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The Diversity and Distribution of Spiders (Arachnida: Araneae) Along an Outdoor – Indoor Habitat Gradient: Preliminary Findings from Piedmont Virginia

William Kish and Sujan Henkanaththegedara[1]
Longwood University

ABSTRACT

Although the United States supports a considerable diversity of spiders, some aspects of spider habitat use and niche specialization are poorly documented. Specifically, little attention has been given to explore how urban development affects the diversity and abundance of arthropods. We sampled spiders along an outdoor – indoor habitat gradient at Longwood University to understand the impact of urbanization on species diversity and abundance. We found 50 taxa of spiders belonging to 43 genera and 16 families. Overall, the most abundant spider family across three sampling sites was *Araneidae* (orb-weavers; 18.2%) followed by *Lycosidae* (wolf spiders; 14.8%), *Salticidae* (jumping spiders; 13.6%) and *Linyphiidae* (sheetweb spiders; 12.5%). We found the highest species richness, spider abundance, and Shannon-Wiener diversity from Lancer Park (i.e. outdoors habitat), followed by the habitats associated with outside of the science center building (i.e. marginal habitat) and the lowest spider diversity inside the science building (i.e. indoors habitat). We also found a strong positive correlation between overall spider diversity and air temperature for outdoors and marginal habitats, but no correlation with relative humidity. Our study adds original knowledge about habitat use of spiders along an outdoor - indoor habitat gradient and arthropod use of indoor biome. More importantly, our study stresses the need for more extensive systematic studies to fully understand how spatial and temporal variation of arthropod diversity and abundance may be influenced by alterations of habitats by humans through urbanization.

INTRODUCTION

Spiders are one of a few cosmopolitan groups of organisms utilizing a range of habitats from hot deserts to the cold Arctic (Foelix 2011) to urban habitats with man-made structures. Worldwide, there are about 48,000+ (World Spider Catalog 2019) formally described species of spiders including at least 3,800 species in North America (Bradley 2013). Although spiders are ubiquitous, little attention is typically given by the ecology research community, to study their diversity, biology, and ecology, possibly due to their small size, seemingly secretive behavior, lack of information on true diversity and

[1] *henkanaththegedarasm@longwood.edu*

subjective fear of spiders in general. With that being said, the true diversity of spiders in the eastern United States may be poorly documented (Howell and Jenkins 2004).

Spiders play important ecological roles in their habitats, mainly as predators and prey. They are important predators in the natural ecosystem (Foelix 2011, Mallis and Rieske 2011) and are typically generalist predators, many feeding on different terrestrial arthropods, but some are specialists (Mallis and Hurd 2005, Mallis and Rieske 2011). Agriculturally, spiders are very helpful in limiting the amount of pest populations in crops. It is estimated that spiders consume 400-800 million tons of prey annually (Mallis and Hurd 2005). Spiders are very efficient as natural pest control agents, hence some rice farmers in Asia do not use pesticides (Nyffeler and Benz 1987). Additionally, spiders have complex trophic networks and may belong to more than one trophic level based on their diet and size (Wise et al. 1999). For example, larger wolf spider species tend to prey on herbivores while smaller wolf spiders in leaf litter prey on detritivores, fungivores, and herbivores (Mallis and Hurd 2005). On the other hand, spiders are also a source of food for many larger organisms including birds (Rogers et al. 2012).

Although the United States supports a considerable diversity of spiders, some aspects of spider habitat use and niche specialization are poorly documented (Howell and Jenkins 2004). A recent study concluded that eastern hemlock canopies were more diverse than deciduous canopies for spiders (Mallis and Rieske 2011). Mallis and Hurd (2005) reported 50 species of ground-dwelling spiders from a successional gradient of habitats in southwestern Virginia including habitat specialists and generalists. Smith et al. (2018) compared spider diversity between mesic and xeric habitats in Pike County, Alabama, and reported 82 species belonging to 24 families (Smith et al. 2018). Some relatively unexplored aspects of spider ecology are the use of man-made structures as habitat by spiders and how urbanization affects them.

With the rapid expansion of human population, the impacts of urbanization generally cause loss of native species diversity (Blair 1996, Gagne and Fahrig 2011). However, urbanization may also promote a few urban-adapted taxa and lead to biotic homogenization (Blair 1996). Overall, little attention has been given to explore how urban development affects the diversity and abundance of arthropods (McIntyre 2000, Shochat et al. 2004) despite the ubiquitous nature of arthropods in human dwellings. Spiders are one of many arthropod groups commonly associated with urban habitats and human dwellings. Shochat et al. (2004) showed that the transformation of a xeric natural habitat into an urban habitat caused reduced spider diversity and the establishment of a few spider taxa that can tolerate the new urban setting. Additionally, a recent study that analyzed the diversity of the indoor arthropod biome found that spiders represent nearly one-fifth of the indoor arthropod diversity (Bertone et al. 2016). Therefore, the differences in diversity and abundance of spiders may reflect the changes in trophic structure in human-altered systems (Shochat et al. 2004).

In this study, we conducted a survey of spiders along an outdoor – indoor habitat gradient at Longwood University to understand the impact of urbanization on species diversity and abundance. Specifically, our goals included 1) comparing and contrasting spider diversity from three distinct habitats covering an indoor-outdoor habitat gradient, 2) exploring the relationships between environmental conditions and the diversity of spiders, and 3) generating a preliminary species list for Longwood University premises. We predicted that indoor habitats would support less diversity of spiders compared to outdoor and marginal habitats. Additionally, we expected a positive correlation between spider diversity and two environmental variables, temperature and relative humidity.

MATERIALS AND METHODS

Study Area

This study was conducted at Longwood University in Farmville, Virginia (37.2972971,-78.3972648). We selected three specific habitats to represent an outdoor – indoor habitat gradient. We selected the lowland floodplain of the Buffalo Creek at Lancer Park as the outdoor habitat. This relatively small land area (0.12 km^2) represents a diverse array of both aquatic and terrestrial habitats including a third order stream, a series of seasonal pools, several man-made ponds, eastern deciduous forests, grasslands and hedge habitat, and some buffer habitat with parking lots and roads. We specifically sampled grassy areas with shrub or tree margins at Lancer Park (i.e. outdoor habitat). Additionally, we sampled inside the Chichester Science Building as the indoors habitat including classrooms, lab spaces, and stairwells (i.e. indoor habitat), while habitats outside Chichester Science Building including walls, windows, and adjacent vegetation up to 5 m from the building (i.e. marginal habitat) (Fig. 1). We sampled all study areas in March and April of 2018. Outdoor and marginal habitats were sampled four times, but indoor habitats were sampled only twice due to logistical limitations.

Figure 1. The major sampling locations for this study. The Lancer Park flood plain (A) served as the outdoor habitat and the Chichester science building (B) served as the indoor and marginal habitats.

Field Data Collection and Spider Identification

We collected spiders by opportunistic sampling (Motley et al. 2017) within each sampling location using an array of sampling methods during day time. Visual observations and hand picking were mainly employed in indoor habitats and additionally, sweep nets and beat sheets were used for outdoor sampling. These methods allowed us to collect spiders from diverse microhabitats. Sampling was conducted for two hours at Lancer Park and another two hours covering inside and outside of the Chichester Science building. All spiders were photographed and released back to the original capture locations. Environmental data such as temperature and humidity were collected at capture locations using the RockyMars ® RT36 temperature and humidity meter. Spiders were identified to the lowest possible taxa (i.e. genus or species) using field guides and identification keys provided by Howell and Jenkins (2004), Gaddy (2009), Bradley (2013) and Ubick et. al. (2017).

Data Analysis

Overall relative abundance of spiders for each family was estimated by dividing the pooled number of individual spiders belonging to a given family by the total number of spiders. Shannon-Wiener diversity index (H') and Simpson's dominance index (D) were computed for each sample using the following formulae (Krebs 1999) to estimate overall diversity and dominance of spider communities in each sample respectively.

$H' = -\sum (P_i * \ln P_i)$

$D = \sum (P_i)^2$

Where, Pi = fraction of the entire population made up of species i.

The mean differences between location and sampling dates for 1) number of species, 2) overall abundance, and 3) Shannon-Wiener diversity index were analyzed using non-parametric Kruskal-Wallis rank sum test. We used this test due to the small sample size of our data. The effects of measured environmental conditions on overall spider diversity calculated by the Shannon-Wiener diversity index were analyzed using simple linear models considering temperature and relative humidity as predictor variables. All statistical analyses were conducted using R statistical software program (R Core Team 2016).

RESULTS

Overall Spider Diversity

We found 88 individual spiders belonging to 50 taxa under 43 genera and 16 families (Table 1, Appendix 1). The highest diversity of spiders was reported in Lancer Park (i.e. outdoors habitat) and the least diversity inside the science building (i.e. indoors habitat). The habitats associated with the outside of the science building (i.e. marginal habitat) had an intermediate level of spider diversity. Out of 36 total spider taxa reported from Lancer Park, spiders belonging to 8 families, 27 genera and 33 taxa were restricted only to Lancer Park. Only three spider taxa were reported from inside the science building and 2 taxa belonging to a single genera (*Pholcus*) and a single family (Pholcidae; cellar spiders) were restricted to only inside of the science building. Additionally, out of 14 total spider taxa reported, 11 taxa belonging to 9 genera were restricted only to marginal habitats associated with outside of the science building (Fig. 3).

Table 1. The checklist of spiders reported during this study from both outdoor and indoor habitats. The species reported only from indoors are marked with an asterisk.

Family	**Common name**	**Number of Genera**	**Number of Species**
Anyphaenidae	Anyphaenid sac spiders	1	1
Araneidae	Orb-weaver spiders	9	9
Clubionidae	Sac spiders	1	1
Gnaphosidae	Ground spiders	1	1
Linyphiidae	Sheetweb spiders	3	3
Lycosidae	Wolf spiders	6	7
Oxyopidae	Lynx spiders	1	2
Philodromidae	Running crab spiders	1	2
Pholcidae*	Cellar spiders*	1*	2*
Pisauridae	Nursery web spiders	2	3
Salticidae	Jumping spiders	8	9
Tetragnathidae	Long-jawed orb-weavers	1	1
Theridiidae	Cobweb spiders	4	4
Thomisidae	Crab spiders	2	3
Uloboridae	Hackled orb-weavers	1	1

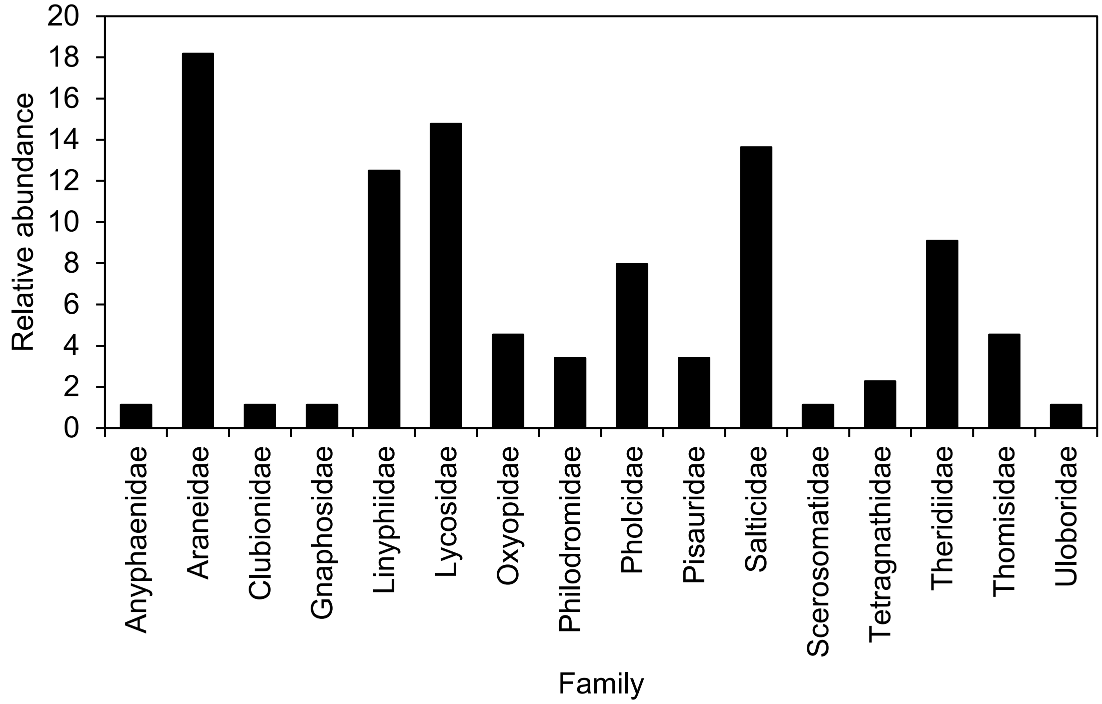

Figure 2. The relative abundance of spider families reported across Lancer Park (outdoor habitat), inside of the science building (indoor habitat) and outside of the building (marginal habitat).

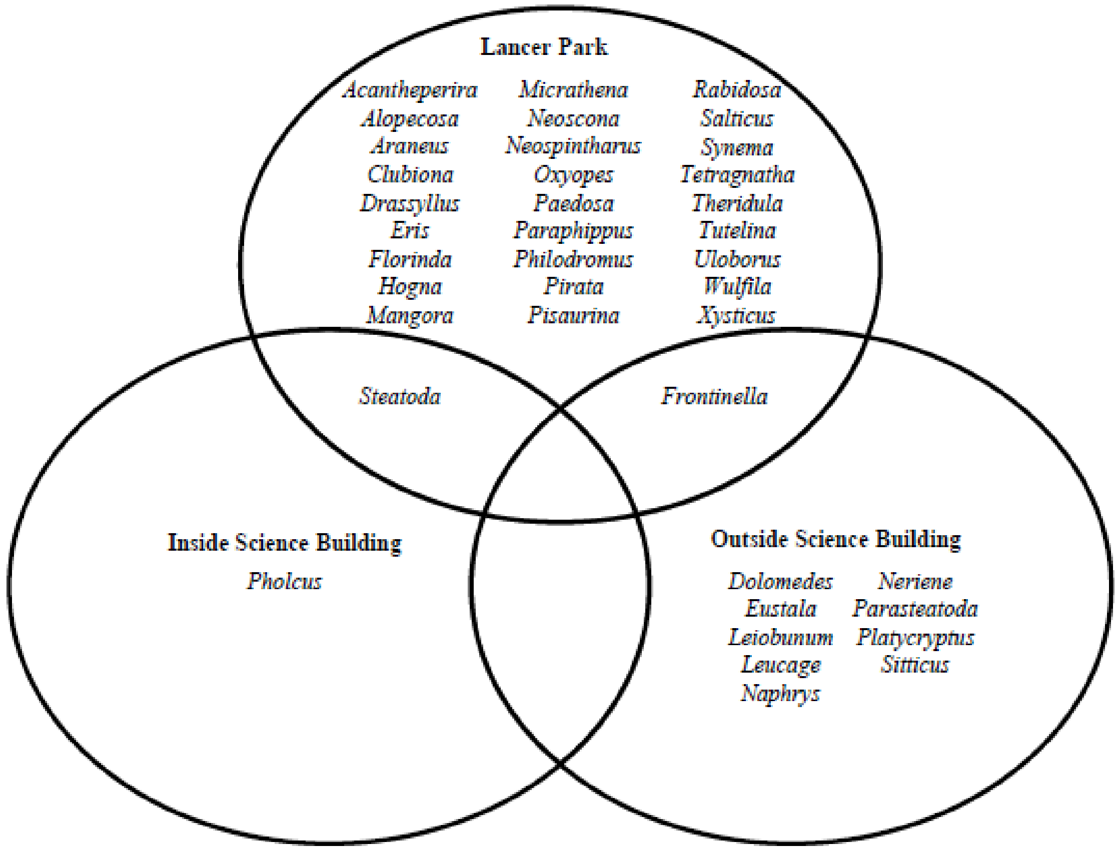

Figure 3. Venn diagram summarizing unique genera and overlapping genera of spiders from Lancer Park (outdoor habitat), inside of the science building (indoor habitat) and outside of the building (marginal habitat).

Overall, the most abundant spider family across three sampling sites was Araneidae (orb-weavers; 18.2%) followed by Lycosidae (wolf spiders; 14.8%), Salticidae (jumping spiders; 13.6%) and Linyphiidae (sheetweb spiders; 12.5%) (Fig. 2). The least abundant families were represented by single specimens for Anyphaenidae (Anyphaenid sac spiders), Clubionidae (sac spiders), Gnaphosidae (ground spiders), and Uloboridae (hackled orb-weavers) (Fig. 2). Typically, we found single individuals of spiders belonging to each species from each sampling location during each sampling session, indicating low abundance. However, relatively higher abundances (i.e. more than 3 individuals per sampling session) were reported for families Linyphiidae (sheetweb spiders), Lycosidae (wolf spiders), and Oxyopidae (lynx spiders) for Lancer Park; Pholcidae (cellar spiders) for inside science building; and Araneidae (orb-weavers), Linyphiidae (sheetweb spiders), Salticidae (jumping spiders) and Theridiidae (cobweb spiders) for the marginal habitat. Genus *Frontinella* (Bowl and Doily spider, *F. pyramitela*) was shared between the Lancer Park and outside of the science building, while genus *Steatoda* (False black widow spider, *S. grossa*) was shared between the Lancer Park and inside the science building (Fig. 3). None of the spider genera were shared between inside and outside of the science building or among all three habitats. Five spider families were shared between the Lancer Park and outside of the science building (Araneidae, Linyphiidae, Lycosidae, Pisauridae and Salticidae) while none were shared exclusively between the Lancer Park and inside the science building or exclusively between inside and outside of the science building (Fig. 3). Only one family (Theridiidae; cobweb spiders) was shared among all three habitats. The very limited shared taxa among three habitats suggests unique spider assemblages in each sampled habitat (Fig. 3).

Effects of Sampling Location on Spider Diversity

Overall, we found the highest species richness, spider abundance, and Shannon-Wiener diversity from Lancer Park (i.e. outdoors habitat), followed by the habitats associated with outside of the science center building (i.e. marginal habitat), and the lowest spider diversity inside the science building (i.e. indoor habitat) (Fig. 4). On average, the highest number of species was recorded from the Lancer Park (9.75 ± 4.71), followed by the science center building outside (4.50 ± 2.18) and inside (2.5 ± 0.50). However, we did not see a significant difference of number of species among locations (chi-squared = 2.5555, d.f.= 2, p = 0.2787; Fig. 4-A), possibly due to our small sample size. A similar trend was observed for overall abundance of spiders, where the highest abundance was recorded from the Lancer Park (12.00 ± 5.07), followed by the science center building outside (8.00 ± 5.67) and inside (4.00 ± 0.00). Again, we did not see a significant difference of abundance among locations (chi-squared = 2.0124, d.f. = 2, p-value = 0.3656; Fig. 4-B). Additionally, a similar, non-significant (chi-squared = 3.1058, d.f. = 2, p-value = 0.2116; Fig. 4-C) trend was observed for Shannon-Wiener diversity with the highest diversity occurring at the Lancer Park (1.84 ± 0.51), followed by the science center building outside (1.16 ± 0.34) and inside (0.80 ± 0.24).

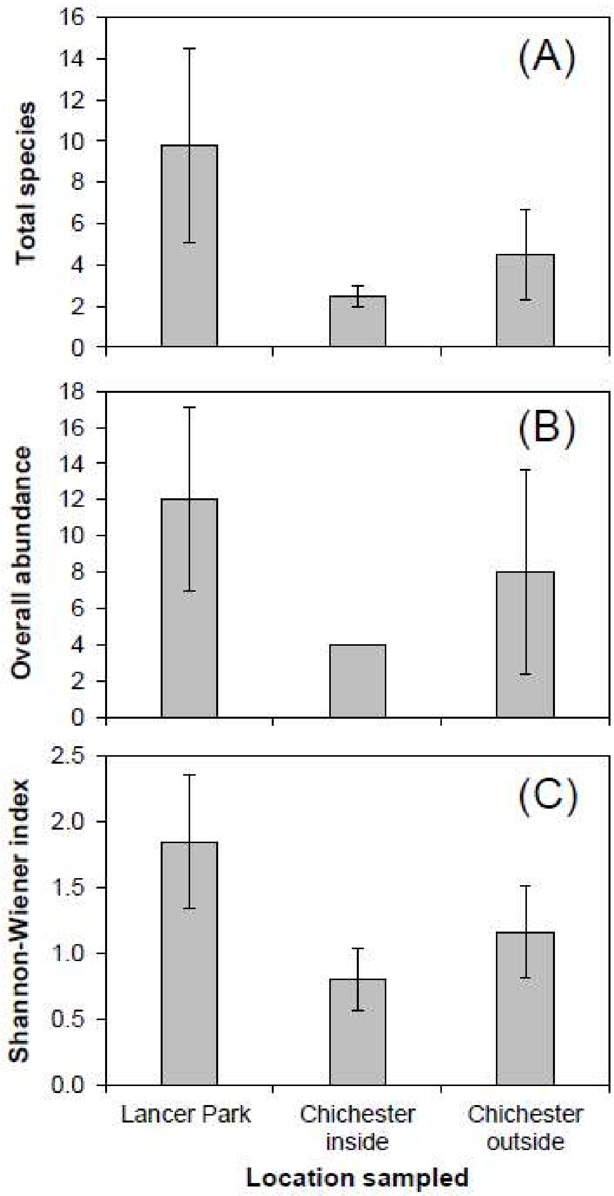

Figure 4. The average (± S.E.) number of species (A), overall abundance (B), and Shannon-Wiener diversity (C) reported for three sampling locations, Lancer Park (N = 4), inside of the science building (N = 2) and outside of the building (N = 4).

Effects of Sampling Date on Spider Diversity

Overall, we found a steady increase of species richness, spider abundance and Shannon-Wiener diversity from Lancer Park (i.e. outdoors habitat) from mid-March to late-April (Fig. 5). The spider diversity was relatively low in the habitats associated with outside of the science center building until mid-April; however, the diversity increased rapidly by late-April with a similar abundance level compared to the Lancer Park. The spider diversity was relatively low and maintained at those low levels for habitats inside the science center building regardless of the sampling time (Fig. 5). However, the collective effects of sampling date across all habitats were not significant on species diversity (chi-squared = 4.0778, d.f. = 3, p-value = 0.2532), abundance (chi-squared = 4.4953, d.f. = 3, p-value = 0.2127) and Shannon-Wiener diversity (chi-squared = 2.3788, d.f. = 3, p-value = 0.4976), possibly due to small sample size.

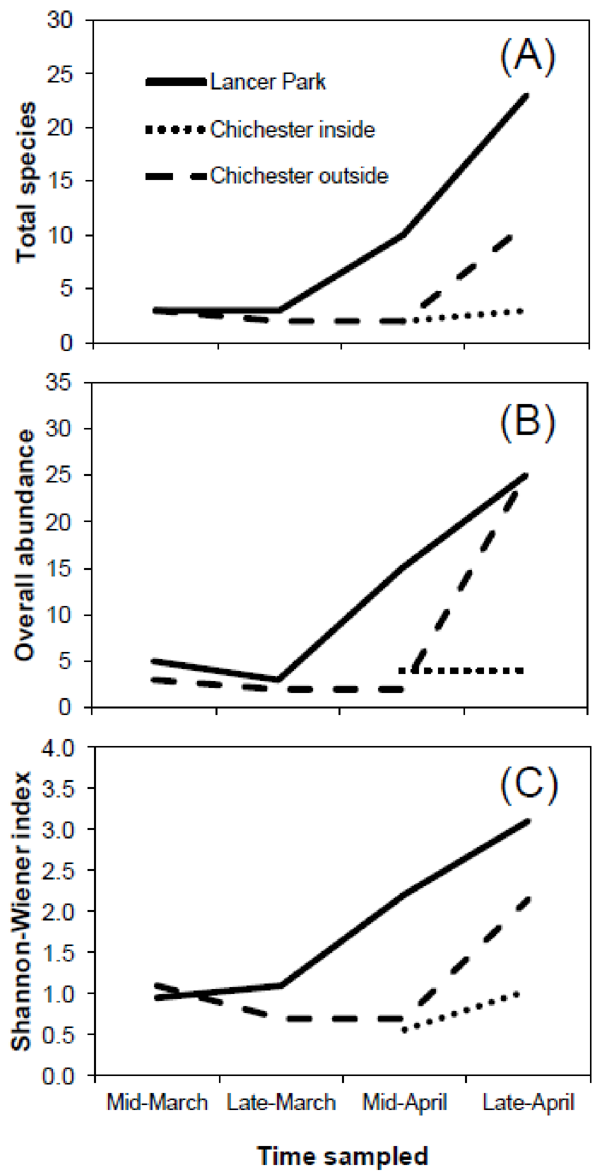

Figure 5. The effects of sampling time on number of species (A), overall abundance (B), and Shannon-Wiener diversity (C) reported from mid-March to late-April for three Sampling locations, Lancer Park (N = 4), inside of the science building (N = 2) and outside of the building (N = 4).

Effects of Environmental Conditions on Spider Diversity

We found a significant positive correlation between Shannon-Wiener diversity and temperature (R^2= 0.7092; $F_{1,8}$ = 22.95; P < 0.001) suggesting a significant increase of overall spider diversity as the temperature increases. However, we did not find any correlations between overall spider diversity and relative humidity (R^2= -0.1211; $F_{1,8}$ = 22.95; P > 0.05) suggesting no effect of relative humidity on spider diversity (Fig. 6).

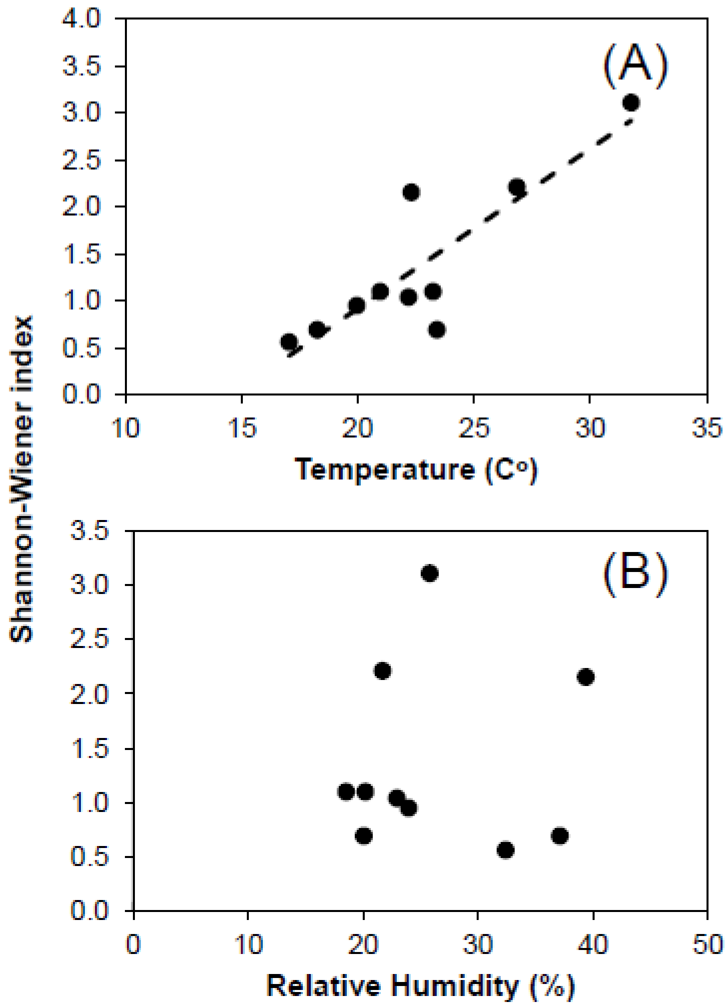

Figure 6. The effects of environmental conditions on spider diversity. A significant increase of overall spider diversity was observed as the temperature increases (R^2= 0.7092; $F_{1,8}$ = 22.95; P < 0.001), however no effect of relative humidity (R^2= -0.1211; $F_{1,8}$ = 22.95; P > 0.05). We have included both indoor (i.e. science building) and outdoor data for this analysis and each filled circle represents a single sampling event.

DISCUSSION

This preliminary survey of spiders along an outdoor-indoor habitat gradient has yielded an impressive 50 taxa of spiders (43 genera and 16 families) from a very limited study area, and with a relatively low sampling effort. The most abundant family was Araneidae (orb-weaver spiders) and the most abundant spider species was furrow orb-weaver (*Larinioides cornutus*; 9% of overall abundance). Additionally, wolf spiders (Lycosidae; 14.8%) and jumping spiders (Salticidae; 13.6%) also represented abundant groups. Spider species reported as only single specimens such as *Wulfila saltabundus* (Anyphaenidae), *Clubiona abboti* (Clubionidae) and *Drassyllus depressus* (Gnaphosidae) may represent rare taxa in the Piedmont region. Similarly, other regional studies that attempted to survey the diversity of spiders have yielded relatively higher values for the number of spider taxa with new state records (Mallis and Hurd 2005; Smith et al. 2018). This may indicate the hidden diversity of spiders in the eastern United States and emphasize the need for more research (also see Howell and Jenkins 2004) to document the full range of spider diversity covering a wide variety of habitats.

The highest diversity of spiders was reported from the outdoors habitats (i.e. Lancer Park = 36 taxa), followed by the marginal habitat (i.e. outside of the science building = 14 taxa), and the indoors habitats (i.e. inside the science building = 3 taxa). This may be due to habitat diversity together with the presence of varied microclimates in outdoors habitats compared to indoors and marginal habitats. Additionally, pest control within and around the Science Center using chemical agents may impact the spider diversity and abundance. Lancer Park is composed of various habitats including eastern deciduous forests, grasslands, hedge habitats, some buffer habitats (e.g. roads and parking lots) and aquatic habitats, which may create multiple niches to support diverse spider communities. Smith et al. (2018) also found a strong correlation between heterogeneity of habitats and spider diversity in Alabama. Upland xeric habitats with more plant diversity and moderate amounts of disturbance (i.e. fire) supported more spider diversity compared to less diversity in lowland ravine habitats. However, Mallis and Hurd (2005) found no relationship between the diversity of ground-dwelling spiders and successional age with various degrees of habitat complexity of six successional habitats in southwestern Virginia. Another possible reason for the observed correlation between spider diversity and habitat heterogeneity may be the diversity of prey base available for spiders. A more heterogeneous outdoor habitat would support a more diverse prey base compared to more homogenous indoor habitats, hence supporting a higher diversity of spiders in an outdoor habitat (Miyashita et al. 1998).

In general, urbanization poses a negative impact on species diversity and promote few urban-adapted taxa (Blair 1996). Therefore, one would expect less diversity of arthropods in indoor habitats compared to outdoor habitats. Although only a little attention has been given to the biodiversity of indoors by scientific communities, hundreds of arthropod taxa make human dwellings their home (Bertone et al. 2016) and have been co-existing with humans for thousands of years (Martin et al. 2015). Spiders are one of the major successful arthropod groups utilizing indoor environments including human dwellings (Bertone et al. 2016). However, to our knowledge, there are no reported studies comparing the spider diversity of indoor habitats with outdoor habitats. Therefore, our study adds new information on indoor habitat use by spiders. Although we have observed marked increases of both number of species and abundance of spiders in outdoors and marginal habitats from mid-March to late-April, the indoor spider diversity was maintained at a low and constant level throughout the study period. The most abundant indoor spiders in our study were cellar spiders (*Pholcus* spp.). This may represent an indoor-adapted taxa since we did not find it from outdoor and marginal habitats, and it has a global distribution associated with human dwellings (Gaddy 2009). The lack of temporal variation of spider diversity in indoor habitats may be explained by the constant environmental conditions inside buildings (e.g. air temperature and humidity; Shochat et al. 2004), and very limited species diversity may be explained by the limited prey base and special adaptations needed to deal with urban environments (Blair 1996).

The temporal and spatial variation of spider diversity and abundance may be associated with variations in environmental conditions (Bolger et al. 2000; McIntyre et al. 2001) and spider life-history (Foelix 2011). We found a strong positive correlation between overall spider diversity and air temperature for outdoors and marginal habitats. Additionally, overall spider diversity and abundance have dramatically increased from mid-March to late-April, probably due to increased air temperature and hatching of egg sacs. McIntyre et al. (2001) also reported a positive correlation between spider diversity and abundance with air temperature. This may be due to more activity of spiders (and their prey) with increasing air temperature (Foelix 2011) and/or migration of spiders to suitable habitats tracking the increased temperature (Shochat et al. 2004). Although, some studies found a positive correlation between rainfall and spider diversity and abundance (Bolger et al. 2000), others reported no effect (McIntyre et al. 2001). We did not test the effects of rainfall, but we found that there was no effect of relative humidity on spider diversity.

Although limited in scope, our study adds original knowledge about the habitat use of spiders along an outdoor-indoor habitat gradient and arthropod use of the indoor biome. Additionally, our species occurrence data may be useful to update regional biodiversity inventories for the central Piedmont of Virginia. More importantly, this study adds novel information of potential impacts of urbanization on diversity and abundance of arthropods and stresses the need for more extensive studies to fully understand how spatial and temporal variation of arthropod diversity and abundance may be influenced by alterations of habitats by humans through urbanization.

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Appendix 1. The checklist of the spiders reported from the Lancer Park and Chichester Science Building at Longwood University.

Family	Common name	Scientific name
Anyphaenidae	Ghost Spider	*Wulfila saltabundus*
Araneidae	Arabesque Orbweaver	*Neoscona arabesca*
	Arrow-Shaped Micrathena	*Micrathena sigittata*
	Furrow Orbweaver	*Larinioides cornutus*
	Hackled Orbweaver	*Uloborus diversus*
	Humpback Orbweaver	*Eustala anastera*
	Marbled Orbweaver	*Araneus marmoreus*
	Orbweaver Sp.	*Larinioides sp.*
	Spotted Orbweaver	*Neoscona sp.*
	Star-Bellied Orbweaver	*Acantheperira stellata*
	Tuft-Legged Orbweaver	*Mangora placida*
Clubionidae	Leaf-Curling Sac Spider	*Clubiona abboti*
Gnaphosidae	Ground Spider	*Drassyllus depressus*
Linyphiidae	Filmy Dome Spider	*Neriene radiata*
	Black-Tailed Red Sheetweaver	*Florinda coccinea*
	Bowl and Doily Spider	*Frontinella pyramitela*
Lycosidae	Carolina Wolf Spider	*Hogna carolinensis*
	Pirate Wolf Spider	*Pirata sp.*
	Rabid Wolf Spider	*Rabidosa ribida*
	Thin-Legged Wolf Spider	*Paedosa sp.*
	Wolf Spider Sp.	*Alopecosa aculeata*
Oxyopidae	Lynx Spider Sp.	*Oxyopes aglossus*
	Striped Lynx Spider	*Oxyopes salticus*
Philodromidae	Running Crab Spider	*Philodromus placidus*
	Running Crab Spider	*Philodromus sp.*
Pholcidae	Cellar Spider	*Pholcus manueli*
	Long-Bodied Cellar Spider	*Pholcus phalangioides*
Pisauridae	Dark Fishing Spider	*Dolomedes scriptus*
	Nursery Web Spider	*Pisaurina mira*
	White-Banded Fishing Spider	*Dolomedes albineus*
Salticidae	Bold Jumper	*Phidippus audax*
	Bronze Jumper	*Eris militaris*
	Flat Jumper	*Platycryptus undatus*
	Golden Jumper	*Paraphidippus aurantius*
	Jumping Spider Sp.	*Phidippus sp.*
	Jumping Spider Sp.	*Tutelina elegans*
	Jumping Spider Sp.	*Sitticus ammophilus*
	Jumping Spider Sp.	*Naphrys pulex*
	Zebra Jumping Spider	*Salticus scenicus*

Tetragnathidae	Long-Jawed Orbweaver	*Tetragnatha straminea*
	Orchard Orbweaver	*Leucage venusta*
Theridiidae	Common House Spider	*Parasteatoda tepidariorum*
	False Black Widow	*Steatoda grossa*
	Cobweb Spider Sp.	*Theridula opulenta*
	Cobweb Spider Sp.	*Neospintharus trigonum*
Thomisidae	Elegant Crab Spider	*Xysticus elegans*
	Ground Crab Spider	*Xysticus ferox*
	Tricolored Crab Spider	*Synema parvulum*
Uloboridae	Hackled Orbweaver	*Uloborus glomosus*