THE ROLE OF URBAN GREEN ROOFS AS INVERTEBRATE HABITAT

by

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ABSTRACT

DANIELLE MERRITT. The role of urban green roofs as invertebrate habitat. (Under the direction of DR. SARA GAGNÉ)

Developed countries witnessed an 80% expansion of urban land use between 1990 and 2015. This is leading to degradation of ecosystems and habitats, resulting in a general loss of biodiversity in urban areas. I investigated the habitat potential of urban green roofs in Charlotte, NC, to evaluate the effect of local environmental variables on invertebrate diversity and abundance on urban green roofs. I specifically considered five green roofs in Charlotte, NC, and set up pan and pitfall traps as well as vacuum sampling in order to collect invertebrate samples. I recorded the quality of habitat by measuring temperature, relative humidity, and vegetation cover at each trap location; I identified individuals to order. I hypothesized that older, larger roofs would have higher abundance and richness. I predicted higher temperature and humidity to result in lower abundance and richness. I also predicted higher cover of vegetation to be associated with higher abundance and richness. My results found a dominant association of local roof characteristics with total abundance, order richness, and Berger-Parker evenness. Higher temperatures and lower humidity were associated with lower abundances. Vegetative cover played a more varied role: higher cover of forbs predicted lower abundances, while higher cover of graminoids predicted higher abundances. While most results matched my predictions, it is recommended that individual factors be explored in greater detail to help uncover potentially masked or complex effects captured by the broad measures recorded in the present study.

DEDICATION

This thesis is dedicated to my daughter Scarlet, who participated in field season, and to my husband Jason, without whom life would be significantly less interesting.

ACKNOWLEDGMENTS

Enormous thanks are due to the undergraduate volunteers who worked with me in lab to help identify many thousands of my specimens. Especial gratitude goes out to Mackenzie Featherstone for fearlessly identifying all the endless ranks of spiders we caught, and for braving the summer heat on the roofs to help me with the less glamorous side of field work.

Gratitude goes out to Will Nash, a no-nonsense roof manager whose efforts and observations while I was not present on the roofs went above and beyond watching me lug my bugs around.

I could not have completed this work without the support of my husband, Jason Merritt, who often carved time out of his own schedule to help me with the heavy lifting.

Lastly, and not least, I am eternally grateful for the exemplary guidance and expertise of my advisor, Dr. Sara Gagné, whose conversation was always enlightening and thoughtful. Our bi-weekly lab readings developed my thinking as a scientist and my ethics as an environmentalist. She believed in my ability from the start, and her continuing friendship is invaluable.

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LIST OF ABBREVIATIONS

Roof	Roof location
T_AVG	Average 24-hour temperature
RH_AVG	Average 24-hour relative humidity
Xtotveg	% total vegetation cover around trap
Xsucc	% succulent cover around trap
Xgram	% graminoid cover around trap
Xforb	% forb cover around trap
Xmoss	% moss cover around trap
B-P Evenness	Berger-Parker Evenness

CHAPTER 1: INTRODUCTION

As of 2008, more than 50% of the Earth's population lives in urban areas, and by 2050, the United Nations projects this proportion to increase to 67% (Kolhase, 2013). The process of urbanization has increased in the latter half of the past century: between 1982 and 1997 alone there was a 34% increase in land used for urban purposes (Alig, Kline, & Lichtenstein, 2004), and between 1990 and 2015 developed countries witnessed an 80% expansion of urban land use (Wihbey, 2016).

This expansion of urban land results in the degradation of ecosystems and habitats (Foley et al., 2016; Vitousek et al., 1997). Generally, urbanization results in land clearing, leaving little, if any, remnant habitat behind (Vitousek et al., 1997). In addition to habitat loss, the intensification of land use results in significant disturbance (e.g., from chemical, light, and/or noise pollution), and decreased resource availability (Foley et al., 2016; Kohlhase, 2013). In consequence, there is a general loss of biodiversity in urban areas, as many species are not able to thrive under the characteristically high-stress environments of cities (McKinney, 2002).

Invertebrate richness is no exception. Urbanization is generally associated with a loss in species richness and abundance (McKinney, 2008). A greater proportion of non-native species tends to thrive in the urban core compared to more rural environments (McKinney, 2008). McKinney (2008) found that not only does increasing intensity of urbanization eliminate habitable area (i.e., vegetated area), urbanization also negatively impacts the quality of the remaining vegetation that could be used as habitat. This is often because green spaces in urban environments are maintained by practices such as removing leaf litter and trimming branches that remove viable microhabitats, which serve as prime invertebrate habitat (McKinney, 2008). However, in some cases, invertebrate richness increases with increasing urbanization, likely owing to an increase in habitat heterogeneity (Jones & Leather, 2012).

Green roofs, or vegetated roofs, are often put forward as an example of a green infrastructure that can at least partially act as replacement habitat (VanWoert et al., 2005). Green roofs are built up in layers, including a waterproofing membrane, substrate, and vegetation (Luckett, 2009); they can be either retrofitted to existing roofs, or designed along with the building. Most green roofs are shallow (<6 inches substrate) extensive types, while intensive green roofs are deeper (>6 inches substrate) and can support a greater variety of vegetation, including shrubs and small trees (Luckett, 2009). The claimed benefits of green roofs often include the provisioning of habitat, although evidence to this effect has only begun to accumulate (Banting, 2005; Oberndorfer et al., 2007) and is often anecdotal (Williams, Lundholm, MacIvor, & Fuller, 2014; VanWoert et al., 2005). Traditional roofs are characterized by low abundance and richness, and the few species that can be found are usually sparsely distributed and often only transiently present (Kazemi, Beechum, Gibbs, & Clay, 2009). Invertebrate abundance on green roofs is often found to be quite high: in studies comparing green roofs to ground level habitats, it was not uncommon for roofs to host higher abundance (Jones, 2002; Kadas, 2006; MacIvor & Lundholm, 2011). Abundance is not distributed evenly among species, with usually one or two species dominating the number of individuals collected (Braaker, Ghazoul, Obrist, & Moretti, 2014; Jones, 2002; MacIvor & Lundholm, 2011; Nagase & Nomura, 2014). For example, two ant species alone, the common carpenter ant (*Camponotus* sp.) and pavement ant (*Formica* sp.), accounted for 64% of the 12,136 individuals collected from green roofs in Halifax, Nova Scotia, by MacIvor and Lundholm (2011). Finally, rare or endangered species have been found in most studies of invertebrate richness on green roofs (Jones, 2002; Kadas, 2006; MacIvor & Lundholm, 2010; Nagase & Nomura, 2014; Sattler, Duelli, Obrist, Arlettaz, & Moretti, 2010).

The causes put forward for the patterns of invertebrate richness on green roofs differs from study to study. This may be a consequence of the lack of consistent sampling method across studies. For instance, only Nagase and Nomura (2014) explicitly observed a difference in invertebrate richness between roofs of different heights, remarking that a 10^{th} floor green roof was lacking in certain butterfly species with weaker flight capabilities. The conclusion reached by Braaker, et al. (2014) was that local variables were most closely connected to low-mobility (e.g., carabid and spider) communities, whereas dispersal processes (and connectivity) mattered more for high-mobility (e.g., weevil and bee) species. Interestingly, in a study by Nagase and Nomura (2014), most of the invertebrates found on their roof were herbivores. Nagase and Nomura (2014) speculate that this could be because many invertebrates that lay eggs in the soil are herbivores, and the eggs were transplanted with the vegetation at the time of installation.

Despite the evident potential of green roofs to act as habitat, the factors underlying patterns of invertebrate richness on roofs are not well understood (Madre, Vergnes, Machon, & Clergeau, 2013; Nagase & Nomura, 2014, Oberndorfer et al., 2007; VanWoert et al., 2005). Elements of green roof design that may influence habitat amount and quality include vegetation amount and type, substrate type and depth, maintenance regimes, and roof size (Francis & Lorimer, 2011; Madre et al., 2013; Oberndorfer et al., 2007). Some of these factors are likely to be correlated with one another, to describe the structural complexity of the roof; for example, substrate type and depth will determine the vegetation selected (Madre et al., 2013). For extensive green roofs substrate depth is limited to less than 6 inches, and they are dominated by low growing *Sedums* (Nickerson et al., 2017; Oberndorfer et al., 2007). Madre et al. (2013) found that roofs of this type tended to show a lower species richness and abundance of arthropods than roofs with higher richness of plant functional form or variance of substrate depth.

Objective

The objective of the present work was to contribute to our understanding of the habitat potential of green roofs, specifically by examining the underlying factors that encourage or restrict populations of invertebrates. To this end, I catalogued the invertebrate orders on all the green roofs in Charlotte, North Carolina, USA and determined the relative importance of environmental variables to variation in total invertebrate abundance and richness and the abundance of each order.

Hypothesis

I hypothesized that local physical and environmental conditions on green roofs would play a significant role in determining the abundance and richness of invertebrates on roofs. Specifically, I expected that with increasing vegetative cover, the abundance and richness of invertebrates sampled would increase. Higher plant abundance has been associated with higher levels of invertebrate abundance and richness (Brown, 1984). Instead, larger vegetated areas are expected to host higher numbers and richness of plants, which in turn will support a larger and more diverse invertebrate community (Kazemi, et al., 2009).

I also expected to observe an increase in invertebrate abundance and richness for roofs with larger roof area, lower height, and greater age and substrate depth. Age of the green roof may also be important and related to how species assemblages will change through time (Kadas, 2006; Oberndorfer et al., 2007; Sattler et al., 2010; Schrader & Boning, 2006). Some evidence suggests that typical succession patterns exist on green roofs, and thus, with increasing roof age, I expected an increase in invertebrate abundance and richness (Brown, 1984; Kadas, 2006; Kazemi, et al., 2009; Nagase & Nomura, 2014; Schrader & Boning, 2006). Kadas (2006) observed that sites sampled over time tended to increase in richness, as succession and maturation of vegetative community progressed. Thus, different assemblages of invertebrates could be expected for different ages of green roofs, with richness increasing rapidly for a period of two to three years until the roof has been established (Brown, 1984).

Finally, I predicted an increase in invertebrate abundance and richness with decreasing temperature and decreasing relative humidity. Temperature is one of the most important factors in determining the presence and population growth of invertebrates (Overgaard, Kearney, & Hoffmann, 2014). A green roof experiences more extreme environmental conditions compared to the surrounding matrix of urban habitat, so consideration of temperature is an important variable in assessing green roofs as invertebrate habitat. This is especially important for small invertebrates because they are ectotherms, meaning that they do not regulate their own body temperature and exhibit little to no difference between internal temperature and local air temperature (Stevenson, 1985).

One mechanism of regulating their body temperature is to use short periods of optimal temperature for most activities and retreat to an insulating layer during more extreme conditions (Stevenson, 1985). Green roofs may represent a microsite with optimal air temperatures, considering that the substrate could represent a suitable insulating layer. Several researchers noted in their studies that a greater abundance of invertebrates were found in sheltered or shaded sections of the green roof (Jones, 2002; Nagase & Nomura, 2014). Temperature will also interact with relative humidity in characterizing the microclimate a green roof (Howe, 1967). Relative humidity influences insect growth and behavior by affecting their ability to regulate water loss (Palumbo, Perring, Miller & Reed, 2015). A study by Beament in 1967 demonstrated that insects can transfer water directly to their blood from the air with relative humidity as low as 70%. In another study, a negative correlation was found between relative humidity and population growth of insects in a biological retention basin (Palumbo, et al., 2015). It is expected that green roofs will have higher relative humidity compared to surrounding urban habitat, due to the evapotranspiration activity of the roofing plants.

CHAPTER 2: METHODS

Green Roof Study Sites

My study focused on the city of Charlotte, North Carolina, USA. Charlotte is located in a temperate, deciduous forest biome, with a mean annual temperature of 59.8 °F. Over the summer months from June through September, the normal average temperature is 75.5 °F (usclimatedata.com, 2017). There is no distinct wet or dry season, although summers often see the most rainfall. The urban land cover in Charlotte is somewhat poly-centric, with an area of intensely urbanized land in the center and several nodes of development further out. Charlotte is currently experiencing a phenomenal increase in population, with a 10% annual increase of residents (United States Census Bureau, 2015). As a result, increased construction will lead to intensified urbanization and an increased proportion of developed land cover.

Four extensive or semi-extensive green roofs were identified in the center of Charlotte, with a combined total of 128,271 square feet; fifty-nine trapping locations were ultimately selected (Table 1). Characteristics recorded were: total roof area, roof vegetated area, age, height, substrate type and approximate depth at each trap location. Roof characteristics were collected both from in situ observation, interview of management personnel, and calculation from digitized maps. The Federal Reserve building was the largest of the roofs, and the only location that included multiple levels. All roofs were extensive, except for the roof at the Duke Energy building, which was intensive and actively managed. Over the course of the study, only the Autobell Carwash and Duke Energy building roofs were irrigated. Discovery Place was not weeded at all, while the

Federal Reserve and Autobell locations received sporadic weeding performed by workers at those locations. The Duke Energy building had a dedicated landscape contract and was managed as a garden retreat for employees.

Table 1 Roof design characteristics.

Roof	Total Area (sqft)	Number of Traps	Vegetated Area (sqft)	Proportion Vegetated	Substrate type	Substrate depth (inches)	Age (years)	Roof height (ft)	Year Established
Federal Reserve	85244	36	64486	0.756	expanded shale	5	8	70	2008
FR1	25397	6	19428	0.765	expanded shale	5	8	107	2008
FR2	11561	5	9693	0.838	expanded shale	5	8	50	2008
FR3	10004	6	8092	0.809	expanded shale	5	8	42	2008
FR4	38281	19	27272	0.712	expanded shale	5	8	81	2008
Duke Building	26508	9	19408	0.732	gravel/mulch	10	6	208	2010
Discovery Place	12654	10	7704	0.609	expanded shale	2	9	28	2007
Autobell Carwash	3865	4	2591	0.670	expanded shale	2.5	4	15	2012
Averages	32067	59	23547	0.692			6.75	80.25	

Note: Subroofs are parsed for the Federal Reserve but excluded from averages.

Vegetation was recorded within a 5-foot radius around the center of each trapping location as proportions for the cover of succulents, graminoids, forbs, and moss (Table 2). Moss was not originally intended to be recorded, but proved to be consistently present at some locations, and was, in fact, sometimes the *only* vegetative cover, especially at locations without active irrigation or management. *Sedum* was the intentional plant type, but over the years, various other “weeds” volunteered themselves, changing the planned vegetative community.

Table 2 Average percent vegetative cover in 5-ft radius around each trapping location.

Roof	Total Vegetation	Succulent	Graminoid	Forb	Moss
Federal Reserve	50.0	9.53	28.98	7.20	0.96
Discovery Place	54.8	9.26	24.73	4.59	8.09
Duke	57.2	9.33	7.35	7.17	0
Autobell	52.9	27.42	13.81	5.44	0
Total	53.8	13.88	18.72	6.10	2.26

Invertebrate Collection

I used pan trapping, pitfall trapping, and vacuum sampling as my three methods of invertebrate collection. Coleoptera, Diptera and Hymenoptera will be targeted by pan trapping (Abrahamczyk, Steudel, & Kessler, 2010; Sanders & Luck, 2012); Araneae, Carabidae, Formicidae, Apidae, and Isopoda by pitfalls (Buccholz & Hannig, 2009; Zaller, et al., 2015); and Hemiptera, Diptera, and Hymenoptera by vacuum sampling (Doxon, et al., 2011). Sampling stations were roughly equidistant, with an estimated sampling density between 1-2 sampling locations per 1000-ft^2 of green roof, depending on roof configuration. I used a total of 59 traps across all roofs. Each sampling location included three pan traps and one pitfall trap.

Pan trapping consisted of a bowl filled with water with a drop of dish soap left at the collection site. The traps themselves were constructed from plastic cups or bowls, and then placed on the ground (but not flush with the substrate) with grouped bowls touching (Abrahamczyk, Steudel, & Kessler, 2010; Sanders & Luck, 2012). Pitfall trapping consisted of a cup or jar filled with propylene glycol and a drop of dish soap and positioned with the lip of the bowl flush with the edge of the ground (Buccholz & Hannig, 2009). Pan traps were placed, touching, a few inches from the center of the sampling location as marked by the LogTag. The pitfalls and pan traps used for this study were about 2 inches deep, so that the pitfalls would fit within the often-shallow upper layers of the extensive green roofs. The pitfall traps were placed on the opposite side from the pan traps, flush with the ground. Collection began weekly, but was changed partway through the field season to biweekly, alternating between the larger Federal Reserve location in one week and the other three locations in the next. Collection started June 02, 2016 and continued through September 14, 2016.

I conducted vacuum sampling at each location within a 5-foot circular radius of each location. Sampling was conducted approximately an inch from the ground with the intake swept through about two passes in a circular motion (Doxon et al., 2011; Jones, 2002). In this study, a Black and Decker cordless blower/vacuum was used, with a short pantyhose style sock fitted around the opening to trap the invertebrates. Vacuum sampling occurred on July 20, August 20, and September 20, 2016 for all locations.

Over the course of the season, 39 samples were collected across all roofs, including 3 vacuum samples. I identified all individuals to order using Arnett (2000), Ciegler (2000), Glassberg (1999), Michener (2007), and Ubick (2005). I recorded abundance as the normalized count of individuals, diversity as the richness of orders and as Berger-Parker evenness. Normalization was carried out by counting the number of successful trapping events (per location, a successful trapping event was a retrieved non-missing, non-damaged and empty trap or vacuum sample on each date of sample retrieval) and dividing by the total raw cumulative abundance.

Habitat Variables

I measured percent vegetation cover in a 5-foot radius around each trapping location at the same time as the vacuum samples, on July 20, August 20, and September

20, 2016. The percent cover of forbs, mosses, succulents, or graminoids was recorded as percent cover around the trap.

LogTags recorded temperature and relative humidity data at each trap location every half hour from June 2 through September 20, 2016. During the season, 14 of the 59 units returned corrupted or unusable data. Therefore, at those locations, temperature and humidity data was interpolated using ArcGIS 10.4. First, existing temperature and humidity points were processed using inverse distance weighted interpolation to create a raster of estimated values. Then point estimation extracted estimated temperature and humidity values coinciding with trap locations.

Analyses

An information-theoretic (IT) approach was utilized in this study, following recent trends in landscape ecology acknowledging this simpler approach as more appropriate for biological questions than singular regression and P-value methods (Anderson & Burnham, 2001; Richards, 2005). A generalized linear model was developed incorporating the independent variables roof, relative humidity, temperature, and the percentage of vegetated cover around each trapping location, including total, succulent, graminoid, forb, and moss covers. Response variables were first logged to increase the likelihood for models to satisfy assumptions of normality and homoscedasticity. The response variables of abundance, richness, and Berger-Parker evenness were each initially fitted to a model using the “glm()” command, Gaussian distribution, and identity link function in R version 3.4.2. This initial model was then used for model selection using the “dredge()” function in the MuMIn package to evaluate all possible models with one or more predictor variables.

The output models were first limited to those with degrees of freedom 6 or less because my models only included 6 possible explanatory variables, and then ranked according to Akaike's Information Criterion corrected for small sample size (AIC_c). Models with delta $AIC_c < 2$ were retained (Anderson and Burnham 2001). I then averaged the predictor estimates in the retained models using the "model.avg()" function.

CHAPTER 3: RESULTS

Environmental Variables

The average temperature on the roofs was 84.2 °F, with a standard deviation of 4.7°F, while relative humidity was 61.7% with a standard deviation of 5.3%. The average temperature in Charlotte, NC, during this same period was 80.1°F, and the average relative humidity was 72.3%. Temperature and humidity were in line with *a priori* expectations that they would be hotter and less humid than average ground conditions, and agreed with the reviewed findings of Sonne (2006) and Francis and Jensen (2017).

Explanatory Models

After selecting models according to AIC_c, response variables were described with between one to eight models. In general, most models included Roof as an explanatory variable, and several of the response variables with greatest abundances also included proportion of forb cover as an explanatory variable. (Table 5.)

Invertebrate Response

A total of 17,917 individuals were collected, representing 12 orders. The average number of individuals collected at each trapping location was approximately 300 with an average 0.95 proportion of successful traps. (Table 3).

Raw abundance counts were normalized to account for trapping effort. Some traps were damaged or went missing from week to week, so raw abundance counts were normalized by dividing by the sum of successful traps plus the number of times vacuum sampled. The Duke location was notable for 91% of its abundance represented by Isoptera:

several traps filled with up to 400+ individuals at a time, which far outnumbered even the average trap count at any location for any one collection event. (Table 4.)

Table 3 Average response variable per trapping location per roof

Roof	Total Abundance	Avg N Individuals per Trap	Richness	Avg N Orders per Trap	(Min, Max) B-P Evenness	Avg B-P Evenness
Federal Reserve	11526	320	12	7.5	(0.358, 0.807)	0.556
Discovery Place	1932	193	12	6.3	(0.328, 0.559)	20
Duke Energy	3903	434	12	8.0	(0.333, 0.979)	0.777
Autobell	556	139	7	6.5	(0.443, 0.663)	0.561

Table 4 Percent order abundance on each roof

	Federal Reserve	Discovery Place	Duke Energy	Autobell
Aranae	9%	4%	<1%	10%
Coleoptera	2%	2%	<1%	1%
Hymenoptera	5%	42%	3%	5%
Diptera	24%	21%	3%	23%
Hemiptera	58%	30%	1%	57%
Lepidoptera	1%	1%	1%	4%
Odonata	<1%	<1%	<1%	<1%
Orthoptera	<1%	<1%	<1%	<1%
Blattodea	<1%	<1%	<1%	<1%
Gastropod	<1%	<1%	<1%	<1%
Isoptera	<1%	<1%	91%	<1%
Diplopoda	<1%	<1%	<1%	<1%

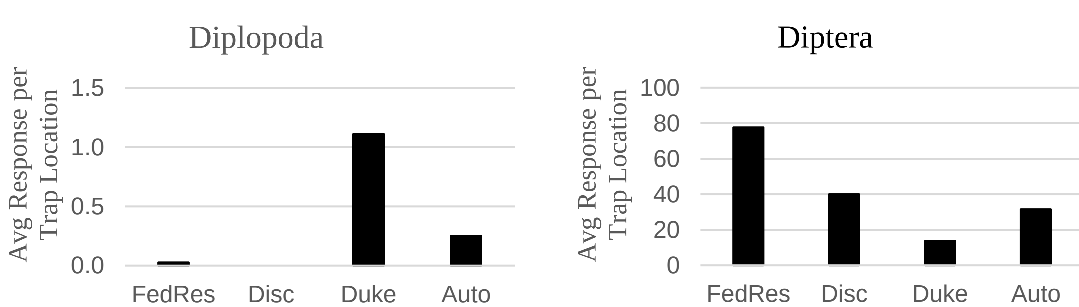
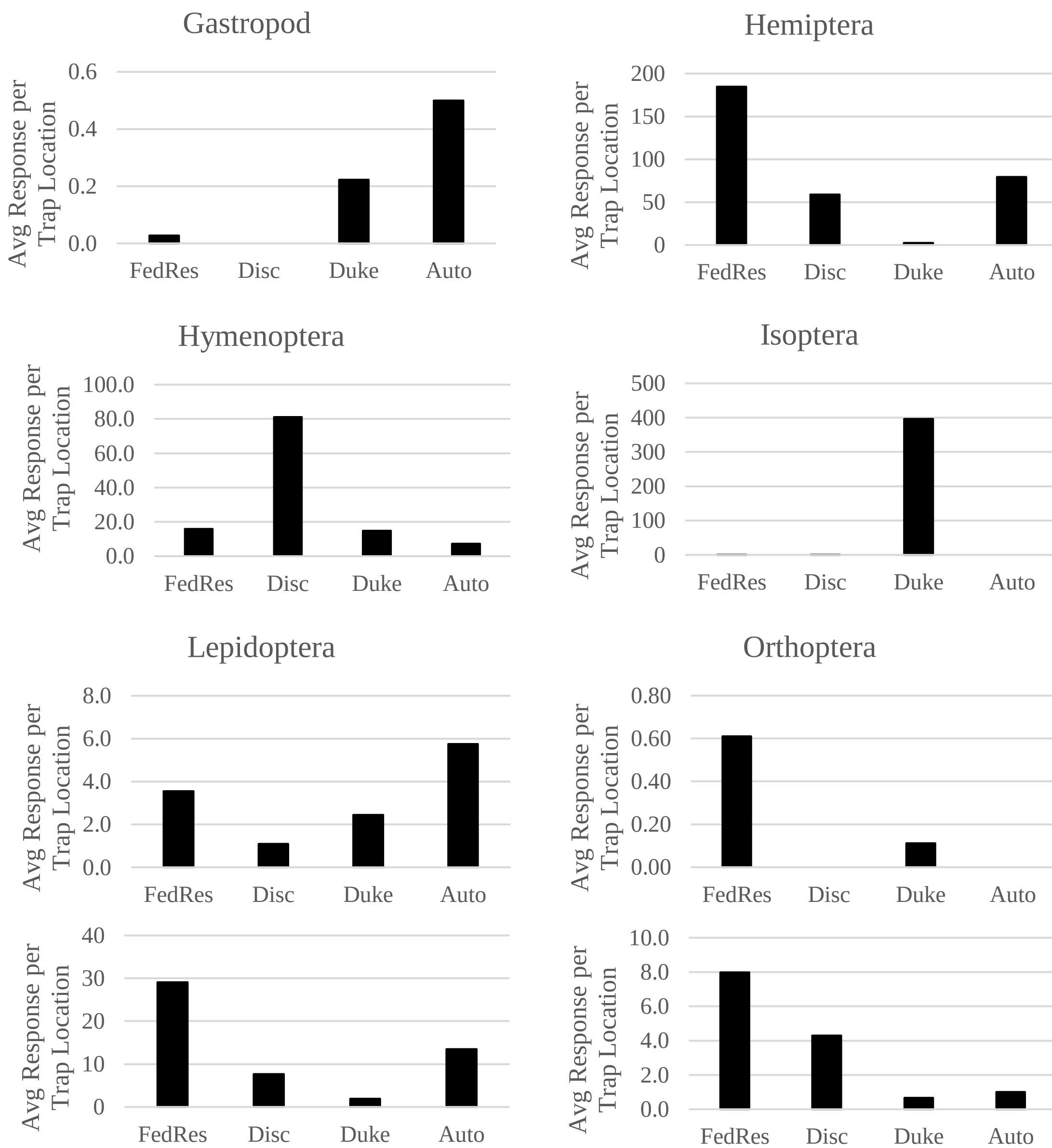


Figure 1 Average responses per trapping location



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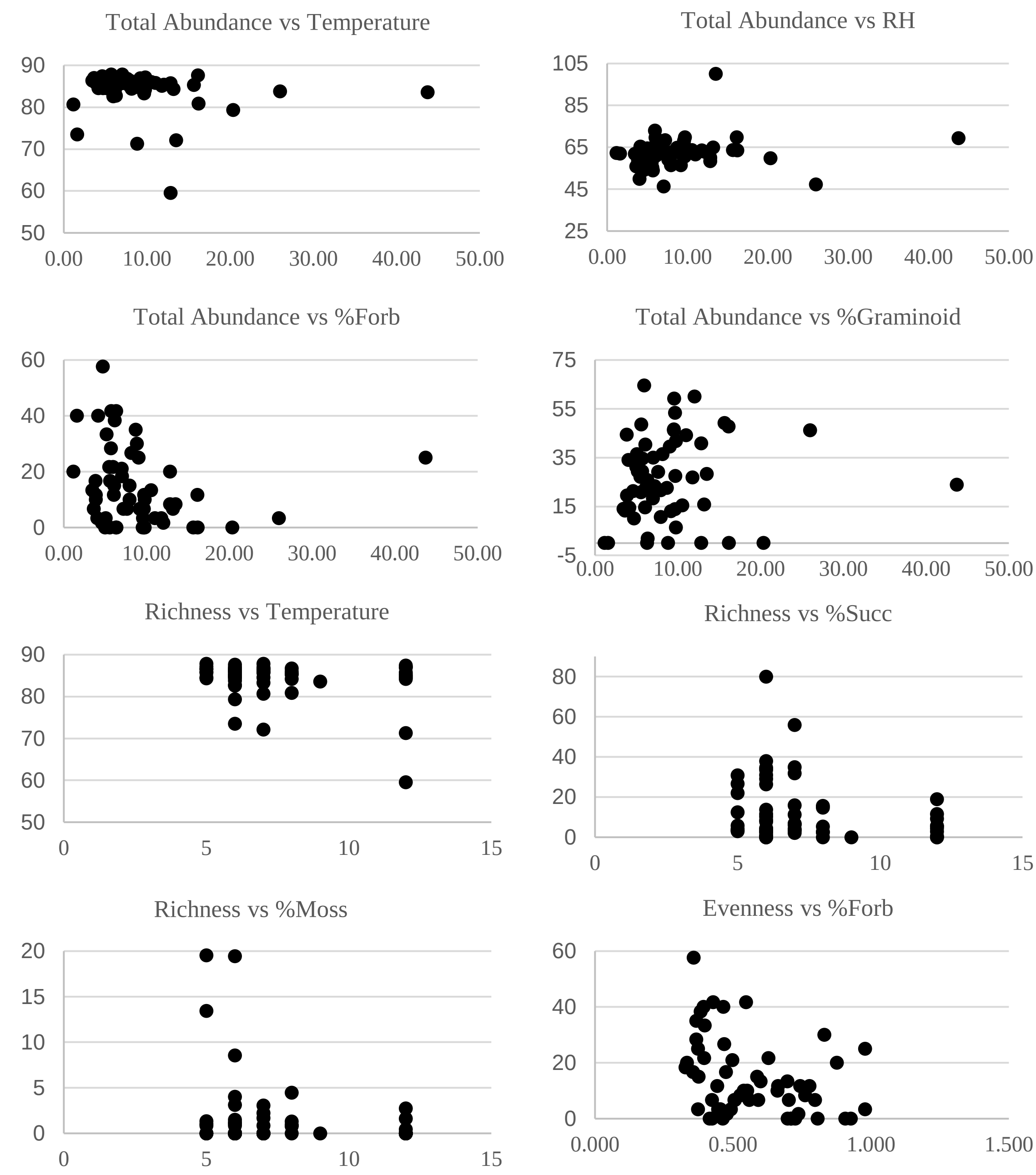

Figure 2 Response vs Explanatory Variable for Selected Variables

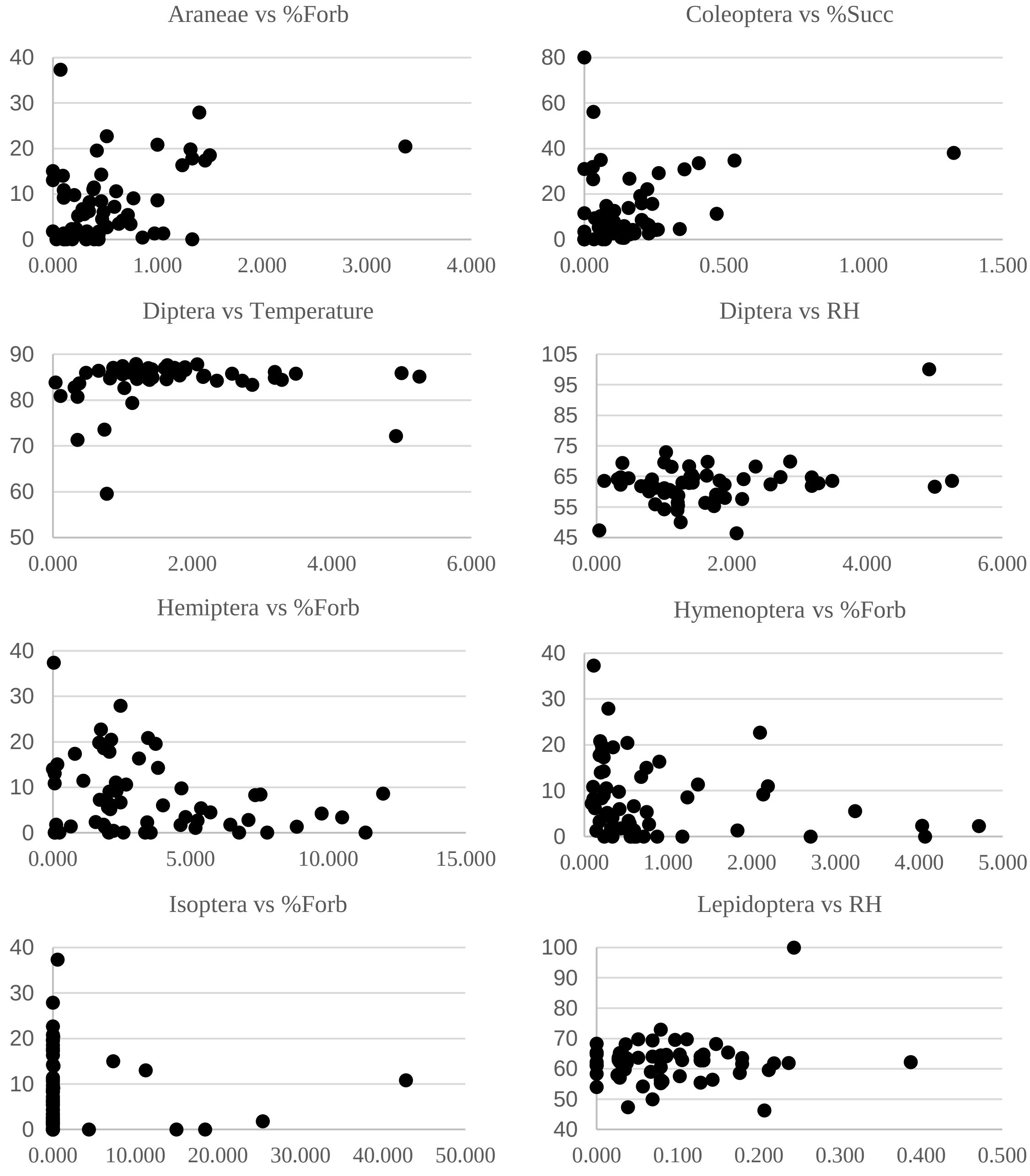

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Table 5 Selected models per response variable for Δi<2.

Response	Model	AIC$_c$	Δ_i	w_i
Total Abundance	log(Total Abundance + 1) ~ T_AVG + Xforb + Xgram	80.319	0	0.476
	log(Total Abundance + 1) ~ Roof + Xforb	81.048	0.729	0.331
	log(Total Abundance + 1) ~ RH_AVG + T_AVG + Xforb + Xgram	82.130	1.811	0.193
Richness	log(Richness) ~ T_AVG + Xmoss + Xsucc	17.130	0	0.202
	log(Richness) ~ T_AVG + Xsucc	17.391	0.261	0.177
	log(Richness) ~ Xmoss + Xsucc	17.422	0.292	0.174
	log(Richness) ~ T_AVG	17.866	0.736	0.140
	log(Richness) ~ T_AVG + Xmoss	17.939	0.809	0.135
	log(Richness) ~ Xmoss	18.743	1.613	0.090
	log(Richness) ~ Xsucc	18.895	1.765	0.083
Evenness	log(Berger.Parker + 1) ~ Roof + Xforb	-119.523	0	1.000
Araneae	log(Araneae + 1) ~ Roof + Xforb	-12.162	0	1.000
Blattodea	log(Blattodea + 1) ~ RH_AVG + Xgram	-390.449	0	0.316
	log(Blattodea + 1) ~ RH_AVG + Xsucc	-389.002	1.447	0.153
	log(Blattodea + 1) ~ RH_AVG + Xforb	-388.811	1.638	0.139
	log(Blattodea + 1) ~ RH_AVG + Xmoss	-388.762	1.687	0.136
	log(Blattodea + 1) ~ RH_AVG + T_AVG	-388.646	1.803	0.128
	log(Blattodea + 1) ~ RH_AVG + Xtotveg	-388.638	1.811	0.128
Coleoptera	log(Coleoptera + 1) ~ Roof + Xsucc	-79.120	0	1.000
Diplopoda	log(Diplopoda + 1) ~ Roof + Xsucc	-280.985	0	0.721
	log(Diplopoda + 1) ~ Roof	-279.085	1.9	0.279
Diptera	log(Diptera+ 1) ~ RH_AVG + T_AVG	28.203	0	0.643
	log(Diptera+ 1) ~ RH_AVG	29.381	1.178	0.357
Gastropod	log(Gastropod + 1) ~ Roof + T_AVG	-368.579	0	0.452
	log(Gastropod + 1) ~ Roof	-367.947	0.632	0.329
	log(Gastropod + 1) ~ Roof + Xgram	-367.129	1.45	0.219
Hemiptera	log(Hemiptera + 1) ~ Roof + Xforb	67.697	0	1.000
Hymenoptera	log(Hemiptera + 1) ~ Roof + Xforb	-22.502	0	1.000
Isoptera	log(Hemiptera + 1) ~ Roof + Xforb	82.301	0	1.000
Lepidoptera	log(Lepidoptera + 1) ~ Roof	-152.782	0	0.717
	log(Lepidoptera + 1) ~ Roof + RH_AVG	-150.918	1.864	0.283
Odonata	log(Odonata + 1) ~ Xgram	-348.527	0	0.234
	log(Odonata + 1) ~ Xforb	-347.640	0.887	0.150
	log(Odonata + 1) ~ T_AVG	-347.231	1.296	0.122
	log(Odonata + 1) ~ Xforb +Xgram	-347.044	1.483	0.111
	log(Odonata + 1) ~ Xsucc	-346.755	1.772	0.096
	log(Odonata + 1) ~ Xmoss	-346.750	1.777	0.096
	log(Odonata + 1) ~ RH_AVG	-346.741	1.786	0.096
	log(Odonata + 1) ~ Xtotveg	-346.731	1.796	0.095
Orthoptera	log(Orthoptera + 1) ~ Roof	-291.757	0	0.213
	log(Orthoptera + 1) ~ Roof + Xforb	-291.442	0.315	0.182
	log(Orthoptera + 1) ~ Roof + RH_AVG	-291.192	0.565	0.160
	log(Orthoptera + 1) ~ Xgram	-291.094	0.663	0.153
	log(Orthoptera + 1) ~ Roof + Xgram	-290.482	1.275	0.112
	log(Orthoptera + 1) ~ Xforb + Xgram	-290.272	1.485	0.101
	log(Orthoptera + 1) ~ Xforb	-289.761	1.996	0.078

Table 6 Averaged estimates for model of richness and abundance responses >180, excluding roof

Response	Adjusted R^2	Roof	T_AVG	RH_AVG	% Succulent Cover	% Graminoid Cover	% Forb Cover	% Moss Cover
Total Abundance	0.326	X	-0.018 *(0.020)*	0.004 *(0.007)*		0.005 *(0.005)*	-0.027 *(0.007)*	
Richness	0.104		-0.018 *(0.020)*		-0.021 *(0.022)*			-0.057 *(0.076)*
Evenness	0.461	X					-0.006 *(0.001)*	
Araneae	0.511	X					0.013 *(0.003)*	
Coleoptera	0.281	X			0.003 *(0.001)*			
Diptera	0.456	X	-0.025 *(0.011)*	1.32E-08 *(1.53E-05)*				
Hemiptera	0.671	X					-0.019 *(0.006)*	
Hymenoptera	0.802	X					-0.009 *(0.003)*	
Isoptera	-0.014						-0.019 *(0.007)*	
Lepidoptera	0.782	X		2.48E-04 *(7.32E-04)*				
N Models Included		9	3	3	2	1	6	1

Table 7 Averaged estimates for response variables for roof with respect to Autobell

Response	RoofDiscovery	RoofDuke	RoofFederal
Abundance	0.172	0.396	0.272
Standard Error	0.259	0.4659	0.335
B-P Evenness	-0.092	0.147	0.005
Standard Error	0.048	0.049	0.043
Araneae	-0.120	-0.332	0.173
Standard Error	0.120	0.123	0.107
Coleoptera	0.168	0.045	0.218
Standard Error	0.071	0.071	0.065
Diptera	0.201	-0.540	0.358
Standard Error	0.169	0.197	0.151
Hemiptera	-0.130	-1.048	0.470
Standard Error	0.237	0.242	0.211
Hymenoptera	1.112	0.226	0.158
Standard Error	0.110	0.113	0.098
Isoptera	0.011	2.260	0.037
Standard Error	0.268	0.274	0.239
Lepidoptera	-0.125	-0.087	-0.072
Standard Error	0.037	0.038	0.033

Temperature was important for total abundance, richness, and abundances for Blattodea, Diptera, Gastropod and Odonata. In general, higher temperature predicted lower abundance and richness. This was not true for Blattodea and Odonata. (Table 6)

Relative humidity was important for total abundance, richness, and abundances for Blattodea, Diptera, Lepidoptera, Odonata, and Orthoptera. The effect of higher humidity was associated with higher abundances.

Interestingly, the estimate of effect of forb cover on total and order abundances was negative, except for Araneae. Greater forb cover was also associated with a greater evenness, although forb cover did not factor into any of the selected richness models. Forb cover also did not factor into models for Coleoptera, Diplopoda, Diptera, Gastropod, or Lepidoptera.

Fewer models included other vegetation covers. Total vegetation was positively associated with abundances for Blattodea and Odonata. Cover of graminoids was positively associated with abundances for total abundance, Blattodea, Gastropod, and Orthoptera. Cover of succulents was a predictor of lower richness and Blattodea and Odonata, and higher abundance for Coleoptera and Diplopoda.

CHAPTER 4: DISCUSSION

Results indicated that inclusion of both roof characteristics and environmental conditions improved prediction of invertebrate abundance and richness on urban green roofs. I found that roof characteristics had a more consistent impact on invertebrate populations than temperature, relative humidity, or surrounding vegetative composition/structure because the most commonly included variable was the Roof covariate. This finding agreed with the study carried out by Braaker et al. (2014), who also found evidence that local roof characteristics outweighed vegetation in explanatory power. Madre et al. (2013) found consistent relationships for both roof characteristics and vegetation in their final interpretation of explanatory variables, however, their results indicated that vegetative complexity was the more important factor. I would explain this discrepancy by noting that their study focused more on roof type and relied upon vegetative complexity as determined by substrate depth, which was included with my Roof covariate. This made it difficult to separate the effect of substrate from vegetative complexity.

Roof was included as a covariate in the analysis in order to control for the differing design, age, and location elements among different trapping locations. The Federal Reserve and Duke Energy locations were the most often associated with the highest overall abundances and evenness. They were the two largest roofs in total area and vegetated area; they also had the deepest substrate (5 and 10 inches, respectively,Table 1). This suggests that the effect of three-dimensional habitat area (surface area plus substrate depth) plays a more important role than specific substrate type or age by providing more habitat to support higher abundance and richness, and would match with observations by Madre et al. (2013).

Brenneisen (2006) further suggested that deeper substrates were important to allow for retreat of ectothermic invertebrates into deeper, cooler, and wetter areas, which led to the small observed effect of substrate depth and roof area in his study. However, while the Federal Reserve location was the oldest of the roofs included in this study, Duke Energy was the youngest. The absence of a clear trend with respect to age goes against findings by Brenneisen (2006), Kadas (2006), Oberndorfer et al. (2007), Sattler et al. (2010), and Schrader and Boning (2006), who all observed more diverse and abundant invertebrate populations on older roofs. Duke and Autobell were both regularly visited by either a dedicated landscaping team or the building manager to control for spontaneous colonization of non-specified vegetation (i.e., graminoids and other weeds). Following this line of thinking, variation in landscaping practices would account for the lack of a noticeable trend with age of roof, because ongoing maintenance of the initial plantings would “freeze” the plant composition as per the roof design and prevent any succession processes.

Temperature was included in models for total and order specific abundance as well as the model for richness. It was not included as a predictor for evenness. As predicted, increasing temperature was negatively associated with invertebrate abundance and richness. While temperature was predicted to be a strong predictor of invertebrate abundance and richness (Overgaard, Kearney & Hoffman 2014), the difference in roof temperature to ground temperature was less extreme than for conventional roofs, and so the effect may have been less pronounced as a result. Relative humidity was included in models for total abundance and the less abundant orders (Blattodea, Lepidoptera, Odonata, Orthoptera), with the exception of also predicting Diptera, which was one of the most abundant orders. Insects can transfer water directly through their skin (Beament 1967), and favorable relative humidity conditions play a significant role in invertebrates' ability to regulate water loss (Palumbo, Perring, Miller & Reed 2015). Since green roofs are typically lower in humidity overall, the most favorable conditions are considered to occur at trap locations with higher relative humidity. So, the effect of relative humidity did not match predictions with respect to abundance, with higher relative humidity associated with an increase in abundance. However, humidity did not play a role in in predicting richness or evenness. The direction of effect for humidity was more variable than temperature, suggesting that the ectothermic nature of invertebrates is the more limiting factor. This would agree with the work by Howe (1956) who found that survival rates of invertebrate eggs were consistently high over a range of humidity, but the survival rates of eggs dropped off sharply for temperature thresholds.

Specific vegetation type was more likely to be included as a predictor for a given response variable. Forb was most often included as a predictor of abundances or evenness. This was similar to the findings of Braaker et al. (2014), who found that cover of forbs was more important than richness of plant species, although no other cover types were included in their analysis. However, in my study, forbs were generally negatively associated with abundances and evenness, but had no effect on richness. This is the opposite of expectation, as flowering vegetation would be expected to attract pollinators to trap locations with higher forb counts, as per Tonietto, Fant, Ascher, Ellis, and Larkin (2011). This negative direction of effect might have masked another effect at work which I did not include in the analysis. I received anecdotal evidence of birds eating insects from some of the evaporated traps. If this was the case, then it might be expected that traps with higher surrounding forb cover would initially contain more individual specimens, attract a hungry bird, and subsequently be recovered with fewer individuals than would otherwise be expected. However, a bird might discriminate against a particular invertebrate type, leading to the observed negative association with evenness.

Succulent and moss cover were also negatively associated with abundances and richness but had no effect upon evenness. Both structural types are low growing, and might contribute to higher instances of predation, due to the relatively more exposed growth structure compared to more complex forms (Schrader and Boning, 2006). Madre et al. (2013) found the same effect, classifying roofs with predominantly moss and *Sedums* as muscinal (M-type) roofs. The M-type roofs had the lowest abundance and species richness for Coleoptera, Hymenoptera, and Araneae (Madre et al, 2013). Moss in particular was associated with more barren areas of the roof. Therefore, the presence of moss may act as an indicator of the failure of more complex vegetation to survive. Moss often survived where other plants failed due to drought.

Likewise, graminoids, which on the green roofs in this study were mostly spontaneously colonizing “weeds”, provided a denser overall structure, often reaching heights of two to three feet and better obscuring the substrate. Graminoids were the only vegetation type associated with higher abundances, but had no observable prediction value for richness or evenness. Studies in the literature found that graminoids were often associated with spontaneous colonization and higher plant diversity, and were associated with higher invertebrate abundances and richness (Brenneisen, 2006; Nagase & Nomura, 2014). This observation was also in line with the study by Madre et al. (2013) who found higher abundances and species richness on predominantly herbaceous (defined as gramineous and non-woody plants) roofs compared to muscinal roofs.

Total vegetation played a less consistent role in predicting abundances, richness, or evenness that predicted. Total vegetation cover was only included in 2 out of 15 models and was positively associated with higher abundance. That total vegetative abundance was not included in most models also echoed a general pattern in the literature that plant composition matters more than simply vegetative biomass (MacIvor & Lundholm, 2011; Madre et al., 2013; Tonietto et al., 2011). However, MacIvor and Lundholm (2011) went further in stating that structural complexity matters more than species richness of plants.

I catalogued slightly higher diversity on the green roofs in my study than similar studies in the literature: Nagase and Nomura (2014) found 11 orders, Sattler et al. (2010) found 9 orders on green roofs, MacIvor and Lundholm (2010) found 11 orders, and Jones (2002) found 12 orders on green roofs in their respective studies. Both Jones (2002) and MacIvor and Lundholm (2010) found one individual Collembolan on their roofs, which is the only order not also observed on the roofs in my study. While very few studies included abundance counts, but Kadas (2006) reported an average of 150 individuals caught per trap location. This is lower than the average 270 individuals caught across all trap locations in my study, although this number varied from 139 on the Autobell roof to 434 on Duke Energy (Table 3). Thus, it appears that order richness on the urban green roofs of Charlotte are in line with the findings of previous studies in the literature, although this is, to my knowledge, the first comprehensive catalogue of order richness on urban green roofs carried out in the subtropics.

Green roofs can be either retrofitted to existing roofs or included in the initial design of new buildings. New roofs should be designed to incorporate shaded areas and sufficient irrigation to provide consistently favorable temperature and humidity conditions. Designers for new green roofs should also consider including deeper substrate and higher percentage of greened areas for the green roof to provide a larger three-dimensional volume of potential habitat; this ability to provide more habitat area would have to be weighed against the higher cost of construction. For retrofitted green roofs, static design elements such as total roof area cannot be changed, but considering the type of cover and management practices in the greened areas may help increase the habitat value of the roof overall. Management should consider tolerating the spontaneous colonization of graminoids. While this might change the original aesthetic of the roof, it could lead to more diverse plantings in a successionary process, and could increase the overall abundances of invertebrates, as was observed in the "weedier" roof areas in my study. However, intervention in the green roof vegetative cover may be warranted when a predominance of *Sedums* and moss are developed, as these were associated with lower invertebrate richness. Moss in particular was most dominant in the least irrigated areas, and may indicate that a non-irrigated green roof design has failed. Regreening and deliberate irrigation of these sites are recommended to recover the habitat values of the green roof.

Future studies would also benefit from focusing on one specific aspect of environmental roof conditions as they relate to habitat value. The time aspect of invertebrate observations might reveal greater sensitivity to discrete events and local conditions on a green roof. For example, Discovery Place was not actively irrigated during the summer of 2016, but on the last day of sampling, workers were present with preparations to install a new irrigation system to replace the older system already in place. This would presumably change the vegetative make up, temperature, and humidity on the roof, which might then influence the invertebrate population.

While this study focused on the higher taxonomic level of order, a logical successor to this study would be to identify these specimens to family or morphospecies. With finer detail available to analyze richness, more specific biological hypotheses could be developed to explain the broader effects described here.

CHAPTER5: CONCLUSION

This study provided evidence that individual roof characteristics are the controlling factor in invertebrate abundance and richness on urban green roofs. While local environmental factors contribute to invertebrate abundance and richness, factors such as temperature, relative humidity, and vegetation cover are more likely to modify the invertebrate population dictated by the roof characteristics.

It is unlikely that green roofs overall will ever provide a one-to-one replacement value for habitat degraded, destroyed, or altered by the urbanization process. However, it is clear that urban green roofs are far from sterile environments hosting only the initial vegetative plantings. Invertebrates inevitably colonize these green roofs and the opportunity exists to improve their habitat value through choice of design values.

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APPENDIX: GREEN ROOFS AND TRAPS LOCATIONS

Figure 3 Green roofs and trap locations. Clockwise from top left: Federal Reserve, Duke Energy, Discovery Place, Autobell Carwash.