EFFECTS OF THE URBAN HEAT ISLAND ON ANURANS IN REMNANT AND STORMWATER CONTROL PONDS IN THE CHARLOTTE METROPOLITAN REGION

by

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ABSTRACT

ADRIENNE FRANCES BOUCHER. Effects of the urban heat island on anurans in remnant and stormwater control ponds in the Charlotte Metropolitan Region. (Under the direction of DR. SARA GAGNÉ).

The urban heat island (UHI) has been documented to increase urban air temperatures compared to rural areas, but little is known about the effects of UHI-induced meteorology on anuran breeding and diversity. In this thesis, I describe the first direct test of the effect of meteorology associated with an UHI on breeding activity and diversity of anurans. Twelve evening call surveys were conducted at 66 ponds in the Charlotte Metropolitan Region to assess anuran breeding activity. To account for meteorological conditions, air temperature and relative humidity at ponds both breeding seasons are recorded and monthly average rainfall and average temperatures for each landscape are measured. To account for variation in local habitat quality and landscape composition in 2014 and 2015, pond descriptors and vegetation in and around each pond are measured, as well as the proportions of landscapes covered by forest and agricultural, wetland density, and road density. Landscape variables are quantified for 13 concentric scales ranging from 0.5-20 km of each pond. Occupancy analysis and generalized linear modeling is used to assess the effects of meteorological variables on occupancy and detectability of individual anuran species and on anuran species richness. There was no evidence to support that the UHI alters anuran species richness. However, there is evidence that the UHI may alter species occupancy and detectability at ponds. Thus, as UHIs continues to increase in magnitude, breeding activity of some species is likely to be altered from effects of the UHI.

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INTRODUCTION

Over the last few decades, global populations have experienced a dramatic shift towards urban living. Currently, over half of the world's population resides in urban areas, and this percentage will only continue to rise over the next fifty years, with a projection of 66% of the world's population to reside in urban areas by 2050 (United Nations 2014). This worldwide trend is mirrored by the growth of population size and land occupation in the southeastern region of the United States, where regional shifts to urban living are reshaping the landscape through land cover change (Milesi et al. 2002; Grimm et al 2008; Terando et al. 2014). In the southeast, conversion of forests, agricultural land, open spaces, and wetlands into urban areas is occurring at a rate higher than that of the United States national average, and population sizes will continue to grow over the next few decades (Milesi 2002; United Nations 2014).

Urbanization has caused amphibian habitats to diminish drastically in quality and quantity over the last several decades (Alford & Richards 1999; Cushman 2006). Native amphibians of the southeast region of the United States include anurans, which require fresh water to breed, but then migrate to a terrestrial habitat as an adult to forage and overwinter (Cushman 2006). Land cover change, specifically roads and infrastructure, fragments contiguous habitat into isolated patches, decreasing anurans ability to migrate, resulting in decreased species richness and evenness in urban areas (Gibbs 1998). Anurans, like other amphibians, are also known to respond quickly to changes in temperature, precipitation, relative humidity, and pollutant levels. This relatively quick response time, compared to other wildlife, has resulted in anurans being recognized as bio-indicators (Welsh & Ollivier 1998).

As urbanization, through land cover change, continues to increase the amount of impervious surface cover, it simultaneously decreases the amount of vegetation in an urban area, through which a phenomenon known as the Urban Heat Island (UHI) can be produced. An UHI is defined as increased temperature in an urban area with respect to its rural surrounding (Imhoff 2010). These increases in air temperatures can largely be attributed to an urban area's ability to absorb a large amount of solar radiation, but only emitting low amounts of energy from what was absorbed. In contrast to an urban area, the city's surrounding rural areas absorb less amounts of solar radiation, while simultaneously emitting a higher amount of absorbed energy. An urban area's high absorption and low emittance rate, in turn, directly causes the average mean temperatures in the urbanized area to be higher than that of surrounding rural areas. This increased rate in absorption of solar radiation into large amounts of impervious surface cover, paired with decreased amounts of vegetation in an urban area can be seen to alter the magnitude, or intensity, of an UHI. UHIs have been recorded to have magnitudes that can range from 0.2℃ up to 9℃, with the larger UHI magnitudes found in cities that displace temperate broadleaf, mixed, and temperate coniferous forest biomes, such as the Charlotte metropolitan region (Imhoff 2010).

Not only has the presence of the UHI been documented to affect temperatures, but it has also been documented to alter a city's relative humidity and precipitation. Increased air temperatures can initiate convective activity in an urban area, altering water availability across the geographical region (Holmer & Eliasson 1999; Bornstein & Lin 2000). Urban areas are found to contain decreased amount of moisture compared to rural surroundings, because moisture in an urban area is not readily absorbed by soils or vegetation, but rather, urban areas have increased rates of evaporation from increased amounts of impervious surface cover. This higher amount of impervious surface cover, in turn, decreases available moisture from lack of soils and vegetation, and thus will reduce relative humidity in an urban area (Jauregui & Tejeda 1997; Homer & Eliasson 1999).

These alterations of environmental temperatures can potentially alter the breeding activity of temperate anuran species, which require a minimum threshold temperature to call (Table 1). In most temperate species, calling commences after this minimum temperature threshold is surpassed. As long as the temperature falls below this critical level, calling ceases as energy reserves required for calling become low and energy is focused on survival. On the other hand, if temperatures become too high to sustain continuous calling during the day, anurans can also delay calling activities until the temperatures decreases to a suitable level at nightfall (Cui et al. 2011). Because of the presence of the UHI, the minimum calling threshold differences in an urban area compared to a rural area, even in the same geographic location, may alter species occupancy and detectability. The UHI can influence species to call at an urban pond, while the same species may not be calling at a rural pond on a given night. Likewise, the UHI may also deter breeding calls if air temperature at an urban pond is too warm to support calling activity (Oseen & Wassersug 2002).

Relative humidity fluctuations can also alter anuran calling activity, by increasing or decreasing the amount of available moisture. The skin of most amphibians, including anurans, is highly permeable and acts largely as a free water surface that has little to no resistance to evaporative water loss (Keen 1984). Therefore, anuran’s habitat distribution and activity patterns are greatly influenced by the need to maintain physiological water balance (Keen 1984). Likewise, anuran calling activity patterns largely depend on relative humidity at a given pond. When pond conditions have a higher relative humidity, evaporative water loss would be negligible, thereby potentially increasing calling activity. However, with less soils and vegetation in an urban area, moisture will evaporate from impervious surfaces relatively quickly, causing lower relative humidity, in turn decreasing calling activity. Consequently, the UHI may decrease calling activity at a pond, as it will likely decrease relative humidity in an urban area.

In addition to air temperature and relative humidity, anurans are also seen to respond behaviorally to fluctuations in precipitation and temperature at the landscape-scale (Cui et al. 2011). Increased temperature and precipitation can promote anuran breeding activity in some species (Oseen & Wassersug 2002) by triggering migration from terrestrial, overwintering habitats to pond breeding habitats. An insufficient amount of precipitation or lower temperatures at the landscape-scale may delay or even deter some species migration. The presence of an UHI can affect summer daytime thunderstorm formation and/or movement, as it has the potential to bifurcate a moving thunderstorm. The separated storm then essentially avoids the city center and moves on the outskirts of a city, due to a building barrier effect (Bornstrein & Lin 1999). As the UHI increases in magnitude, it had been documented that it can cause increased precipitation in some areas, while simultaneously decreasing precipitation in other areas of a geographic region (Walls, Barichivich, & Brown 2013). This varying precipitation at the landscape-scale can alter the onset of migration and consequently breeding activity, by increasing precipitation in some areas, yet decreasing precipitation in other areas. Similarly, the UHI may cause variation in temperature at the landscape-scale, which can alter the onset of migration and consequently breeding activity, by increasing temperature in some areas.

As most urban areas are continuing to increase in population size, land cover change will likewise continue to increase the magnitude of UHIs. This research focusing on the effect of the UHI on anurans is novel, yet imperative to understand the consequences of human induced climatic conditions on anuran breeding activity and species richness in an urban area. Their relatively fast response time to temperature and available moisture may render anurans more susceptible than other flora and fauna to increasing UHI effects, while simultaneously acting as a precursor of how other species in an urban area may respond to UHIs.

In this thesis, I describe the first study to explore the effects of UHI induced climatic conditions on anuran breeding activity and species richness in an urban area. I applied occupancy analysis and general linear modeling to anuran call survey data from two years at 66 remnant and storm water control ponds in the Charlotte metropolitan region to determine the effects of landscape-scale precipitation and temperature, and pond-scale relative humidity and temperature on the breeding activity of individual anuran species and anuran species richness. I also applied occupancy analysis and general linear modeling to anuran call survey data from two years at 46 remnant and storm water control ponds in the Charlotte metropolitan region to determine the effects of landscape-scale precipitation and temperature, and pond-scale relative humidity and temperature on species occupancy and detectability of calling activity. I predict that an increase in temperature and a decrease in relative humidity at pond-scale will affect species richness, and landscape-scale precipitation and landscape-scale temperature will affect species richness at ponds. I also predict that an increase in in temperature and decrease in relative humidity at ponds will affect anuran calling activity and that landscape precipitation and landscape temperature will affect anuran occupancy.

METHODS

In order to find the effects of the UHI on anuran species richness, occupancy, and detectability, 66 ponds were selected throughout the Charlotte metropolitan region for our study. Twelve anuran call surveys were conducted in order to document anuran calling activity in spring of 2014 and 2015. To determine the effects of the UHI, landscape-scale precipitation and temperature, and pond-scale relative humidity and temperature are measured at each pond. I conducted habitat quality surveys and analyzed landscape context variables to also account for their effects on anuran species richness, occupancy, and detectability.

Study Area

The study area occurs within the Piedmont region of North Carolina which includes Mecklenburg county and the 14 surrounding counties, also known as the Charlotte Metropolitan Region (CMR). The CMR is located in the transitional region between the Appalachian Mountains and the Southeastern Plains, dominated by low, rolling hills with oak-hickory forests and mixed oak-pine forests, with pine on drier sites (Johnson and Sharpe 1976). Historically, hydrology consisted of streams and rivers, but mills dammed many of the streams in the region, creating mill ponds throughout the region, remaining as remnant ponds throughout the region (Napton et al. 2012). The CMR has a humid subtropical climate, with four distinct seasons, where winters are short and generally cool and summers are hot and humid (Napton et al. 2012).

The CMR was predominately agricultural, cropland, and mills until the early twentieth century, however, a shift in economies prompted reforestation throughout the region until the mid-to-late twentieth century (Napton et al. 2012). At the end of the twentieth century, Charlotte began its transition to the banking and financial capital of the south, and Mecklenburg County alone was seen to nearly double in population size, an eighty-one percent increase from 1988 to 2008. The fourteen county region surrounding Mecklenburg County was not far behind in population growth, increasing about fifty-five percent over the same time period. As the population size increased rapidly, so did urbanization, causing Mecklenburg County to lose thirty-three percent of its tree canopy and three percent of its open space, while simultaneously gaining sixty percent of urban area in just twenty years (American Forests 2010). It is estimated that the CMR will lose an additional 212,650 ha of both forested and agricultural land to urban land-use development by 2030 (Meentemeyer et al. 2013).

Site Selection

In the CMR, anuran breeding activity, local habitat quality, and local climatic conditions are measured at 47 permanent ponds in 2014 and twenty additional ponds in 2015 (Figure 1). Ponds are selected to represent all possible combinations of high, medium, and low impervious surface area and high, medium, and low precipitation amounts in landscapes surrounding ponds, in order to capture the full variability of the CMR's UHI (Figure 2). The criteria used to select the study ponds are based on average annual precipitation between December and June 2009-2014 CoCoRaHS data. (Figure 2) CoCoRaHS is a volunteer based dataset that records the amount of precipitation of actual rainfall events over an area, which can fairly accurately measure and map precipitation events. The criteria for amount of impervious surface cover data was taken from the 2006 National Land Cover Data base (NLCD). Ponds are classified by the proportion of surrounding landscapes, within a 1.5 km radii, covered by impervious surfaces, a common surrogate index for air temperature, and average precipitation (Figure 2).

Anuran Call Surveys

I conducted call surveys at all ponds the North Carolina Calling Amphibian Survey Program protocol. Six surveys occurred from January until June 2014, and again in 2015, on warm humid nights, with little to no wind. Each survey occurred between a half-hour after sunset and 1AM. Call surveys were conducted by trained volunteers, who were randomly assigned to driving routes across the CMR. Routes were driven from one pond to the next closest pond, and each route included up to 10 ponds. The start of routes was rotated randomly between all ponds in a route, as to allow for a pond to be surveyed at different times in the night. Calling activity is measured by: (0) no calling; (1) individuals can be counted; (2) calls of individuals can be distinguished, but there are overlapping calls; and, (3) full chorus, where calls are constant, continuous, and overlapping. Cloud cover is measured by: (0) few clouds; (1) partly cloudy (scattered) or variable sky; (2) cloudy or overcast; and, (4) fog or smoke. Precipitation is measured by: (0) no precipitation; (1) misty rain; (2) light rain or drizzle; and, (3) heavy rain. Noise level is measured by: (0) no appreciable effect; (1) slightly affecting sample; (2) moderately affecting sample; (3) seriously affecting sample; and, (4) profoundly affecting sample. Wind is measured by; (0) calm; (1) light air; (2) light breeze; (3) gentle breeze; and, (4) moderate breeze. The target anuran species for these surveys include: Bullfrog (*Rana Catesbeiana)*, Green Frog (*Lithobates clamitans)*, Southern Leopard Frog (*Rana sphenocephala)*, Pickerel Frog (*Rana palustris)*, American Toad (*Bufo americanus)*, Fowler's Toad (*Bufo fowleri)*, Eastern Narrowmouth Toad (*Acris crepitans)*, Cope's Gray Treefrog

(*Hyla chrysoscelis)*, Northern Cricket Frog (*Acris crepitans)*, Upland Chorus Frog (*Pseudacris feriarum)*, Spring Peeper (*Hyla crucifer)*, and Green Treefrog (*Hyla cinerea)*.

Pond-Scale Climatic Conditions

Pond-scale temperatures and relative humidity are recorded by LogTags at all ponds every thirty minutes, on the hour and half-hour, from February 1st to June 30th (2014) and January 25th to June 30th (2015). LogTags are small devices which are programmed to record both temperature and relative humidity at a determined time interval. They were attached to trees on the north side of the pond, approximately five feet off of the ground, and six feet from the ponds edge. If a pond did not have a tree on the north side to attach the LogTags to, it was attached to the closest tree possible.

Landscape-scale climatic conditions

I used PRISM data from 2014 and 2015 to measure the climatic conditions in landscapes surrounding ponds. These datasets are the modeled averages using climatologically-aided interpolation (CAI) using as many of the weather station networks and data sources as possible. PRISM calculates a local climate-elevation relationship for each grid cell, whether it be for precipitation a temperature and uses nearby station data to populate the regression function. PRISM calculates climate-elevation regression by weighing the station data points to control for the effects of a wide variety of physiographic variables. In addition to topographic facets, PRISM has station weighting functions that account for proximity to coastlines, the location of temperature inversions and cold air pools, and several measures of terrain complexity (PRISM 2016). Both the monthly precipitation and minimum temperature are averaged at each landscape, at every pond, for each month over the six-month study period from January to June 2014 and

2015. In order to find the optimal scale, or the scale which has the strongest effect on the anuran species-landscape relationship (Jackson & Fahrig 2015), 13 different concentric landscapes sizes around a given pond are analyzed. The first ten landscape sizes ranged from half of a kilometer, which is smaller than the average dispersal distance for all species studied, to five kilometers, increasing by half of a kilometer intervals. The final three landscape sizes included ten, fifteen, and twenty kilometers scales, which are larger than the average dispersal distance of all species studied.

Pond Habitat Quality

Habitat quality surveys occurred in April 2014 and May 2015 to collect data on vegetation variables, pond dimensions, and water variables at a given pond. At each of the four cardinal directions, four-meter line transects ran perpendicular to the ponds edge, beginning two meters in the pond and reaching two meters onto the shore. Storm water control ponds have four additional line transects, which start two meters back from the pond bank and run ten meters parallel to the pond bank, between the perpendicular transects to capture cover variability throughout the habitat. The transects at the cardinal direction of each pond measure the proportion of ground cover by measuring percentage of leaf litter, grass, bare earth, impervious surface, herbaceous cover that touch the transect. These transects also measure proportion of shrubs by measuring percentage of woody vegetation. These transects also measure proportion of ground cover in the pond by measuring percentage of submerged vegetation, emergent vegetation, floating vegetation, submerged objects, and submerged bare ground. Depth at 1 meter and 2 meter are recorded for all ponds. A water probe collected data for temperature, pH, and conductivity within each pond. Presence or absence of fish are recorded for all ponds.

Amount of trees surrounding pond's edge are estimated by: (0) no trees; (1) a few trees; (2) trees surrounding half of the pond or slightly more than half; or, (3) completely surrounded by trees. The additional transects at the storm water control ponds measure proportion of ground cover around the pond by measuring percentage of leaf litter, grass, bare earth, impervious surface, herbaceous cover that touch the transect. These transects also measure proportion of shrubs by measuring percentage of woody vegetation. These transects also measure proportion of trees around a pond's edge by measuring canopy cover using a densitometer.

Landscape Context

Forest cover, agricultural cover, wetland density, and road density are also measured using the same landscape sizes as those used to measure landscape-scale climatic conditions. Forest cover is comprised of all evergreen, deciduous, and mixed classes of National Land Cover Data (2006). Agricultural cover comprised of pasture, hay, and cultivated crops of National Land Cover Data (2006). The forest cover and agricultural cover, are the proportion of a landscape covered by forest and agricultural, respectively. Both wetland density and road density are also estimated for each of the 13 landscape scales, for each pond. Wetland density is found by using the National Wetland Inventory to find the number of wetlands per unit landscape area. Road density is found by using TigerLine Data (2010) to find the length of roads per unit landscape area. This was completed in ArcGIS 10.3.

ANALYSES

Two Principal Component Analyses (PCA) were run on both the 2014 and 2015 habitat quality survey data to find the best explanation for the variance in local pond habitat data. For each year Tree amount, fish presence, pH, conductivity, water temperature, depth at one meter, depth at 2 meters, surface vegetation, emergent vegetation, floating vegetation, submerged bare ground, leaf litter on the bank, grass, bare ground on bank, herbaceous vegetation, and woody vegetation are all standardized by scaling and included in the PCA. The top three components of each PCA are selected using the Kaiser-Guttman criterion, where only the components with eigenvalues greater than one are considered. Of the four eligible components, only the top three components from each year are chosen for the PCA analysis (Table 2).

For anuran occupancy at a pond, overall pond-scale temperature and overall pond-scale relative humidity are averaged for the entire study period. The pond-scale coefficients of variation for both temperature and relative humidity are found by dividing the standard deviation by the mean for variable at each pond. This was to account for the variability in both temperature and relative humidity at all ponds.

For anuran detectability, LogTags recorded pond-scale temperatures and relative humidity at all ponds to determine if the UHI is affecting temperature and relative humidity enough to alter detectability of a given species. Pond-scale average minimum temperature is calculated during the time of each of the surveys that occurred, at every pond. In a similar manner, average relative humidity is calculated for the time that each of the surveys occurred, at every pond.

For anuran species richness, both the monthly precipitation and minimum temperature are averaged at each scale, at every pond, for each month over the six-month study period from January to June 2014 and 2015.

I ran the occupancy and detectability modeling in PRESENCE, version 10.6 (Hines 2006). I ran both the PCA analysis and the general linear modeling in R, version 3.2.4 (R Core Team 2015).

Occupancy and Detectability

The first analytical approach that is implemented is simple multiple-season occupancy modeling to model anuran occupancy and detectability for all anuran species, as a response to pond-scale and landscape-scale climatic conditions. I tested for an effect of average minimum temperature, average precipitation, agricultural cover, forest cover, wetland density, and road density at a 1.5 km landscape combined with volume of noise disturbances, amount of precipitation, and wind disturbance for all species. This landscape size of 1.5 km is chosen because it is the average dispersal distance of all species studied. The top three habitat components at each pond's edge are also tested for an effect on species occupancy. All site covariate predictor variables and pond-scale climatic covariate predictor variables are transformed to a functional scale by dividing each value by 100, as to allow the modeling to find the true maximum likelihood estimates of the model parameters (MacKenzie et al. 2005). Sample covariate variables occurred at an individual pond during one survey period of that pond and categorical sample covariates (i.e. noise, wind) are transformed to explain categorical effects of a given variable. Pond-scale climatic variables are only used as a predictor for detectability, as these variables may influence calling activity of a given species. Landscape-scale climatic variables are only used as predictors for occupancy, as these variables may influence migration to a pond by a certain species. Neither sample nor site covariates are not used to estimate extinction and colonization probabilities.

I used Akaike's Information Criterion corrected for small sample sizes (AICc) to determine the most parsimonious models by comparing models representing possible variations of up to seven predictor variables and choosing the best models ($\Delta_i \leq 2$) for each species. All models conformed to assumptions of normality and homoscedasticity. For each best model, PRESENCE calculated model average estimates, standard error, Δ_i, and weight.

Species Richness

I used general linear modeling to investigate the effects of UHI climatic conditions on maximum anuran species richness over two years. I tested for an effect of pond-scale average temperature, relative humidity, coefficient of variation in temperature, and coefficient of variation in relative humidity, and landscape-scale average minimum temperature and average precipitation on species richness using general linear modeling. I also included landscape-scale agricultural cover, forest cover, wetland density, and road density and pond scale habitat quality in the general linear modeling to account for their effects on species richness. Each landscape scale is analyzed separately.

I used Akaike's Information Criterion corrected for small sample sizes (AICc) to determine the most parsimonious models by comparing models representing possible variations of up to seven predictor variables and choosing the best models ($\Delta_i \leq 2$) for each landscape size. All models conformed to assumptions of normality and homoscedasticity.

I calculated model-averaged standardized partial estimates for the explanatory variables in the best ($\Delta_i \leq 2$) models and used unconditional variances to calculate their standard errors (Burnham & Anderson 2004). For each explanatory variable I calculated the relative variable importance (RVI). This is accomplished by summing the Akaike weights of all the best models for a landscape in which a variable is included (Burnham & Anderson 2004). Using a rule-of-thumb borrowed from Bayesian model averaging I then interpreted all RVI values. For Bayesian model averaging, the strength of evidence is determined by the following ranking of variable posterior probabilities: <0.50, no evidence; 0.50-0.75, weak evidence; 0.75-0.99, strong evidence; >0.99, very strong evidence (Viallefont et al. 2001). This interpretation of RVI values simply indicated the importance of variables as predictors of species richness (Burnham & Anderson 2004). Thus, the ranking of RVI values underscores the relative strength of evidence of their explanatory importance for all predictor variables.

In order to find the variables which had the strongest effect on species richness I combined all top models, across all scales. I then recalculated Δ_i for all models and again selected best models ($\Delta_i \leq 2$). For the new top models, RVI values, Δ_i, weight, and model average estimates are recalculated and strength of evidence is again interpreted using the rule-of-thumb borrowed from Bayesian model averaging.

RESULTS

The collected meteorological data suggests evidence that an UHI exists in the CMR. Ponds were classified based on their percentage impervious surface cover, where urban ponds had more than 60% impervious cover, suburban ponds had between 30% and 60% impervious surface cover, and rural ponds had less than 30% impervious surface cover within a 1.5 km radii of the pond. Comparison between all ponds show that the urban ponds are, on average, are both warmer and receive more precipitation than rural ponds. At the pond-scale level, average temperature at the urban ponds is at 61.1 ℉, 60.3 ℉ at suburban ponds, and 58.9 ℉ at rural ponds. At the 1.5 km landscape urban ponds received an average precipitation of 2.9 inches, suburban ponds received 2.86 inches, and rural ponds received 2.67 inches. Average relative humidity was 67% at both urban and rural ponds and 68% at suburban ponds. The coefficient of variation of relative humidity is 0.34 at urban ponds, 0.32 at suburban ponds, and 0.35 at rural ponds. the coefficient of variation of temperature is 0.28 at urban ponds, 0.29 at suburban ponds, and 0.31 at rural ponds.

Occupancy and Detectability

All twelve species of anurans were detected across the 66 studied remnant and storm water control ponds; southern leopard was found in 65 ponds (98%), bullfrog was found at 62 pounds (94%), spring peeper was found at 58 ponds (88%), upland chorus frog was found at 54 ponds (82%), green tree frog and Fowler’s toad were found at 46 ponds (70%), green frog and northern cricket were found at 45 ponds (68%), eastern narrowmouth toad was found at 44 ponds (67%), pickerel frog was found at 41 pounds

(62%), American toad was found at 39 ponds (59%), and Cope's gray tree frog was found at 29 ponds (44%).

Only one model qualified for a best model ($\Delta_i \leq 2$) for American toad, bullfrog, Southern leopard frog, and spring peeper (Table 3). Two models qualified for best models ($\Delta_i \leq 2$) for eastern narrowmouth toad, Fowler's toad, gray tree frog, green frog, green tree frog, northern cricket frog, and pickerel frog (Table 3). Landscape scale average minimum temperature and landscape scale average precipitation are in the best models for only three species (eastern narrowmouth toad, Cope's gray tree frog, and green tree frog) as a predictor for occupancy. Pond scale minimum temperature and average relative humidity during anuran surveys are a predictor for detectability for all species calling activity in all best models. Road density is in the best models for two species (bullfrog and pickerel frog). Forest cover is in the best models for three species (bullfrog, pickerel frog, and green frog). Agricultural cover is in the best models for two species (Fowler's toad and northern cricket frog). Habitat quality is in the best models for four species (bullfrog, Fowler's toad, green frog, and northern cricket frog) and wetland density is only in one best model (Fowler's toad).

Landscape scale average minimum temperature has a positive effect, while landscape scale average precipitation has a negative effect for all species when these predictors are present in the top model (eastern narrowmouth toad, Cope's gray tree frog, and green tree frog). The effect size of pond scale average minimum temperature and average relative humidity during surveys varied between negative and positive for detectability for all species (Table 4). Pond scale average minimum temperature during surveys is a negative effect on detectability for green tree frog, pickerel frog, southern leopard frog, spring peeper, and upland chorus frog. Pond scale average minimum temperature during surveys is a positive effect on detectability for American toad, bull frog, eastern narrowmouth toad, Fowler's toad, Cope's gray tree frog, green frog, and northern cricket frog. Pond scale average relative humidity during surveys is a negative effect on detectability for American toad, green frog, pickerel frog, Southern leopard frog, spring peeper, and upland chorus frog. Pond scale average relative humidity during surveys is a positive effect on detectability for bull frog, eastern narrowmouth toad, Fowler's toad, Cope's gray tree frog, green tree frog, and northern cricket frog. Road density had a negative effect for all species when it is present in a top model. Forest cover had a positive effect for all species (bullfrog, pickerel frog, and green frog). Habitat quality had a positive effect for bullfrog; however, habitat quality has a negative effect for Fowler's toad, green frog, and northern cricket frog. Agricultural cover has a negative effect on both Fowler's toad and northern cricket frog. Wetland density has a positive effect on Fowler's toad.

Species Richness

Fifteen models qualified as the best models to explain species richness for all scales combined (Table 5). Habitat component 1 is included in all but one of the top models, followed by wetland density (12 models), the coefficient of variation of temperature (11 models), road density (10 models), forest cover (4 models), coefficient of variation of relative humidity (3 models), agriculture cover and average temperature at the pond (2 models each), and average relative humidity at the pond, average minimum landscape temperature, and habitat component 3 (1 model each). Average precipitation and habitat component 2 are not in any of the top models.

There is strong evidence for both habitat component 1 and wetland density in all top models as important predictors of anurans species richness (Table 6). The coefficient of variation in temperature and road density showed weak evidence to explain anuran species richness. There is no evidence for any of the other remaining predictor variables to explain anuran species richness. Road density had the largest effect size (-0.31), followed by habitat component 1 (-0.21), wetland density (-0.21), and coefficient of variation of temperature (-0.19) (Table 6). Road density, habitat component, wetland density, and coefficient of variation of temperature all had negative effects on species richness.

Average minimum temperature has the largest effect at the 0.5 km scale and as scale size increases, effect size is seen to decrease (Figure 3). Average precipitation has the largest effect at the 0.5 km scale and as scale size increases, the effect of average precipitation is seen to decrease to 1.5 km and then seen to begin to slowly increase again from 3 to 5 km. The effect of the coefficient of variation of temperature is seen to increase as scale size increases reaching the largest effect at the 2 km scale, it is then seen to decline as scale size continues to increase. Average temperature has the largest effect size at the 2.5 km scale, with the effect size increasing to 2.5 km and then decreasing to 10 km, where there is another increase in effect size, but then decreasing to 15 km. As scale size increases, coefficient of variation of relative humidity also increased reaching the largest effect at the 5 km scale, where it then decreases as scale size increases. Average relative humidity is seen to increase in effect size as scales increase until it has the largest effect size at the 10 km scale, where effect size then decreases to 10 km, but increases again to 20 km.

DISCUSSION

There is evidence that an UHI exists in the CMR, as the meteorological evidence supports that there is warmer temperatures at the urban ponds compared to those of rural ponds. Although relative humidity does not fluctuate between urban, suburban, and rural ponds, most likely due to close proximity of evaporation occurring from the pond, both temperature and precipitation amount is seen to be affected, depending on the amount of impervious surface cover. Urban ponds are seen to have an increased temperature comparted to that of rural ponds, due to increases in impervious surface cover and decreased vegetation. Urban ponds are also seen to have increased amount of precipitation compared to rural ponds, potentially caused by induced convective activity. There is also evidence that variation of temperature is higher at rural ponds compared to urban ponds, suggesting that the UHI maintains stable temperatures within an urban area, results which has been associated with an UHI previously (Kim & Baik 2002).

Occupancy and Detectability

It is well documented that landscape characteristics are important for determining anuran occupancy at ponds (Mazerolle & Rochefort 2005; Cushman 2006; Pillsbury & Miller 2008; Hamer, Smith, & McDonnell 2012). Forest cover is often seen increase occupancy of anuran species as it provides cover and connectivity for migration from terrestrial overwintering, foraging habitats to pond breeding habitats (Cushman 2006; Pillsbury & Miller 2008; Hamer, Smith, & McDonnell 2012). My data found that bullfrog, pickerel frog, and green frog are all positively affected by forest cover. This has also been found in other studies, where increased amount of suitable habitat around a ponds edge, such as forest cover, often increases species abundance for these species (Kolozsvary & Swihart1999; Woodford & Meyer 2003).

Agricultural cover has been found to have decreased occupancy, due to lack of habitat variability, lack of forest cover, and increased agricultural pollution. (Knutson et al. 1999). My data show that both northern cricket frog and Fowler’s toad are both negatively affected by agricultural cover within a 1.5 km scale. Knutson et al. (1999) indicates the northern cricket frog has disappeared from the northern range of the Midwestern United States and although these causes are largely unknown, it may be related to increased agricultural amounts in these areas. On the other hand, Fowler’s toad can typically be found in open woodlands and meadows, yet are often seen in agricultural landscape. However, my data indicate that as agricultural increases, occupancy decreases, potentially by decreasing amount of preferred habitat of woodlands and meadows. My data show that Fowler’s toad is also the only species in a 1.5 km scale which is positively affected by wetland density. This could be explained by their relatively short distance (< 1km) migration, where increases in wetland density is likely to also increase species occupancy at a pond (Brenden 1987). Increases in agricultural may coincide with decreases in wetland density for a 1.5 km scale, both of which would decrease occupancy of this species.

Road density and fragmentation of a landscape are also associated with decreased species abundance (Gagné & Fahrig 2007) and species decline, due to road fragmentation (Gibbs 1998; Carr & Fahrig 2001; Pillsbury & Miller 2008). My data suggests that road density has a negative effect on occupancy for bullfrog and pickerel frog, while both of these species are positively affected by increased forest amounts. It is evident that the pickerel frog and the bullfrog may prefer less fragmented habitats at a 1.5 km scale, with larger amounts of forest cover, potentially due to the ease of migration through the landscape to a pond habitat. My data suggest also suggests that habitat component 1 has a positive effect on both bullfrog and green frog, yet a negative effect on Fowler's toad. This could be due to habitat component 1 being more suitable for bullfrog and green frog, yet being unfavorable for Fowler's toad.

For all 12 species studied, I found that only Cope's gray tree frog, green tree frog, and eastern narrowmouth toad occupancy is affected by landscape scale precipitation and landscape scale temperature. For all of these species as average minimum temperature increases, occupancy is also seen to increase, as temperatures initiates migration in these species (Oseen & Wassersug 2002). However, average landscape precipitation decreases occupancy for eastern narrowmouth toad and green tree frog, but not Cope's gray tree frog. This may be caused by these species migrating to ponds in drier and warmer conditions, closer to the end of spring and beginning of summer. Cope's gray tree frog occupancy, however, is seen to increase with more precipitation and warmer minimum temperatures at a 1.5 km scale, as more precipitation is likely to increase migration from the overwintering habitat.

The detectability for all anuran species studied in the CMR is greatly influenced by both relative humidity and temperature at the pond during surveys. As hypothesized, I found that for all species studied, pond scale average minimum temperature and pond scale average relative humidity during a survey influenced whether or not a species is detected by calling activity. Reiterating the importance of pond scale climatic conditions for anuran calling activity, as anurans will only call when both their temperature and available moisture requirements are met. Relative humidity at the pond-scale level, is a predictor of anuran calling activity, as it both conserves energy in the calling process and it may aid in the transmission of the call, as sound travels better through humid air (Oseen & Wassersug 2002). Throughout the CMR relative humidity at the pond-scale is fairly similar, but this may be biased as all recordings may be detecting higher moisture content in the air due to increased evaporation associated with the pond. Temperature at the pond-scale level is also predictor of anuran calling activity, as it also conserves energy in the calling process and when temperature thresholds are met as well as other climatic variables, calling activity occurs (Oseen & Wassersug 2002).

Overall, I found that landscape precipitation and landscape temperature will affect anuran occupancy for some species. This is important to understand as species shift in distribution across a geographical region are seen due to the UHI. It is also important to further understand the linkages between the UHI and a species' response to UHI induced climatic conditions at larger magnitudes.

Species Richness

For all scales combined, my data show that anuran species richness is not affected by any of the UHI climatic conditions, except the coefficient of variation of temperature. However, there are some caveats to these results. These temperate species have likely already evolved somewhat to forms of environmental uncertainty and increasing temperatures and precipitation (Walls et al. 2013), and are not exhibiting negative effects at the current magnitude of the CMR's UHI. However, my data did show that anuran species richness is seen to be affected by pond habitat quality, wetland density, and road density, all of which have larger effect sizes than the variation of coefficient of temperature. These results align with many other studies (Gibbs 1998; Carr & Fahrig 2001; Cushman 2006; Pillsbury & Miller 2008; Hamer, Smith, & McDonnell 2012), which also highlight the importunate of landscape context on anuran species richness.

Several studies indicate that increased habitat quality increases species richness at ponds (Gibbs 1998; Cushman 2006; Hamer, Smith, & McDonnell 2012), as habitat is seen to provide resources, such as cover, for breeding activity (Wells 2007). Opposed to these findings, however, habitat quality in my results, condensed as habitat component 1, shows that there is strong evidence for a negative effect on species richness. These habitat components are seen to account for the variability in habitat at a pond, however, it may not be most suitable habitat for anuran species. For example, amount of grass surrounding a pond has a large effect for habitat component 1, but grass does not offer cover for anurans, nor is it as important as tree cover for connecting habitats (Cushman 2006; Hamer, Smith, & McDonnell 2012). It is also noted that habitat quality is species-specific, and while some anurans prefer forested areas, others may prefer agricultural land (Cushman 2006). This may also contribute to the negative effect which habitat component 1 has on species richness.

Anurans are particularly susceptible to species declines due to fragmentation caused by roads, because their life history characteristics require them to move between habitats (Gibbs 1998; Carr & Fahrig 2001; Gagné & Fahrig 2007; Pillsbury & Miller 2008). My data mirror these results, suggesting that road density in a landscape is considered to be a major factor in the decrease of species richness at ponds in the CMR. The construction of roads increases the mortality and decreases the possibility of dispersal for anurans, as they either can no longer access their natural habitats or croak while trying (Cushman 2006). A study by Carr and Fahrig (2001) highlights that dispersal is highly sensitive to road density, suggesting the that it may not solely be the habitat factors that determine species richness, but also the possibility of species surviving, or not surviving, the migration to a particular pond.

Other studies have often found that wetland density within a landscape is often found to increase species richness (Cushman 2006; Brand & Snodgrass 2010), as it typically allows more viable and successful breeding habitats. Yet, my results indicate, that increased wetland density in a landscape decreases species richness. This finding could be driven by increased availability of suitable habitat for anuran species, such as wetlands that are closer proximity to foraging and overwintering habitats are preferred over more isolated pond (Houlahan & Findlay 2003).

The coefficient of variation of temperature is the only UHI predictor on species richness, where increases in temperature variation decreases species richness. This effect could be attributed to species richness being dependent on stable climatic conditions at a given pond. These stable climatic conditions could be attributed to the presence of the UHI, as temperatures have been documented to remain consistent under windless condition of the UHI (Kim & Baik 2002).

Anurans play an important role in wetlands and forests, as they compose a significant proportion of the vertebrate biomass that are both consumers and prey species (Hamer, Smith, & McDonnell 2012). Furthermore, it is clear that these amphibians can persist with in an urban area, functioning as key carnivores and prey in urban ecosystems as well. As the UHI continues to alter temperatures, relative humidity, and precipitation throughout a geographic location, urban populations may face shifts in distribution potentially causing isolation, which could, in turn, drive local extinctions.

Although this study did not show immediately threating effects on anuran species richness, it is becoming increasingly important to understand how species richness is affected by UHI climatic conditions, especially as most UHIs will continue to increase in magnitude and size. It is difficult to suggest ways to mitigate the effects of UHI, especially as most urban areas will likely only experience urban growth. Increasing amount of vegetation in an urban area may mitigate the effects of the UHI by increasing amount of available moisture and decreasing temperatures. Nevertheless, this will not eradicate the UHI completely, nor is it a feasible solution for most urban areas. Anuran species in an urban area should continue to be monitored, as their relatively fast response time to temperature and available moisture may render them more susceptible than other wildlife to increasing UHI effects. Anuran species evenness should also be studied, as some species may become more dominant in an urban landscape due to their insensitivity to both the effects of the UHI and urbanization.

CONCLUSION

Although there seems considerable interest pivoting around how climate change may affect anuran species richness, occupancy, and detectability, this study is the first to focus on how anthropogenic induced climatic conditions in an urban area may affect these responses. Through the comparison of multiple remnant and storm water control ponds, I did not find evidence that the UHI alters anuran species richness. However, I did find that the UHI may alter species occupancy at ponds. As UHIs continues to increase in magnitude, which is expected in urban areas with increasing urbanization rates, breeding activity of some species is likely to be altered from effects of the UHI.

In the future, as the magnitude UHIs continue to increase in urbanizing areas, it is imperative to continue researching and understanding its effects on vegetation and wildlife, especially anurans and other bio-indicators. Additional studies are needed to further compare and contrast urban to rural habitats and how anuran species may be influenced by habitat climate conditions induced by the UHI.

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APPENDIX A: TABLES

Table 1: Twelve anuran species in the Charlotte Metropolitan Region and their approximate calling temperature thresholds

Species	Approximate Temperature Thresholds - °C
Spring Peeper (*Hyla crucifer)*	5 – 22 *
Southern Leopard Frog (*Rana sphenocephala)*	7 – 26
Pickerel Frog (*Rana palustris)*	8 – X
Upland Chorus Frog (*Pseudacris feriarum)*	10 – 15 +
American Toad (*Bufo americanus)*	12 – 27
Green Frog (*Lithobates clamitans)*	15 – X
Green Treefrog (*Hyla cinerea)*	16- 22
Cope's Gray Treefrog (*Hyla chrysoscelis)*	16 – 25
Fowler's Toad (*Bufo fowleri)*	17.85 – X
Northern Cricket Frog (*Acris crepitans)*	20 – _X
Eastern Narrowmouth Toad (*Gastrophryne carolinensis)*	22 - 31.5
Bullfrog (*Rana Catesbeiana)*	24 – 28

*Will call in this range, but prefer warmer temperatures in range
+ May call slightly out of this range
X – Unknown threshold

Table 2: Correlation coefficients between habitat quality variables that went into the PCA and the scores of the first three components

Variable	2014 Comp.1	2014 Comp.2	2014 Comp.3	2015 Comp.1	2015 Comp.2	2015 Comp.3
Surrounding tree cover	-0.31	0.38	-0.07	-0.44	0.20	-0.01
Fish presence	0.06	0.11	-0.35	-0.09	0.24	0.40
Depth at 1 meter	-0.19	-0.44	-0.35	0.23	0.51	0.04
Depth at 2 meters	-0.23	-0.40	-0.35	0.24	0.52	0.04
Submerged vegetation	0.10	-0.20	0.27	0.11	0.03	-0.48
Submerged bare ground	-0.08	0.26	-0.44	-0.15	0.06	0.45
Floating vegetation	0.49	0.13	-0.14	-0.04	0.29	-0.37
H+	-0.46	0.09	-0.23	-0.25	-0.08	0.11
K	-0.16	-0.25	-0.14	0.07	-0.15	0.17
Temperature	-0.09	-0.08	0.34	0.12	-0.42	-0.08
Bank bare ground	-0.21	0.10	0.11	-0.12	-0.12	-0.29
Bank leaf litter	-0.22	0.03	-0.10	-0.23	0.26	-0.25
Bank grass cover	0.39	-0.30	-0.12	0.41	-0.05	0.24
Bank woody vegetation	-0.16	0.38	0.02	-0.42	0.05	0.10
Bank herbaceous vegetation	-0.03	-0.20	0.39	-0.39	-0.04	0.02

Table 3: The best models ($\Delta_i \leq 2$; Burnham & Anderson 2002) of anuran species occupancy at 66 remnant and storm water control ponds in the Charlotte metropolitan region (North Carolina). Models are listed in decreasing order of support for each species. *K* = the number of estimated parameters; *AICc* = Akaike's Information Criterion corrected for a small sample size; $\Delta_I = AICc_i - minAICc$ for each model *i*; w_i = Akaike weight, or probability of being the best model given the observed data and the set of models evaluated.

Model	*K*	*AICc*	Δ_i	w_i
American Toad				
Pond Scale Temperature + Pond Scale Relative Humidity	6	375.67	0	1
Bull Frog				
Road + Forest + All Habitat Components + Pond Scale Temperature + Pond Scale Relative Humidity	14	612.91	0	1
Eastern Narrowmouth Toad				
Landscape Scale Temperature+ Landscape Scale Precipitation + Pond Scale Temperature + Pond Scale Relative Humidity	8	297.49	0	1
Pond Scale Temperature + Pond Scale Relative Humidity	6	297.94	0.45	0.80
Fowlers Toad				
Agricultural + Wetland Density + All Habitat Components + Pond Scale Temperature + Pond Scale Relative Humidity	14	400.24	0	1
Pond Scale Temperature + Pond Scale Relative Humidity	6	400.9	0.66	0.72
Cope's Gray Tree Frog				
Landscape Scale Temperature+ Landscape Scale Precipitation + Pond Scale Temperature + Pond Scale Relative Humidity	8	289.12	0	1
Pond Scale Temperature + Pond Scale Relative Humidity	6	290.91	1.79	0.41
Green Frog				
Forest Amount + All Habitat Components + Pond Scale Temperature + Pond Scale Relative Humidity	12	309.36	0	1
All Habitat Components + Pond Scale Temperature + Pond Scale Relative Humidity	13	310.4	1.04	0.59
Green Tree Frog				
Landscape Scale Temperature+ Landscape Scale Precipitation + Pond Scale Temperature + Pond Scale Relative Humidity	8	388.5	0	1
Pond Scale Temperature + Pond Scale Relative Humidity	6	389.86	1.36	0.57
Northern Cricket Frog				
Agricultural +All Habitat Components + Pond Scale Temperature + Pond Scale Relative Humidity	13	347.87	0	1
Pond Scale Temperature + Pond Scale Relative Humidity	6	349.61	1.74	0.42
Pickerel Frog				
Forest Amount + Pond Scale Temperature + Pond Scale Relative Humidity	7	426.62	0	1
Road Density + Pond Scale Temperature + Pond Scale Relative Humidity	7	428.14	1.52	0.47

Southern Leopard Frog				
Pond Scale Temperature + Pond Scale Relative Humidity	6	556.05	0	1
Spring Peeper				
Pond Scale Temperature + Pond Scale Relative Humidity	6	631.64	0	1
Upland Chorus Frog				
Pond Scale Temperature + Pond Scale Relative Humidity	6	608.64	0	1

Table 4: Model average estimates of the coefficients of predictors in the best models ($\Delta_i \leq 2$; Burnham & Anderson 2002) of occupancy for each species of the twelve anuran species in 46 remnant and storm water control ponds in the Charlotte Metropolitan Region (North Carolina). Model average estimates of the coefficients of predictors in the best models ($\Delta_i \leq 2$) of detectability (bold) of all species. Standard errors are calculated in PRESENCE.

Model	Estimate	SE
American Toad		
Pond Scale Temperature	5.36	1.81
Pond Scale Relative Humidity	-2.41	1.54
Bullfrog		
Road	-6.51	0.70
Forest cover	12.88	2.27
All Habitat Components	4.99	0.89
Pond Scale Temperature	7.38	1.20
Pond Scale Relative Humidity	1.98	0.92
Eastern Narrowmouth Toad		
Landscape Scale Temperature	0.66	0.024
Landscape Scale Precipitation	-3.51	0.029
Pond Scale Temperature	12.91	2.67
Pond Scale Relative Humidity	0.81	1.50
Fowler's Toad		
Agricultural Cover	-4.87	2.78
Wetland Density	16.01	2.29
All Habitat Components	-19.05	1.11
Pond Scale Temperature	0.86	1.20
Pond Scale Relative Humidity	11.86	2.06
Cope's Gray Tree Frog		
Landscape Scale Temperature	0.28	0.17
Landscape Scale Precipitation	0.47	0.09
Pond Scale Temperature	1.17	1.59
Pond Scale Relative Humidity	5.29	2.19

Table 4: (Continued)

Model	Estimate	SE
Green Frog		
Forest Cover	4.42	1.43
All Habitat Components	-1.15	1.78
Pond Scale Temperature	10.71	2.23
Pond Scale Relative Humidity	-0.45	1.33
Green Tree Frog		
Landscape Scale Temperature	0.22	0.05
Landscape Scale Precipitation	-4.06	0.04
Pond Scale Temperature	-1.52	1.22
Pond Scale Relative Humidity	7.69	1.79
Northern Cricket Frog		
Agricultural Cover	-2.72	1.25
All Habitat Components	-7.73	0.93
Pond Scale Temperature	0.73	1.31
Pond Scale Relative Humidity	16.85	2.66
Pickerel Frog		
Forest Cover	5.07	2.48
Road Density	-0.27	0.15
Pond Scale Temperature	-5.42	1.42
Pond Scale Relative Humidity	-1.78	1.13
Southern Leopard Frog		
Pond Scale Temperature	-3.42	0.99
Pond Scale Relative Humidity	-9.08	1.22
Spring Peeper		
Pond Scale Temperature	-3.13	0.90
Pond Scale Relative Humidity	-6.06	1.06
Upland Chorus Frog		
Pond Scale Temperature	-4.00	1.19
Pond Scale Relative Humidity	-2.25	1.05

Table 5: The best models ($\Delta_i \leq 2$; Burnham & Anderson 2002) across all scale of anuran species richness at 66 remnant and storm water control ponds in the Charlotte Metropolitan Region. Landscape Scale = scale where model is effective; df = degrees of freedom; AICc = Akaike's Information Criterion for a small sample size; Δ_I = $AICc_i$ – minAICc for each model i; w_i = Akaike weight

Model	*Landscape scale*	*df*	*AICc*	Δ_i	w_i
Coefficient of Variation of Temperature + Component 1 + Road density + Wetland density	2 km	6	179.1	0.0	1.0
Coefficient of Variation of Temperature + Component 1 + Forest cover + Wetland density	2 km	6	179.9	0.8	1.0
Coefficient of Variation of Relative Humidity + Coefficient of Variation of Temperature + Component 1 + Road density + Wetland density	2 km	7	180.1	1.0	1.0
Coefficient of Variation of Temperature + Component 1 + Forest cover + Road density + Wetland density	2 km	7	180.2	1.0	0.9
Coefficient of Variation of Temperature + Road density +Wetland density	2 km	5	180.2	1.0	0.9
Average RH + Coefficient of Variation of Temperature + Component 1 + Road density +Wetland density	2 km	7	180.3	1.2	0.9
Coefficient of Variation of Temperature + Component 1 + Component 3 + Road density + Wetland density	2 km	7	180.4	1.2	0.9
Coefficient of Variation of Temperature + Component 1 + Road density + Wetland density	2.5 km	6	180.5	1.4	0.9
Agricultural cover + Coefficient of Variation of Temperature + Component 1 + Road density +Wetland density	2 km	7	180.7	1.6	0.9
Average Temperature + Coefficient of Variation of Relative Humidity + Component 1 + Road density + Wetland density	2 km	7	180.9	1.8	0.9
Coefficient of Variation of Temperature + Component 1 + Forest cover+ Wetland density	2.5 km	6	180.9	1.8	0.9

Average Minimum Temperature + Component 1 + Road density	0.5 km	5	180.9	1.8	0.9
Average Temperature + Component 1 + Road density+ Wetland density	2 km	6	181.1	2.0	0.9
Average Minimum Temp + Coefficient of Variation of Relative Humidity + Component 1 + Road	0.5 km	6	181.1	2.0	0.9
Agricultural + Coefficient of Variation of Temperature + Component 1 + Forest cover	0.5 km	6	181.1	2.0	0.9

Table 6: The relative importance of explanatory variables in the best models of anuran species richness at 66 remnant and storm water control ponds in the Charlotte Metropolitan Region. The strength of evidence of the explanatory importance is borrowed from Bayesian model averaging. Model-averaged standardized partial estimates and standard errors (SE) calculated using unconditional variables are also shown.

Predictor Variable	Relative variable importance	Strength of evidence	Estimate	SE
Component 1	0.93	Strong	-0.21	0.22
Wetland density	0.81	Strong	-0.21	0.24
Pond-scale coefficient of variation of temperature	0.74	Weak	-0.19	0.22
Road density	0.67	Weak	-0.31	0.31
Forest cover	0.27	No evidence	0.09	0.10
Pond-scale coefficient of variation of relative humidity	0.20	No evidence	-0.03	0.04
Agricultural cover	0.13	No evidence	0.01	0.03
Landscape-scale average temperature	0.13	No evidence	0.03	0.03
Pond-scale average RH	0.07	No evidence	0.01	0.01
Component 3	0.07	No evidence	-0.01	0.01
Landscape-scale average minimum temperature	0.06	No evidence	-0.02	0.03
Landscape-scale average precipitation	0.00	No evidence	0.00	0.00
Component 2	0.00	No evidence	0.00	0.00

APPENDIX B: FIGURES

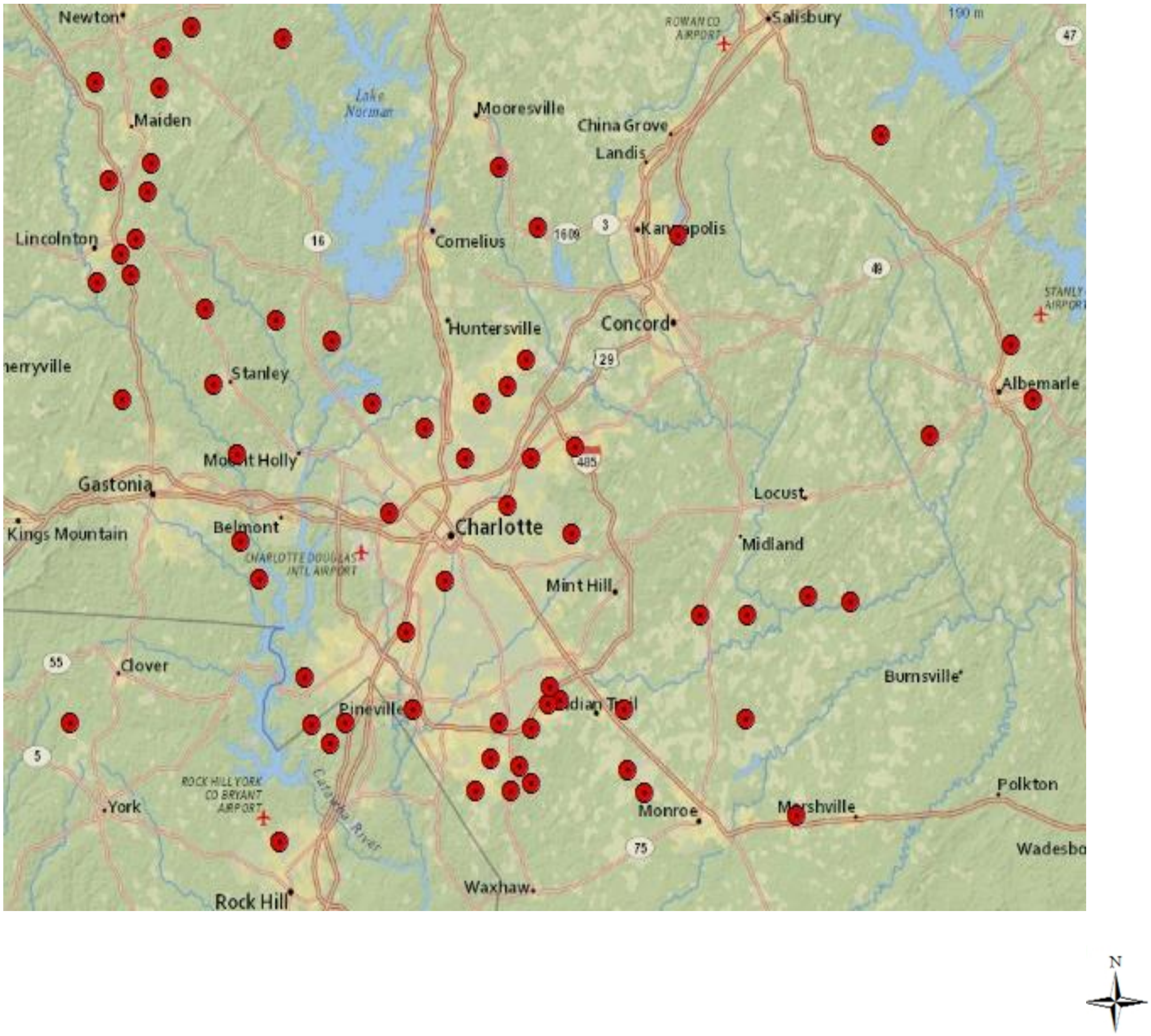

Figure 1: Locations of 66 study ponds in the Charlotte Metropolitan Region

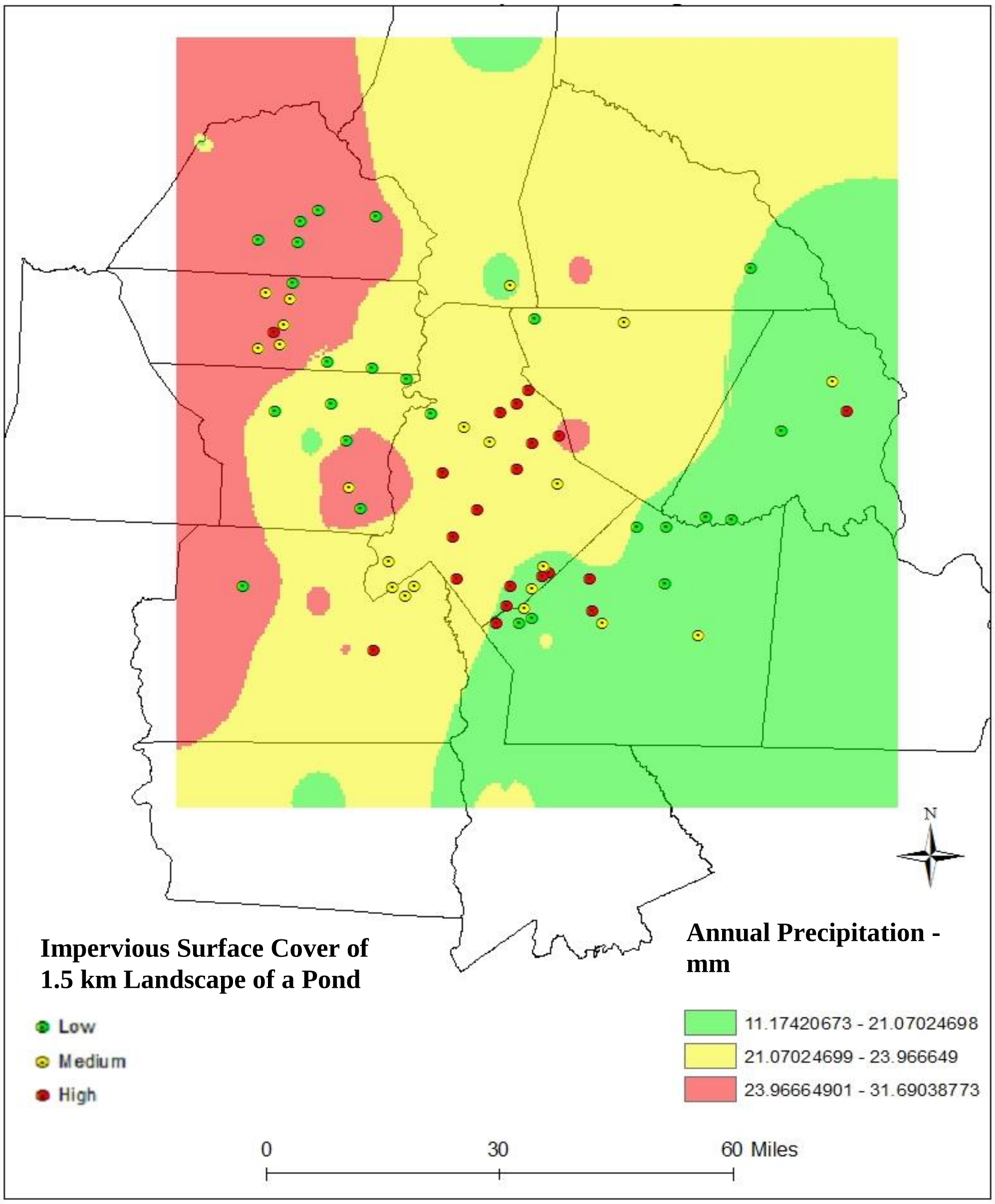

Figure 2: The average annual precipitation (CoCoRaHS 2009-2014) with study ponds classified by impervious surface cover (2011 NLCD)

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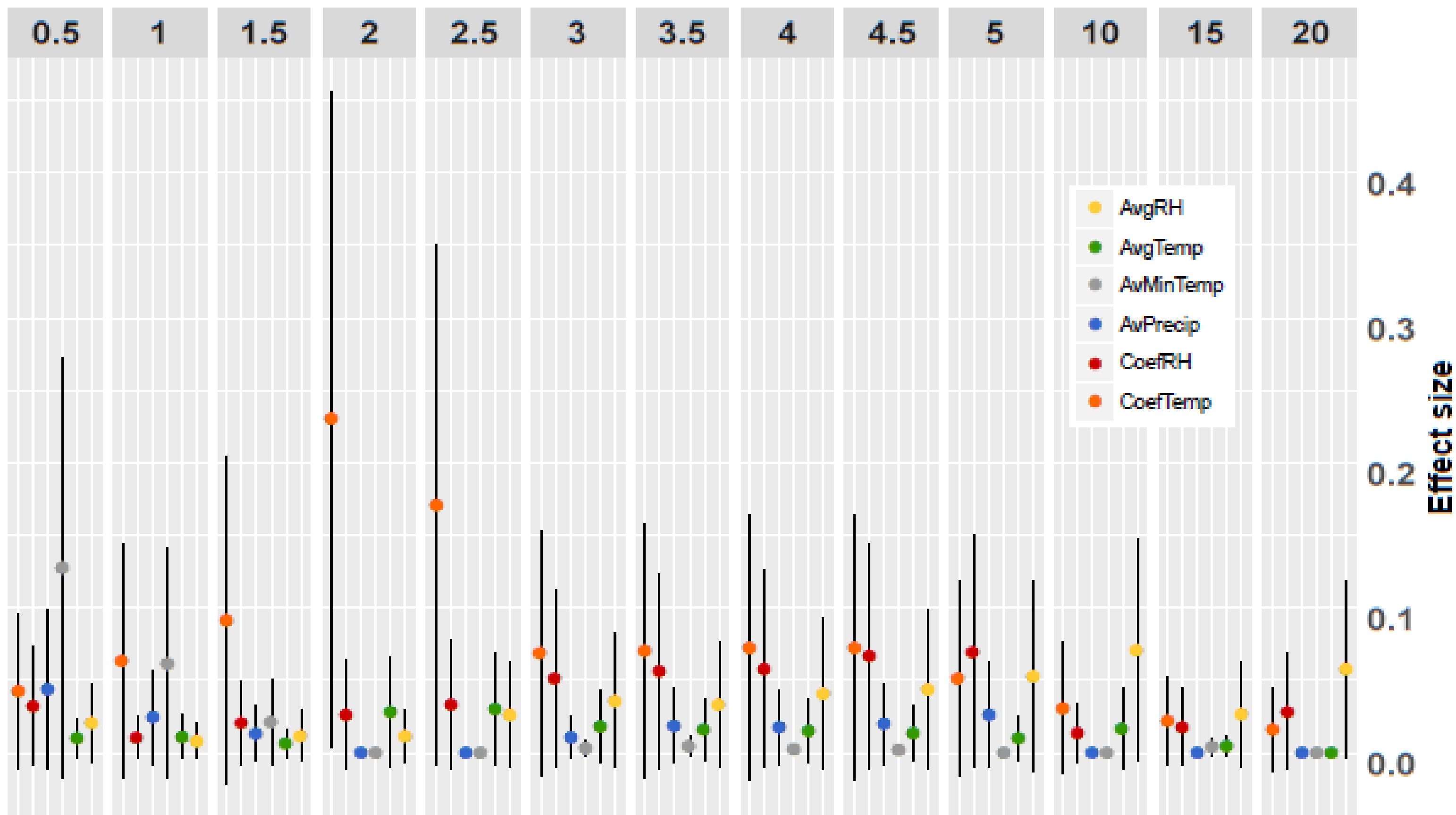

Figure 3: Absolute values of effect sizes of the UHI induced predictor variables on species richness. AvgRH = pond scale average relative humidity; AvgTemp = pond scale average minimum temperature; AvMinTemp = landscape scale average minimum temperature; AvPrecip = landscape scale average precipitation; CoefTemp = coefficient of variation of temperature; CoefRH = coefficient of variation of relative humidity. AvgRH, AvgTemp, and AvPrecip had a positive effect, while AvMinTemp, CoefTemp, and CoefRH had a negative effect on species richness