
Rock cover (%)	0.13	-0.36
Summer canopy cover (%)	0.13	-0.26
Levins index of vertical diversity	-0.08	0.18
Total shrub cover (%)	0.03	-0.10
Log diameter (cm; average)	0.05	-0.02
Snag decay stage (average)	0.17	-0.18
Snag diameter (cm; average)	0.19	-0.20
Soil pH	0.23	-0.11
Leaf litter cover (%)	0.25	0.07
Soil moisture (%)	0.25	-0.01
Log decay stage (average)	0.25	-0.28
Slope angle (%)	0.31	-0.49
Bryophyte cover (%)	0.37	-0.47
Tree canopy cover (%)	0.41	-0.42
Soil organic matter (%)	0.44	-0.37
Leaf-litter depth (cm; average)	0.51	-0.71

sinkhole was surrounded by mature forest versus an open-canopied early successional field) was a strong driver in predicting salamander densities. Our NMS ordination results confirmed these predictions for salamander habitat preferences. Specifically, salamander capture success was greater in habitats with increased soil moisture and moisture-enhancing parameters

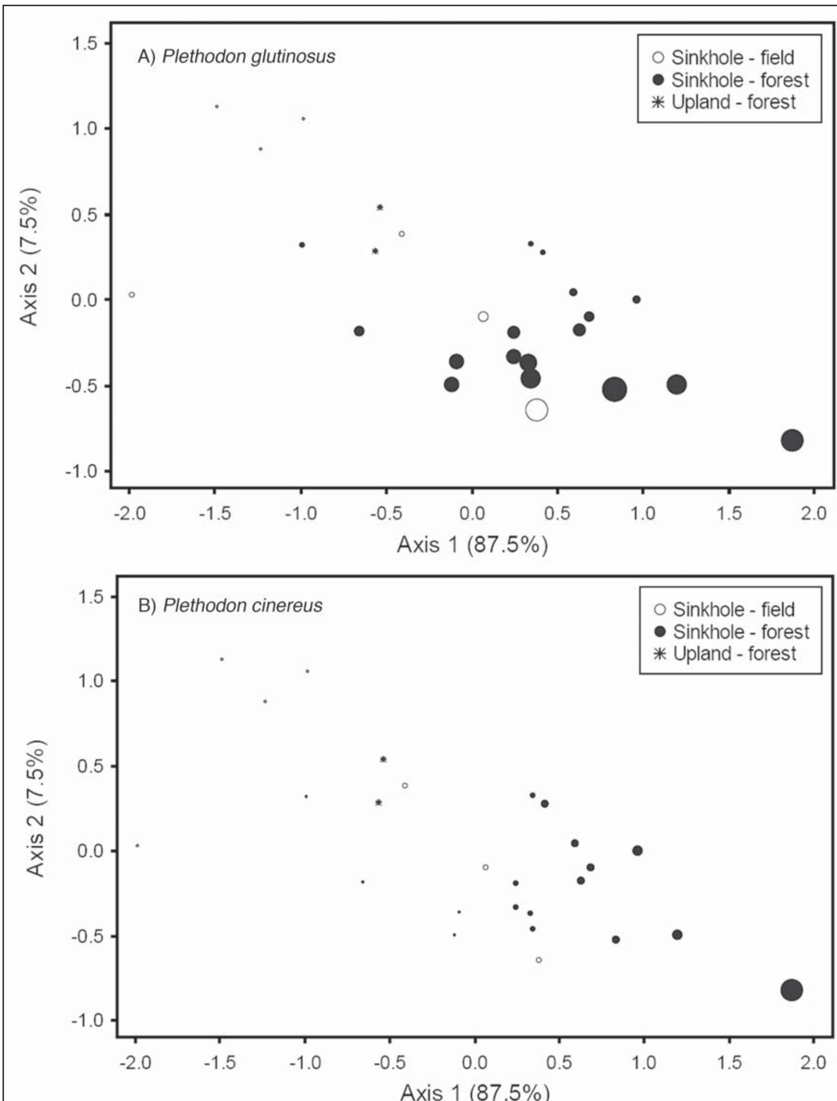

Figure 3. Non-metric multidimensional scaling (NMS) ordination of mean salamander capture success for (A) Northern Slimy Salamanders and (B) Eastern Red-backed Salamders at 26 survey sites at the Selu Conservancy. Symbol size indicates relative capture success at each site. Open circles represent grassland sinkholes; closed circles represent forest sinkholes. Asterisks represent upland control sites (See Fig. 4 for full-sized symbols).

(e.g., tree canopy, bryophyte cover, soil organic matter) and increased habitat cover (e.g., leaf litter, standing snags)—habitat variables indicative of later successional, forested habitats. Given that sites surrounded by or partly defined as an early successional habitat (e.g., fields and thickets) consistently captured fewer salamanders, we believe that isolation from a continuous mature forest may inhibit Red-backed and Slimy Salamander habitation. Future studies incorporating additional upland control sites and field sites at known distances to contiguous forest tracts may help to better explain these findings.

We found that salamander capture success did change across rounds, as success markedly declined as the summer temperatures increased. This trend is typical in salamander research, as salamanders tend to burrow deeper into the soil as ambient temperatures rise (Heatwole 1962). However, we did not find that these changes in capture success were directly in line with soil moisture or soil temperature on a species-specific basis. Our assumed lack of dependence on soil moisture (only significant when both species' capture rates were examined jointly) contradicts a number of studies that emphasize the importance of this habitat measure (e.g., Grover 1998, Heatwole 1962, Marsh and Beckman 2004). It is possible that the range in soil moisture—and, indeed soil temperature, as well—simply remained within a range of tolerance for both species, so that obvious species-specific responses could not be detected.

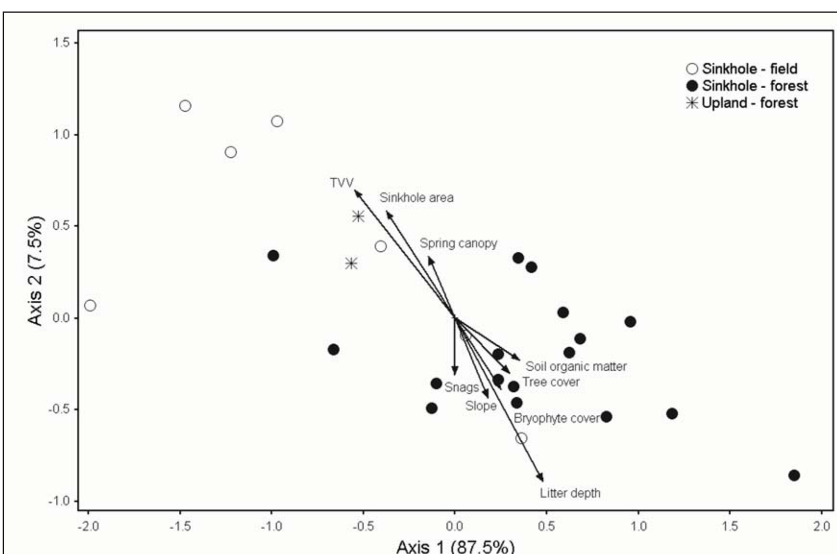

Figure 4. Non-metric multidimensional scaling (NMS) ordination of mean salamander capture success in 26 survey sites at the Selu Conservancy, Montgomery County, VA. Vectors indicate the strength and direction of habitat variable correlations with NMS ordination axes. Longer vectors indicate stronger correlations; correlation reaches its maximum in the direction shown. Open circles represent grassland sinkholes. Closed circles represent forest sinkholes. Asterisks represent upland control sites.

Our negative relationship between salamander capture success and total vegetation volume contradicts previous research, as well. Indeed, Heatwole (1962) found that the amount of vegetation positively influenced salamander abundances—opposite of our findings. However, we believe that our TVV metric reflected grassy sites surrounded by early successional areas—perhaps an indirect indicator of sinkhole isolation rather than a direct reflection of capture success. This isolation from contiguous forest tracts may feed into research on edge effects by Marsh and Beckman (2004). Their study examined the effects of Red-backed and Slimy Salamander densities in relation to distance to forest (gravel) roads—roads similar to those found at the Selu Conservancy. Marsh and Beckman (2004) found differences in moisture regime and capture success at distances from roads of 20–80 m into the forest. Given that the majority of our sites are within 80 m of a forest edge (meeting roads or early successional fields; Fig. 1), the edge effect may be playing a strong role in our capture success and the trends we discovered.

Conclusion

Our results suggest that the immediate surrounding landscape (e.g., sinkholes in a forest matrix vs. sinkholes isolated in a field matrix) affects salamander capture success. Secondarily, microhabitat measures appear to drive relative densities. Because of the variability in microhabitat measures across sinkhole sites, it appears that forested sinkholes provide favored but not unique habitats for these two species of salamanders. However, we emphasize that understanding sinkholes' full value to salamanders is a work in progress, as we are examining trends as a snapshot in time.

To better understand how sinkholes are ecologically valuable, we plan to build on this project, examining the effect(s) of historical land use on salamander populations. Through our collection of over 400 salamander tail samples from this study, genetic analyses may help us to understand if these sinkholes served as refugia for forested salamanders in an historically agriculturally dominated landscape (Leftwich 1992). As we expand our study to sinkholes beyond the Selu Conservancy borders, we plan to include sinkholes with differing past and present uses and varying lengths of time since being part of a contiguous forest habitat. With these continued surveys, we'll determine if these sinkholes serve as sources of genetic diversity on a larger scale.

Acknowledgments

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