

## **ABSTRACT**

PHARR, LAUREN DANIELLE. The Effects of Urban Noise and Light Pollution on Adult Avian Survivorship (Under the direction of Dr. Caren Cooper).

Urbanization, defined as the population shift from rural to urban areas, is projected to increase urban populations by more than 3 billion people between 2010 and 2050. Along with an increased population comes an associated increase in environmental changes, which can have drastic impacts on wildlife. Serving as important indicator species for environmental change and the health of ecosystems, birds have become models to understand the effects of urbanization on wildlife communities, behavior, and health. For example, the amount of artificial light and anthropogenic noise levels change rapidly during the urbanization process, potentially influencing avian health and survival.

We explored the potential effects of artificial light and anthropogenic noise pollution on avian physiology and adult avian survivorship. Depending on species-specific traits, their responses to urbanization may vary. For instance, open-cup nesters might respond differently to anthropogenic noise than species that are cavity nesters; a cavity can act as a buffer to reduce anthropogenic noise whereas foliage can help reduce artificial light. Species that are aerial insectivores might respond differently to artificial light than species that are bark foragers; an abundance of aerial insects attracted to light at night can be beneficial to aerial insectivores that depend on these as a major component of their diet. However, artificial light can be harmful to some insect populations, which have been observed to decrease with increasing artificial light pollution, and, therefore, could negatively affect aerial insectivore populations. Overall, artificial light and anthropogenic noise pollution causes changes in avian species richness, migration ecology, breeding ecology, inter-specific competition, and survival. Chapter 1 reviews the literature of past studies to present an overview of avian responses to urbanization. In Chapter 2,

we describe a plan to explore the effects of artificial light and anthropogenic noise on avian physiology within the Triangle Area (Raleigh, Durham, and Chapel Hill) located in the Piedmont of North Carolina. We recruited 54 volunteers to the project on private residential properties across a range of light and noise pollution levels. Although we developed a field protocol approved by the North Carolina State University IACUC, the COVID-19 pandemic pre-empted our ability to carry out the fieldwork. In Chapter 3, we investigate whether artificial light and/or anthropogenic noise has an effect on the apparent annual survival of birds. We combined mark-recapture data from the citizen science project Neighborhood Nestwatch (NN) with configured artificial light and anthropogenic noise geospatial data in the Washington, D.C., USA area. American Robin, Gray Catbird, Carolina Wren, Carolina Chickadee, House Wren, Northern Cardinal, and Song Sparrow were our seven focal species. We estimated apparent survival with occupancy analyses by constructing a set of *a priori* models for each species. When considering models as being equally supported by the data, we considered models that appeared above the intercept ( $\sim 1$ ), had the lowest likelihood ratios ( $\text{neg2lnl}$ ) and/or the lowest weight, and had  $\Delta\text{AICc}$ 's less than 2. We documented variable patterns across species in relation to effects of light pollution and noise pollution. Gray Catbird and House Wren survival decreased with greater amounts of light pollution, whereas American Robin and Song Sparrow survival increased with greater amounts of light pollution. American Robin, Northern Cardinal and Song Sparrow survival decreased with greater amount of noise pollution, and Gray Catbird survival increased with greater amounts of noise pollution. The most competitive model for each species included the quadratic effect of impervious surface, indicating that survival was greatest at intermediate levels of impervious surface.

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The Effects of Urban Noise and Light Pollution on Adult Avian Survivorship

by  
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## **DEDICATION**

To the students who have found themselves being pulled into the gap of low academic achievement.

I am the living proof that you can accomplish anything.

## **BIOGRAPHY**

Born and raised in the small town of Waxhaw, North Carolina, Lauren D. Pharr has always had a curiosity for nature and love for animals. From a young age all the way through high school she aspired to become a veterinarian. Once she entered college, her dream would soon change as she struggled to find her niche, while being ultimately pulled into a gap of low academic achievement. After completing undergraduate research working with sheep, she found her passion for research; after completing more undergraduate research with birds as well as working at her local waterfowl rescue, she found her passion for wildlife. Lauren graduated with a Bachelor of Science Degree in Environmental Biology from Wingate University in 2019. Wanting to continue her work studying birds, upon her graduation, Lauren was accepted into North Carolina State University's graduate program to pursue her Master's Degree in Fisheries, Wildlife, and Conservation Biology.

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My project, let alone my whole graduate school experience, would not have been possible without some extraordinary people. First and foremost, I would like to thank my committee chair and advisor Dr. Caren Cooper who took the biggest chance on a graduate student whom she knew had more potential than what her undergraduate transcript conveyed. I would like to thank my committee members, Dr. Christopher Moorman, Dr. Olivia Petritz, and Dr. Margaret Voss. Each of them showed extreme excitement and contributed greatly towards my project, although a pandemic disrupted its plans. I will cherish our professional relationships for years to come.

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## **CHAPTER 1**

### **AN OVERVIEW OF AVIAN RESPONSES TO URBANIZATION**

According to Buhang et al. (2013), the world's urban population will increase by more than 3 billion people between 2010 and 2050 because of urban birth rates, conversion of rural land to urban, and, most importantly, human migration to cities driven by climate change. Increasingly populated urban areas will bring an increase in urban infrastructure, such as impervious surface, lights, and roads. Land-use changes alter the structure of Earth's terrestrial and aquatic ecosystems, impacting both the lifespan of organisms as well as dispersal distances (Grimm et al. 2008). The conversion of landscapes to urban land-uses results in loss of habitat for plant and animal species, leading to an increase in species extinctions and biotic homogenization (Filloy et al. 2019).

In avian ecology, a hallmark pattern corresponding to urbanization gradients is community homogenization, yielding lowered avian species richness yet high bird abundance. The explanations for this phenomenon most commonly center on alterations in vegetation structure that reduce avian species richness coupled with higher resource abundance and lower predation rates that permit greater bird abundance. Numerous studies have demonstrated that urbanization-related changes in land cover alter avian diversity, as well as richness, abundance, and composition (Blair 1996; Bellocq et al. 2017). Bird species respond to urbanization-related landscape changes according to their specific physiological and behavioral adaptations, which may or may not allow a particular species to thrive in an urban landscape (Isaksson 2018). Urbanization is associated with loss of specialist species (i.e ground, aerial and foliage insectivores, nectarivores/insectivores, ground/canopy, ground granivores) but not generalist's species (Palacio et al. 2018).

Numerous studies have demonstrated that shifts in food availability associated with urbanization-related land-use changes negatively affect avian reproduction (Summers-Smith

2007). Arthropods, the primary diet for most songbird nestlings, tend to show reduced abundance and diversity with increasing urbanization (Shochat et al. 2004; Anderson 2006; Raupp et al. 2010). As such, parents may have difficulty locating appropriate food sources for chicks (Seress et al. 2012). When the diets of nestlings are low in insects, such as beetles, caterpillars, flies, spiders and aphids, the reduced protein and fat content can limit nestling development. Juvenile house sparrows (*Passer domesticus*) in more urbanized areas had reduced body size, body mass, and fat scores compared to juvenile house sparrows in rural areas (Meillère et al. 2015). Eurasian Kestrels (*Falco tinnunculus*) in Vienna, Austria had lower reproductive success in city centers compared to city surroundings; this may be driven by significant shifts in Kestrel diets from heavy reliance on rodents in the outskirts of the city to reliance on songbirds in the city center (Sumasgutner et al. 2014). However, other urban-dwelling raptors, such as Cooper's hawks, peregrine falcons, and some owls, that thrive in urban landscapes (Boal et al. 1998; Franco et al. 2018; Kettle et al. 2018), rely on a diet of small rodents and passerines.

Predation pressures upon nests are expected to change along a rural-to-urban gradient. It has been hypothesized that predation in urban areas may either increase due to the high abundance of exotic species that act as predators, or decrease due to the lack of natural predators (Gering et al. 1999). Sasvari et al. (1995) detected higher predation rates on artificial avian nests in an urban park than in a mixed oak-beech forest, and concluded that the reduced species richness in urban environments resulted in greater predation pressures; this suggests that urban exploiters may be responsible for increasing predation pressures. Gering et al. (1999) determined the frequency of nest predation to be strongly dependent on site along the urban gradient, indicating that urbanization intensity was an important determinant of nest fate. Predation pressure exhibited an overall decline from natural to urban sites in both years, suggesting that urban environments have

low predation pressures relative to natural areas. These results suggests that predatory relaxation in urban environments may partially explain the greater abundance of some species in urban environments, particularly urban exploiters such as European Starlings (*Sturnis vulgaris*), House Sparrows (*Passer domesticus*), and Rock Doves (*Columba livia*).

Given that urban landscapes introduce novel benefits (e.g., anthropogenic resources) and pressures (e.g., mortality risks), conflicting mechanisms are hypothesized to drive the dynamics of urban bird populations. Previous studies have found that adult avian survival along a rural-to-urban gradient can vary depending upon species. For example, Evans et al. (2015) reported that species like the American Robin (*Turdus migratorius*), Gray Catbird (*Dumetella carolinensis*), Northern Cardinal (*Cardinalis cardinalis*), and Song Sparrow (*Melospiza melodia*) exhibited peak survival at intermediate and upper portions of the rural-to-urban gradient; this pattern supports the hypothesis that bottom-up processes (e.g., resource availability) can drive patterns of avian survival in some species. Stracey et al. (2012) found that apparent survival for adult Northern Mockingbirds (*Mimus polyglottos*) was higher in urban landscapes than in non-urban landscapes, suggesting that this could be driven by dispersal more than mortality, which could likely make an urban landscapes a likely source landscape for this species. Whittaker et al. (2009) found that American Robins used suburban residential areas more than forested areas, whereas the resources used by other species were context specific: (1) the use of residential areas by Song Sparrows was highest where this habitat was least common, (2) the use of forested areas by Spotted Towhees (*Pipilo maculatus*) decreased with increasing level of urbanization, and (3) the use of heavy-medium urban areas by Swainson's Thrush (*Catharus ustulatus*) decreased with increasing abundance of roads.

Urban landscapes are associated with environmental factors that can function as potential physiological stressors. The concentrations of the stress hormone, corticosterone, in the feathers of juvenile House Sparrow (*Passer domesticus*) were positively correlated with the degree of urbanization, though without effects on body size, mass, or other measures of body conditions (Beauguard et al. 2018). Additional findings determined that body condition tended to increase in rural habitats, significantly in the case of yearlings. In a study of House Sparrow populations infected with blood parasites, individuals of high body conditions persisted in urban landscapes, while infected individuals of high and low body conditions persisted in rural landscapes (Jiménez-Peñuela et al. 2019).

Growth in human population and infrastructure have also been accompanied by exponential increases in anthropogenic noise and artificial light (Francis and Barber 2013; Rich and Longcore 2006). As reviewed below, anthropogenic noise (Slabbekoorn et al. 2006; Nemeth et al. 2010) and artificial light (Van Doren et al. 2017; Winger et al. 2019) are novel stressors associated with urbanization, which can affect birds in numerous ways. Anthropogenic noise, including sounds from street traffic, construction, and airports, puts severe constraints on vocal communication by interfering with the detection of acoustic signals. For example, anthropogenic sound can mask natural sounds, affecting intentional communication (i.e., bird song) (Slabbekoorn et al. 2006; Nemeth et al. 2010). To overcome this, certain species of birds can mask anthropogenic sound by changing the characteristics of their song (i.e frequency, pitch; Nemeth et al. 2010; Ortega et al. 2012). Anthropogenic noise can also impact species foraging patterns. Halfwreck et al. (2020) found that noise significantly increased approach and attack latencies in Great Tits (*Parus major*), but that the effect depended on the level of crypsis. Additionally, noise increased latencies for cryptic prey targets, but not for conspicuous and color-matched prey targets. Senzaki

et al. (2016) documented that foraging efficiency in wild owls declined with increasing traffic noise levels due to acoustic masking and/or distraction and aversion to traffic noise. Some studies have shown that depending upon the species; anthropogenic noise can also affect reproductive success. Mulholland et al. (2018) found no evidence for an influence of noise on clutch size, brood size, number of fledglings, or overall nest success in Western Bluebirds (*Sialia mexicana*); however, Ash-throated Flycatcher (*Myiarchus cinerascens*) nests exposed to noise had lower reproductive success than quiet nests due to higher rates of abandonment at the incubation stage.

Increased urbanization creates more artificial light pollution, which can have negative effects on nocturnally migrating birds. Birds heavily rely on stars in the sky and other cues for navigation that are impaired by artificial light. Monitored avian behavioral responses to the National September 11 Memorial and Museum's "Tribute in Light" in New York using radar, acoustic sensors, and illuminations of light beams, showed that when illuminated, birds aggregated in high densities, decreased their flight speed, circled, and increased their vocalizations (Winger et al. 2019). Birds also became spatially disoriented, and their inability to analyze visual and sensory cues became affected. When the lights went out, these behaviors disappeared (Van Doren et al. 2017). Additionally, with migration challenges also comes the chance of flight collisions. Collisions with lighted structures are a major cause of mortality for migratory birds (Cabrera-Cruz et al. 2018; Winger 2019).

The impacts of artificial light on reproduction has been increasingly recognized. Effects of artificial light on timing of egg laying, which is found to be year-dependent, suggests an interaction with climatic conditions such as spring temperature, which is known have strong effects on the phenology of avian breeding (King et al. 1959; Lambrechts et al. 1996). Dominoni et al. (2020) found significantly earlier egg-laying dates in the white and green light vs. the dark treatment, and

similar trends for red light. Another study with Great and Blue Tits (*Cyanistes caeruleus*) found that artificial light disrupts sleep behavior and that these effects are more pronounced during the breeding season. Sleep loss could affect parental health and performance, which could subsequently affect developing nestlings during the breeding season.

Although light pollution can negatively influence breeding patterns, nesting habits, and nestling success (Reale et al. 2005), there are some exceptions. Natural photoperiod cycles cue activation of reproductive systems in birds, and artificial light at night can induce similar physiological responses. Artificial light advances reproduction in species that use long day lengths to time reproductive decisions (Kempnaers et al. 2010, French-Constant et al. 2016). Dominoni et al. (2013) found that European Blackbirds (*Turdus merula*) exposed to artificial light at night in cities developed their reproductive system up to one month earlier compared to European Blackbirds in forests who experienced either dark or low intensities of light.

Anthropogenic noise is often coincident with night lighting, and only a few studies to date have explicitly considered the effects of both noise and night lighting (Fuller et al. 2007; Da Silva et al. 2014; both involving timing of communication, and Senzaki et al. 2020; involving noise and light pollution effects on reproduction). Ultimately, no studies have investigated the paired effect of noise and light pollution on community structure, adult survival, or avian health, although several recent reviews have emphasized this critical gap in our knowledge (Halfwerk & Slabbekoorn 2015; Swaddle et al. 2015).

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## CHAPTER 2

### CARDINAL CAPTURE: PATTERNS OF AVIAN HEALTH ASSOCIATED WITH ANTHROPOGENIC NOISE AND LIGHT

#### ABSTRACT

With expanding urbanization, the effects of recurring human activity (e.g., changes in light and noise) may affect avian species activity, communication, and physiology. The purpose of this study was to examine the degree to which artificial light and anthropogenic noise were associated with variation in the health and physiology of avian species. Due to its year-around abundance, the Northern Cardinal (*Cardinalis cardinalis*) served as the focal species. We used geospatial noise and light pollution maps of the Triangle Area (Raleigh, Durham, and Chapel Hill) located in the Piedmont of North Carolina, to recruit volunteers in strategic locations to create a sample of yards in which we could capture Northern Cardinals stratified across levels of artificial light and anthropogenic noise. Volunteers could also take additional measures of artificial light. We prepared to obtain morphological and physiological metrics from each bird, including whole blood samples for detailed stress-related biochemical markers for both male and female cardinals. By February 2020, we recruited 54 volunteers, prepared them to use a Dark Sky Meter for light pollution measurements, and began scheduling visits to their yards. In March 2020, prior to fieldwork, the COVID-19 pandemic resulted in lockdowns, which led to the formal cancellation of Cardinal Capture in May of 2020. In this chapter, we document the establishment of Cardinal Capture, the data collection and analysis that we had planned, for these details may serve a future project. This study has the potential to provide insights into how human-induced changes to the abiotic environment might affect songbird health.

## INTRODUCTION

Human activity associated with urbanization may alter avian activity, communication, and physiology (Swaddle et al. 2015). Several decades of research have revealed a wide array of avian responses to global environmental change driven by human activity, with particular attention to climate change (Winkler et al. 2002; Jenouvrier 2013) and habitat loss and fragmentation (Blumstein et al. 2005; Ewers et al. 2006). Two forms of novel environmental change associated with urbanization have received less attention, despite their ubiquity and likely impact on birds: Artificial light (Swaddle et al. 2015; Kempenaers et al. 2010) and anthropogenic noise (Swaddle et al. 2015; Nemeth et al. 2015; Nemeth et al. 2010). The scope of studies of the effects of artificial light and anthropogenic noise on birds includes reproductive success (Dominoni et al. 2013; Malek et al. 2019) and various proxies of fitness such as behavioral activity (Poot et al. 2008; Gaston et al. 2013; Quyang et al. 2017), and adjustments in frequency and/or pitch of vocalizations (Lohr et al. 2013; Nemeth et al. 2010, 2015). No studies have examined the effects of both artificial light and anthropogenic noise on adult survival, but some have assessed various fitness proxies, such as avian physiology (i.e. body mass, blood biomarkers, carotenoid content in tissues) and avian markers of health (Kleist et al. 2018; Injaian et al. 2018; Sehgal 2015).

Assessing avian health as a proxy of fitness can involve measuring multiple traits ranging from morphological, physiological, neuroendocrine, and immune system. Health-related traits are often interdependent. Physiological responses are often dependent on variations in body mass, related to fat or protein stores, and body size, related to skeletal structure. It is unlikely that one single measure is accurately representative of a healthy free-living bird (Wilcoxin et al. 2015). Therefore, indices, such as body size-to-mass ratio, variables of blood components, and structural measures, such as carotenoid concentrations, are informative variables that can contribute to the

analysis of the overall health of a particular individual. Many variables, including biochemical blood parameters, have the added complexity of changing seasonally with molt and the reproductive cycle. Assessing health relative to potential chronic stressors, such as artificial light and anthropogenic noise associated with urbanization, requires attention to measurements relative to seasonal physiological cycles.

Overall body condition is an important determinant in an animal's individual fitness often estimated as body size-to-mass ratio (Green 2001). The overall definition of body condition as defined by multiple studies is a measure of the energetic (or nutritional state) of an individual animal, especially the relative size of energy reserves such as glycogen and fat (Schulte-Hostedde et al. 2001; Gosler 1996; Krebs et al. 1993). A traditional ratio index is used to determine whether a bird is heavy or light for its specific size. However, mass alone is unlikely to serve as a reliable indicator of condition; an animal could just be structurally large (Dobson et al. 1992).

Hematology markers can serve as good indicators of nutrition, stress conditions, and overall avian health. Hematocrit, the ratio of red blood cells (erythrocytes) to plasma after centrifugation of a blood sample, is considered a good indicator of oxygen levels, hydration, and dietary nourishment. Values between 35 and 55% are considered normal for birds. Low hematocrit values reflect a reduction in the number of red blood cells. A reduction in the production of red blood cells can be indicative of bacterial infections and gastrointestinal disorders, including parasitism and hemorrhage or may reflect nutritional deficiencies of minerals, such as iron or copper (Wilcoxon 2015). The number of white blood cells can show whether the body is under stress. The ratio of heterophils to lymphocytes, two types of white blood cells, is considered an indicator of immune health. Heterophils participate in immune response while lymphocytes respond to antigens (Briscoe 2017). Heterophils require less energy

to produce, whereas lymphocytes require more energy to produce and maintain. As a result, birds that are stressed and are allocating energy to survive stressful conditions produce more heterophils relative to lymphocytes (Wilcoxon et al. 2015).

Plasma proteins can be important indicators of avian health because they are necessary for transport of nutrients such as lipids, vitamins, and minerals. Researchers can estimate the total amount of protein in each bird's blood from the optical density of the liquid portion of blood (plasma) (Wilcoxon et al. 2015). Circulating concentrations of protein in the blood are an index of total protein reserves in an animal (Allison 1949).

The presence of blood parasites can be another reliable measure of an individual's overall health. There are many blood parasites which are common in birds; some are very sensitive to environmental conditions. For example, *Haemoproteus fringillae* is an Apicomplexa (the largest phylum of blood parasites) transmitted by mosquitoes and other blood-sucking insects, that infects the host erythrocytes and reduces the cells' ability to carry oxygen.

Feather coloration is related to diet, and therefore can be an indicator of nutritional status. When it comes to colors, birds that use carotenoids to color their feathers must ultimately obtain these pigments from their diet, but they are also capable of metabolically transforming dietary carotenoids into alternate forms that they use as plumage colorants (McGraw et al. 2003). Plumage shape plays a vital role when it comes to sexual selection and finding mates (Mays et al. 2004). Carotenoid levels can be analyzed using either a spectrophotometer (Hunt et al. 2003) or the scoring of feather molts (Lindstrom et al. 1998).

To assess avian health in relation anthropogenic disturbances to the soundscape and nightscape in residential settings of the Triangle Area (Raleigh, Durham, and Chapel Hill) located in the Piedmont of North Carolina, we created a citizen science project called Cardinal Capture

(Appendix 2.1), focused on the Northern Cardinal (*Cardinalis cardinalis*). We predicted that Northern Cardinal health would vary across residential settings across the Triangle area, such that individuals living in areas with higher levels of artificial light and anthropogenic noise (Figure 2.1) will show the following compared to individuals in areas with lower levels of artificial light and anthropogenic sound: 1) lower body mass and size (i.e tarsus, wing); 2) higher heterophil to lymphocyte ratio; 3) lower plasma protein concentrations, 4) higher presence of blood parasites, and 5) lower carotenoid levels due to poor diet and health.

## **METHODS**

### *Configuring and Incorporating Ambient Noise and Light Pollution*

Following the methods of Senzaki et al. (2020), we used data from the second world atlas of artificial night sky brightness (1° resolution) where the estimates of artificial light are a ratio of the zenith anthropic sky brightness to the natural background sky brightness (Falchi et al. 2016, Figure 2.2). We used anthropogenic noise data from a georeferenced map of expected sound pressure levels (270-m resolution; Mennitt et al. 2016). These data model natural sound levels from biotic and physiographic sources and compute anthropogenic noise exceedance levels by logarithmic subtraction of the natural from the existing sound projections. Following the methods of Senzaki et al. (2020), we used anthropogenic daytime A-weighted L<sub>50</sub> sound pressure levels as our estimate of anthropogenic sound.

For each of the visited volunteer sites, researchers will use R to extract corresponding data from the georeferenced maps of artificial light and anthropogenic sound (Figure 2.2). Researchers will follow the methods of Senzaki et al. (2020) and use data from the second world atlas of artificial night sky brightness converted to 270-m resolution (Falchi et al. 2016). The estimates of artificial light were the zenith anthropic sky brightness as a ratio to the natural background sky

brightness. Although artificial light was used to measure how bright it was at a given site, the light pixels most likely provided by satellites were quite coarse. Therefore, the estimates provided are only an average number for the whole pixels. Additionally, data from the satellites treated all light measurements equally. For example, an area with lots of houses or one airport could be shown to emit similar levels of light. To combat this, researchers will compare the mapped light data from the georeferenced maps and the local light data collected by volunteers, in order to see which method is more predictive of avian health.

Researchers will use anthropogenic sound data from a georeferenced map of expected sound pressure levels (Mennitt et al. 2016, Figure 2.2). These data model natural sound levels from biotic and physiographic sources and compute anthropogenic noise exceedance levels by logarithmic subtraction of the natural from the existing sound projections. Following the methods of Sensaki et al. (2020), researchers will use anthropogenic daytime A-weighted  $L_{50}$  sound pressure levels as estimates of anthropogenic sound. Although noise pollution models were comprised of data from both satellite and land-use maps, which were used to measure how loud it was at a given site, it is possible for data to have been contrasting if measurements were initially taken from the ground and collected over a period of time. In addition, measurements only took into account one source of noise, anthropogenic, which could possibly be more ecologically relevant to masking or reproduction, and not that relevant to survival.

To complement the artificial light levels from the georeferenced map of expected light levels of the Triangle area, we created a schedule to loan a Sky Quality Meter (SQM) with instructions for volunteers to make several repeated measures of the amount of brightness outdoors at night at their residence. Volunteer could record brightness anytime during the night, which we defined based on civil twilight periods (i.e., the sun is 6 degrees below the horizon). To retrieve a

reading, volunteers pointed the sensor side of the SQM vertically up to the sky and proceeded to press the “record” button until a value appeared. Volunteers were asked to record these values on a light meter datasheet (Appendix 2.4) provided by the research team for three to five nights in one week. We recommended that volunteers take and record additional measurements in four different spots in their yard, for a total of five measurements in one night.

We set out to recruit volunteers in the targeted cities of Apex, Cary, Chapel Hill, Durham, Garner, Hillsborough, Knightdale, Mebane, Raleigh, Wake Forest, Wendell (Figure 2.4 A), and Wake Forest, Fuquay-Varina and Holly Springs (Figure 2.4 B). Within these targeted cities, we sought to recruit volunteers who resided in various anthropogenic sound and artificial light levels (Figure 2.3).

Approximately 54 volunteers joined the Cardinal Capture Project from 2019 to 2020.

## **STATUS**

In 2020, an emerging infectious disease, COVID-19, spread globally. By March 2020, many areas of the United States were under lockdown conditions. North Carolina State University suspended research activities that involved face-to-face interactions. In April of 2020, the department of Forestry and Environmental Resources gave the choice for students to seek a research exemption to the suspension. Due to the requirements of Cardinal Capture, including taking place in areas with people and involving research assistants, we ended Cardinal Capture to pursue research with existing data (Chapter 3). All activities for Cardinal Capture officially ended in May of 2020 without any visits to volunteer yards.

In the following sections, we describe the planned data-collection protocols, analyses, and anticipated results and their implications had we been able to carry out Cardinal Capture. We include these details specifically for researchers to be able to replicate and use for future projects.

### *Sample Collection*

- Researchers will visit the assigned volunteer's yard between the hours of 7:00AM and 11AM (4 hours) eastern standard time. The homeowner's name, address, date, weather, temperature, GPS location, start time, and end time should be recorded on a field data sheet (Appendix 2.5).
- Researchers will choose an area with at least six feet of open space and a medium amount of vegetation to place a six foot nylon mist net in order to capture birds, which will be extracted upon hitting and falling into one of the mist net's pockets. Once researcher capture a male Northern Cardinal at a given yard, they take down the nets that day. If researchers capture a female North Cardinal before a male, they follow the procedure below specific to females. All other species of birds upon extraction from the net are to be released. Re-visits to a volunteer's backyard will be based on the abundance and amount of Northern Cardinals captured.
- For male North Cardinals, researchers will place a 1A aluminum USGS bird band on the left leg and record the unique band number. To reduce bias data of chronic and acute stress from handling, blood collection will be completed first.
- Use a 25 gauge needle with a 1cc syringe to draw about 0.5 mL of blood from the right jugular vein of male Northern Cardinals. Blood from female cardinals will be drawn from the brachial vein using a hematocrit tube. After the successful draw of blood, both the jugular and brachial veins are to be held off for about 5 minutes to prevent hematoma formation.
- 0.35 mL of blood from male cardinals will be transferred into heparinized microcontainer tube and placed on ice. Split the remaining 0.15 mL of blood into two hematocrit tubes:

one tube to be spun in a portable PVC spinner and labeled correspondingly for further analysis and one tube used to make two blood smears. Label these correspondingly and placed in a smear box for further analysis.

- For females, researchers will collect 2 blood smears and label them to correspond with two subsequent analyses: heterophil to lymphocyte ratio (H/L) and to note the presence of blood parasites.
- Record all hematology data collected in the field as well as timing of capture and release on a corresponding lab data sheet (Appendix 2.6). About 1-2 male cardinals per site will be sampled via blood from the jugular vein. Female cardinal numbers can be unlimited, but will be excluded from other health analyses due to their reproductive cycle.
- Measure wing chord, head to bill ratio, tarsus length, tibiotarsus length, and tail length and record on the corresponding field data sheet. The band number, sex, age, cloacal protuberances (CP), brood patch (BP), fat score, flight feather (FF) molt, mass, and status upon release will all be recorded on a separate USGS bird banding data sheet (Appendix 2.3). Data will be collected and recorded for both male and female cardinals.
- To evaluate carotenoid levels, 9-10 feather samples will be taken from male cardinals: 3 feathers from the crown, 3 feathers from the gular/ upper throat region, 3 feathers from the middle breast/secondary plumage, and 1 feather from the secondary covert/shoulder region. Feathers will be placed in plastic bags and labeled accordingly for further analysis. For completion of all 3 data collections: morphology, hematology, and carotenoids; all birds should be handled for no more than 15 minutes.
- Lastly, researchers will place cardinals in a weigh cup and record their weight.

*Lab Analysis*

Researchers will take any hematology samples to a lab to be run and analyzed appropriately within an hour of returning from the field site. To analyze specific analytes: Aspartate Aminotransferase (AST), Bile Acids (BA), Creatine Kinase (CK), Uric Acid (UA), Glucose (GLU), Phosphorous (PHOS), Calcium (CA<sup>++</sup>), Total Protein (TP), Albumin (ALB), Globulin (GLOB), Potassium (K<sup>+</sup>), and Sodium (Na<sup>+</sup>), 0.2 mL of whole blood from the male cardinal samples will be transferred into an Vetscan Abaxis Avian/Reptilian Profile Plus Rotor. Rotors should spin for 7-10 minutes; researchers will transfer readings onto the corresponding lab data sheet.

To analyze hematocrit levels, or total red blood cell volume, PCV tubes from both male and female cardinals should be spun using a portable centrifuge. When completed, a reading will be produced and should be recorded on the corresponding lab data sheet.

To measure plasma protein content, the top portion of the hematocrit tube should be broken and 0.1 mL of blood placed onto a refractometer. A total solids reading will be produced and should be recorded on the corresponding lab data sheet.

To analyze heterophil to lymphocyte ratio (H/L) and to note the presence of blood parasites, blood smears from both male and female cardinals should be stained and viewed with a microscope on low (10x) power. A minimum of 100 leukocytes should be counted and sorted into categories: small or medium lymphocytes, monocytes, heterophils, basophils, and eosinophils. Atypical lymphocytes should be noted and recorded on the corresponding lab data sheet. With any remaining blood, two different slides should be made (a thin slide and a thick slide) and analyzed using a Giemsa stain to note the presence of any blood parasites found.

### *Data Analysis*

Researchers will compile all morphology data into an excel spreadsheet. Data from the bird banding sheets should be entered into the Bird Banding Lab database. Researchers will summarize measurements of the wing chord, head to bill ratio, tarsus, tibiotarsus, and mass.

Researchers will examine regressions based on these measures of artificial light and anthropogenic noise to determine the relationship between the measured individual avian health variables. Researchers will use Principal Components Analysis with all the blood analytes, hematocrit levels, plasma protein content, and heterophil to lymphocyte ratio, to create one or two indices of avian health. Researchers will use multivariate linear regression to model variation in avian health (as PC1 and/or PC2) based on variation in noise and light pollution.

### **CONCLUSION**

Artificial light and anthropogenic noise are pervasive features of urbanized landscapes. While some avian species persist in urbanized landscapes, little is known about their health in these environments. Findings from this project will help advance understanding of avian health in relation to patterns of noise and light pollution. This study would have assembled data on an array of health-related variables: mass and size, heterophil to lymphocyte ratios, plasma proteins, blood parasites, and carotenoids. Avian health is ultimately linked to survival. In Chapter 3, we examine survival rates of seven bird species in relation to levels of artificial light and anthropogenic sound.

## LITERATURE CITED

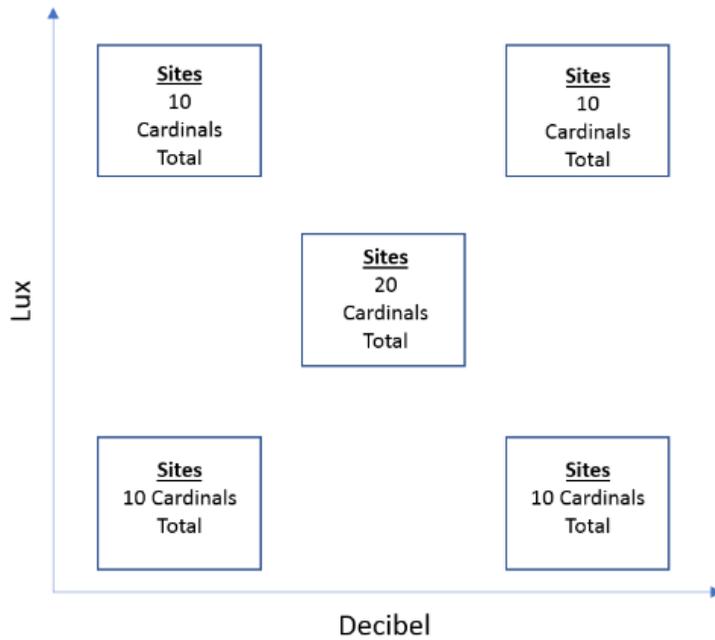
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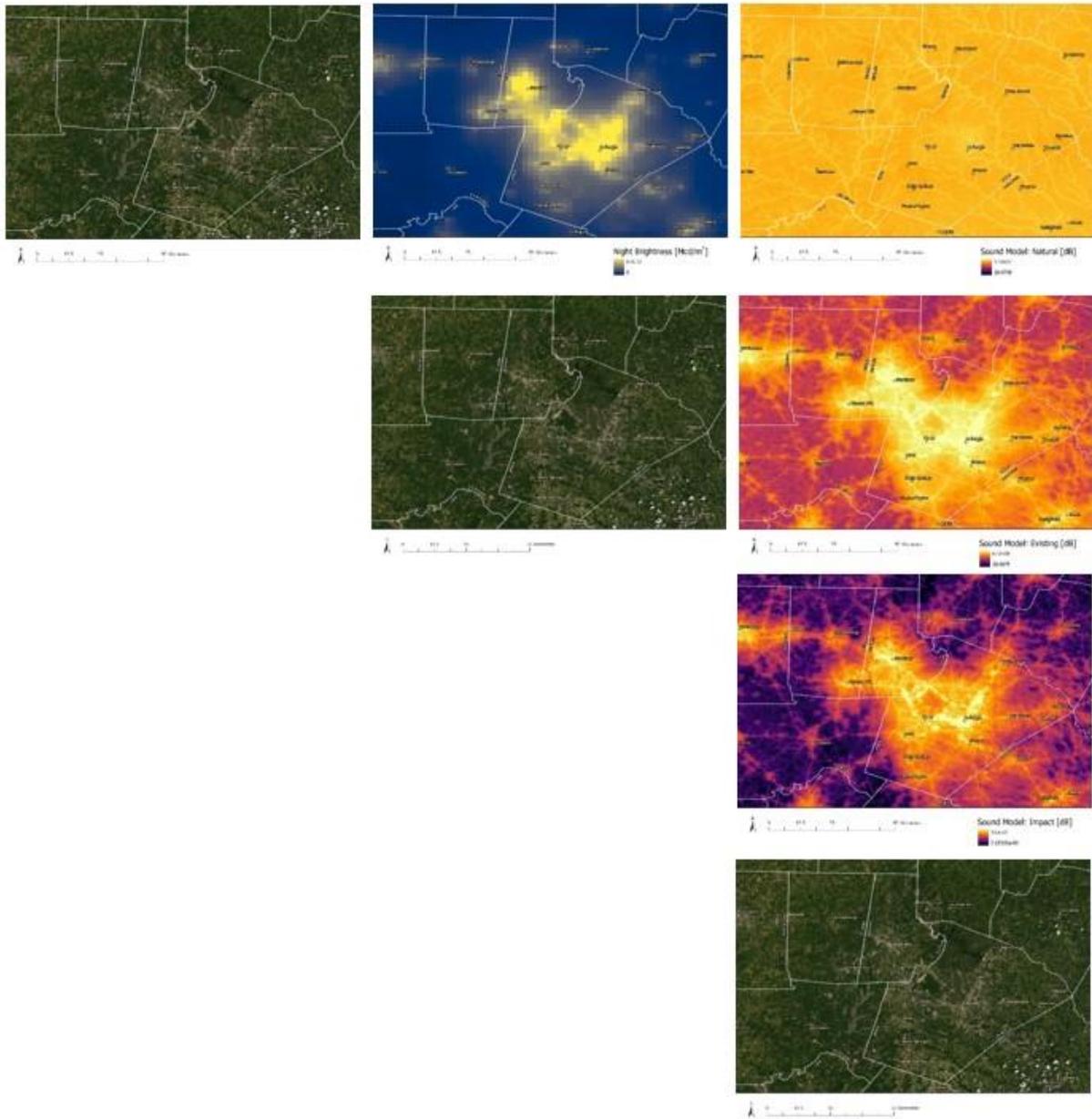
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**TABLES AND FIGURES**

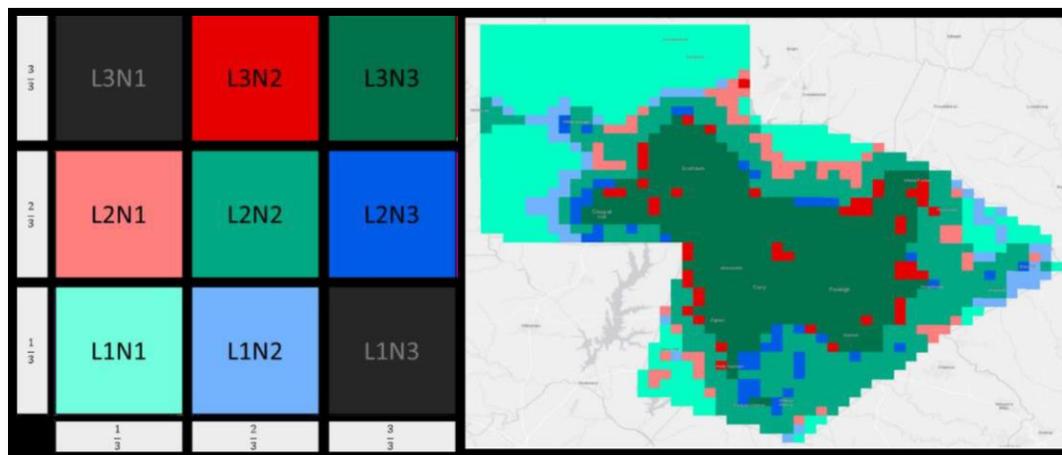
**Figure 2.1** Sampling design with focused efforts on sites at the low and high extremes of anthropogenic noise and artificial light, as well as a range of sites between these extremes.



**Figure 2.2** Geospatial configured land, Night Brightness [Mcd/m<sup>2</sup>], Sound Natural [dB], Sound Existing [dB], and Sound Impact [dB] maps of the Triangle Area to include the areas of Raleigh, Durham, and Chapel Hill.

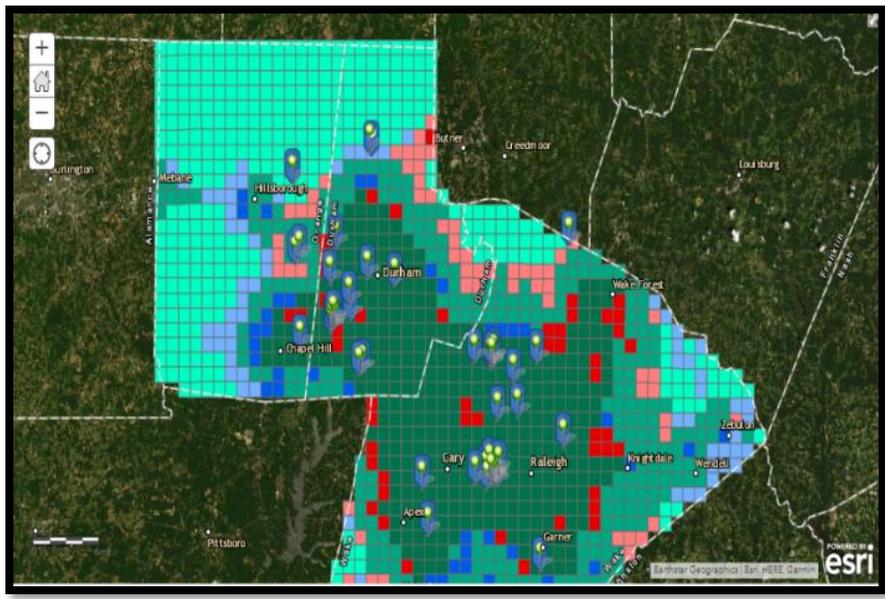


**Figure 2.3** 9 different geospatial noise and light levels (L1N1, L1N2, L1N3, L2N1, L2N2, L2N3, L3N1, L3N2, and L3N3) of the Triangle Area to include the areas of Raleigh, Durham, and Chapel Hill.

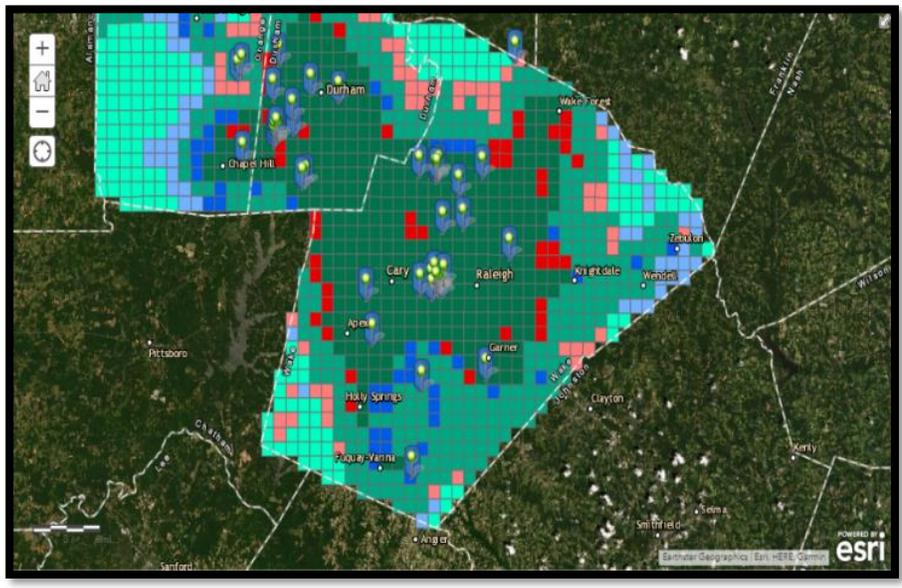


**Figure 2.4** Geographic Information System (GIS) map of the Triangle Area to include the cities of A) Apex, Cary, Chapel Hill, Durham, Garner, Hillsborough, Knightdale, Mebane, Raleigh, Wake Forest, Wendell, and Wake Forest and B) Fuquay-Varina and Holly Springs in various anthropogenic sound and artificial light levels.

A)



B)



### CHAPTER 3

## NEIGHBORHOOD NESTWATCH: SURVIVAL RATES OF ADULT SONGBIRDS IN RELATION TO ANTHROPOGENIC NOISE AND LIGHT ALONG AN URBAN-TO-RURAL GRADIENT

### ABSTRACT

Although many avian species persist in human-dominated landscapes, there are factors within these landscapes that may decrease fitness. Additionally, both top-down and bottom up processes may cause increased survival with greater intensity of urbanization. More specifically, the absence of some predator species (e.g raptors) being lost in urban environments may contribute to an increase in survival; moreover, human density may yield food for generalist bird species, therefore leading to higher survival. Conversely, artificial light and anthropogenic noise pollution might negatively affect individual health, and subsequently reduce survival rates. In this study, we use 20 years of band-resight data collected as a part of the Neighborhood Nestwatch Program (NN), a citizen science project run by the Smithsonian Migratory Bird Center, to examine variation in adult avian survival rates in relation to the amount of light pollution, noise pollution, and impervious surface in greater Washington, D.C. USA. We estimated apparent survival with occupancy analyses by constructing a set of *a priori* models for each species. When considering models as being equally supported by the data, we considered models that appeared above the intercept ( $\sim 1$ ), had the lowest likelihood ratios ( $\text{neg}2\ln l$ ) and/or the lowest weight, and had  $\Delta\text{AICc}$ 's less than 2. We documented variable patterns across species in relation to light pollution and noise pollution. Gray Catbird and House Wren survival decreased with greater amounts of light pollution, and American Robin and Song Sparrow survival increased with greater amounts of light pollution. American Robin, Northern Cardinal and Song Sparrow survival decreased with greater amount of noise pollution, and Gray Catbird survival increased with greater amounts of

noise pollution. The most competitive model for each species included the quadratic effect of impervious surface, indicating that survival was greatest at intermediate levels of impervious surface. The species-dependent responses to light pollution and noise pollution may be tied to natural history traits, trophic cascades, life-history trade-offs, and/or variation in the availability of microhabitats that buffer exposure. Future research on avian responses to light pollution and noise pollution require fine-scale data characterization of avian exposure to light pollution and noise pollution from location-based sampling.

## INTRODUCTION

Although urban areas cover only about 3% of the Earth (Liu 2014), urbanization can fragment habitat, restructure avian communities, and influence the abundance and distribution of bird populations (McKinney and Lockwood 1999, Marzluff et al. 2001; Chace and Walsh 2006; Ciach 2016). The urban population is projected to increase by more than 3 billion people between 2010 and 2050 (Buhang et al. 2013). Increased urban populations will bring an increase in urban infrastructure, such as impervious surface, artificial lighting, and varied forms of noise from transportation. Avian species respond to two anthropogenic features associated with urbanization, artificial light and anthropogenic noise, in a variety of ways that can affect reproduction (Dominoni et al. 2013; Senzaki et al. 2020), nestling growth and development (Beaugeard et al. 2018), individual health (i.e. body condition, Jiménez-Peñuela et al. 2019), communication (Nemeth et al. 2010), foraging behavior (Stracey et al. 2014), sleep (Raap et al. 2017), and migration (Van Doren et al. 2017).

Several forms of behavioral plasticity may allow birds to mitigate potential costs from exposure to anthropogenic noise and artificial light. Avian species, such as the Common Blackbird (*Turdus merulla*) alter their vocalizations to reduce masking by anthropogenic noise (Nemeth et al. 2010). Great Tits (*Parus major*) in areas dominated with low-frequency noise sang with a higher minimum frequency and restricted the range of their repertoire (Slabbekoorn et al. 2003). Viewed cumulatively, by altering communication behaviors, some species of birds appear capable of tolerating the presence of noise pollution, but the fitness consequences of altered communication is not fully understood. Some species exploit new night niches by consuming organisms that are attracted to artificial light (Lebbin et al. 2007). The ability to adjust behaviorally to artificial light, therefore, improves survivorship on some species in urban areas. For example, Northern

Mockingbirds (*Mimus polyglottos*) were more likely to sing at night in the presence of artificial light (Derrickson 1988) and forage after sunset (Derrickson and Breitwisch 1992). Northern Mockingbirds at four different sites were also more likely to continue to feed nestlings past sunset in areas where the average light level around the nest was greater, further supporting the expectation that abundant urban species can exploit light pollution (Stracey et al. 2014).

Avian responses to artificial light and anthropogenic noise may vary based on species-specific natural history traits. For example, unlike cavity-nesting species, species that are open-cup nesters lack sound-attenuating walls around them (Swaddle et al. 2012). Thus, nestlings raised in cavities may experience less exposure to ambient noise than those raised in open-cup nests (Kangas et al. 2010; Martin and Li 1992). Nest success in some bird species was documented to be negatively correlated with noise in forests (Senzaki et al. 2020). Additionally, species-specific changes in reproductive timing and hatching success in response to noise exposure were explained by vocalization frequency, nesting location and diet (Senzaki et al. 2020). For example, noise may delay clutch initiation for species with lower-frequency vocalizations by interfering with male mate attraction songs (Swaddle et al. 2015), which can interfere with stimulation of females by males and delay female sexual receptivity (Huet des Aunay et al. 2017). Birds that nested in dense forest also tended to experience a decline in clutch size with noise exposure (Senzaki et al. 2020). Birds that inhabit areas with dense vegetation vocalize at lower frequencies than those in more open areas (Boncoraglio et al. 2017). Moreover, the effect of noise on partial hatch is lower for birds with plant-based diets than for those with animal-based diets (Senzaki et al. 2020).

Although no studies have investigated the paired effect of artificial light and anthropogenic noise pollution on survival of adult birds, Evans et al (2015) discovered that the apparent survival of American Robin, Song Sparrow, Northern Cardinal, and Gray Catbird increased with greater

amounts of impervious surface, whereas the apparent survival of Carolina Wren and House Wren decreased with increased amount of impervious surface. The survival benefits of urbanization for American Robin, Gray Catbird, Northern Cardinal, and Song Sparrow may be due to elevated food availability with urbanization. These species are often considered habitat generalists (Poole 2013) and may therefore more readily exploit anthropogenic food sources within urban landscapes (McKinney and Lockwood 1999). The lower apparent survivorship of both Carolina Wren and House Wren could be due to a severe reduction in nesting sites due to a loss of adequate cavity trees or interspecific competition for nest cavities with invasive species, European Starling (*Sturnus vulgaris*) and House Sparrow (*Passer domesticus*) (Newton 1994, Blewett and Marzluff 2005).

Despite evidence that both artificial light and anthropogenic noise can be beneficial or disadvantageous to some specific species inhabiting urban areas, our understanding of the direct impacts of artificial light and anthropogenic noise coupled with the influence of impervious surface, on the survival of open-cup and cavity-nesting avian species who also inhabit urban areas is poorly understood. Here we used 20 years of band-resight data to estimate annual survival of seven bird species in relation to light pollution (light), noise pollution (noise), and impervious surface (IMP). While recognizing the potential for behavioral plasticity and different natural history traits in mitigating or amplifying species responses, we tested the null hypothesis that even urban-adapted species experience reduced adult survival with increased light pollution, noise pollution, and their combination, irrespective of their associations with IMP. To test these hypotheses, we developed and compared a set of competing models of annual survivorship using various combinations of model covariates of light, noise, and IMP.

## METHODS

We examined the response of survivorship to light pollution (light), noise pollution (noise), and IMP. Avian count data were collected from 2000 to 2020 as a part of the Neighborhood Nestwatch Program (NN), a citizen science project run by the Smithsonian Migratory Bird Center. With sampling predominately located at the homes of project participants, NN sampling sites were within a 100-km spatial scale encompassing a rural-to-urban land-use gradient in the greater Washington, D.C., USA, metropolitan region. Project participant sites were chosen based on their position along the rural-to-urban gradient as assessed by the proportion of impervious surface; sites were defined as a 100 m radius area surrounding the location of each sampling site (described below). NN sites (n=242) included private residences, community centers, and schools, as well as sites within forested and agricultural landcover. By incorporating privately owned land within the study design, we captured portions of the urban and suburban matrix not normally monitored in avian survivorship studies. To assess whether NN sites adequately represent the urbanization gradient within the study area, proportional land cover within a 500 m radius of sampled sites to randomly selected sites within the study region were compared using a two-sample Kolmogorov-Smirnov test. These analyses showed that the sampled sites were largely representative of the distribution of land cover types typically used to characterize the rural-to-urban gradient (e.g., core urban, suburban, agricultural, and forested).

NN technicians visited sites once annually during the avian breeding season (May-August) and conducted 10-minute, 50-m fix radius point counts (Petit et al. 1995). Birds were captured using target netting with a combination of territorial intrusion playback and mobbing call playback. Individuals were marked with a unique U.S. Fish and Wildlife Service aluminum band and a unique combination of colored plastic bands. During each banding visit, technicians spent one

hour attempting to re-sight previously captured individuals within a 200-m radius of the banding station using the playback techniques as described above.

We examined the influence of light pollution, noise pollution, and IMP on the annual survival of seven species of birds most common across the development gradient within the study region: American Robin (*Turdus migratorius*), Carolina Chickadee (*Poecile carolinensis*), Carolina Wren (*Thryothorus ludovicianus*), Gray Catbird (*Dumetella carolinensis*), House Wren (*Troglodytes aedon*), Northern Cardinal (*Cardinalis cardinalis*), and Song Sparrow (*Melospiza melodia*). We investigated the effects of these individual covariates (light, noise, IMP) on apparent survivorship ( $\Phi$ ) and detection probability by fitting Cormack-Jolly-Seber survivorship models to these data. We used the R package RMark v. 2.14.1 (Laake 2013, R Core Team 2014) to estimate annual survival of the seven focal species at each site.

For each of the 242 NN sites, we used R to extract corresponding data from the georeferenced maps of light pollution, noise pollution, and IMP (Figure 3.1) and examined correlations among these variables across sites. We configured and compared models of each variable, finding light, noise, and IMP to be highly correlated. (Table 3.1).

Following the methods of Sensaki et al. (2020), we used data from the second world atlas of artificial night sky brightness converted to 270-m resolution (Falchi et al. 2016). Our estimates of light pollution were the zenith anthropic sky brightness as a ratio to the natural background sky brightness. Although light pollution was used to measure how bright it was at a given site, the light pixels provided by satellites were quite coarse. Therefore, the estimates provided are only an average number for the whole pixels. Additionally, data from the satellites treated all light measurements equally. For example, an area with lots of houses or one airport could be shown to emit similar levels of light.

We used anthropogenic noise data from a georeferenced map of expected sound pressure levels (Mennitt et al. 2016). These data model natural sound levels from biotic and physiographic sources and compute anthropogenic noise exceedance levels by logarithmic subtraction of the natural from the existing sound projections. Following the methods of Senzaki et al. (2020), we used anthropogenic daytime A-weighted  $L_{50}$  sound pressure levels as the estimate of anthropogenic noise. Although noise pollution models were comprised of data from both satellite and land-use maps, which were used to measure how loud it was at a given site, it is possible for data to have been contrasting if measurements were initially taken from the ground and collected over a period of time. In addition, our measurement only took into account one source of noise, anthropogenic, which could possibly be more ecologically relevant to masking or reproduction, and not that relevant to survival.

We approximated the degree of urbanization of a given site (i.e. point count location) as the proportion of impervious surface (30 m resolution; Xian et al. 2009) within the 100 m radius site area. To characterize the degree of urbanization at each banding station, we used the raster package R (Hijmans 2014) to calculate the proportion of impervious surface (30-m resolution, Fry et al. 2011) within a 500-m neighborhood of each sampling location. Because avian response to urbanization is probably nonlinear, we included both linear (IMP) and quadratic (IMP<sup>2</sup>) impervious terms as model covariates. This scale of analysis has been found to be predictive of avian demographic response to urbanization (Ryder et al. 2010; Evans et al. 2015) and adequately reflects the variation in habitat distribution and quality across the rural-to-urban-gradient (McKinney 2002). Across our samples, IMP was highly correlated with species responses to light pollution and noise pollution.

Because Evans et al. (2015) found that avian adult survival in response to urbanization was often nonlinear, we included both linear (IMP) and quadratic (IMP<sup>2</sup>) impervious terms as model covariates (see Table 3.2). Covariates used in model construction were standardized and are described in detail (also see Table 3.2). (Abbreviations of each variable in the models can be found in Table 3.5).

We used Akaike's information criterion, AIC (Akaike 1973), to select the best models among a set of biologically plausible candidate models. Models in which the  $\Delta\text{AICc}$  between a given model and the best model was less than 2 were considered equally supported by the data (Burnham and Anderson 2002). We used normalized Akaike weights, the ratio of the likelihood of a given model relative to the sum of the likelihood across models, to evaluate the weight of evidence for a given model relative to the full set of candidate models. We used likelihood ratios ( $\text{neg}2\ln l$ ), the comparison of nested models, to evaluate the parameters ( $\text{npar}$ ) of each model. When choosing the best model, we considered support based on  $\Delta\text{AICc}$ , Akaike weights, and  $\text{neg}2\ln l$  (Johnson et al. 2004).

To account for variation or potential bias in the estimates of detectability and survivorship when analyzing the effect of light pollution and noise pollution on apparent survival, we constructed an *a priori* model for each species that included sex. Territorial males may be much more likely to be encountered than females due to behavioral differences (Amrhein et al. 2012); therefore, sex was included as a binary dummy covariate for estimating detectability. We then compared the *a priori* model (sex) for each species with combinations of models that included IMP, and noise and light levels.

Because model selection and subsequent parameter estimates can become unstable (high variance) by over-fitting models (~10 parameters), especially when there is an insufficient sample

size for an individual group variable (Breiman 1996, Burnham and Anderson 2002), we constrained our model set to those in which the parameter estimates were identifiable (see Table 3.6). Here we are referring to extrinsic identifiability, where parameter estimates are at or near their boundary (0 or 1) or are otherwise unidentifiable because of insufficient sample size. Ultimately, we excluded these “over-parameterized” models that contained more parameters than can be accommodated by the data (J. L. Laake, personal communication). Therefore not all covariates could be included in *a priori* models for each species (see Table 3.4). We chose to present the model betas from the lowest  $\Delta AICc$  of each a priori model for each species.

## RESULTS

We included 7351 individuals in the analysis (see Table 3.3). There was supportive evidence that survival and detection estimates varied markedly between males and females and among species (reported across time-since-marking classes in Table 3.3). Models that included light pollution and noise pollution variables received some support for five of the seven species (see Table 3.6).

There was weak model support for variation in apparent survivorship along a light pollution gradient for American Robin, Gray Catbird, House Wren, and Song Sparrow. Using beta ( $\Phi$ ) values, we estimated that annual survival probabilities (Figure 3.3) of light pollution increased for American Robin by (0.324; se=0.165), decreased for Gray Catbird by (-0.224; se=0.102), decreased for House Wren by (-0.505; se=0.163), and increased for Song Sparrow by (0.204; se=0.117). The most competitive model included the quadratic effect of impervious surface, indicating that survival was greatest at intermediate levels of impervious cover (Figure 3.4).

There was weak model support for variation in apparent survivorship along a sound pollution gradient for American Robin, Gray Catbird, Northern Cardinal, and Song Sparrow.

Using beta ( $\Phi$ ) values, we estimated that annual survival probabilities (Figure 1.3) of noise pollution decreased for American Robin (-0.241; se=0.209), increased for Gray Catbird (0.161; se= 0.115), decreased for Northern Cardinal (-0.0863; se=0.0676), and decreased for Song Sparrow (-0.235; se= 0.132). All three species exhibited a linear response to noise pollution (Figure 3.4).

There was weak model support for variation in apparent survivorship with impervious surface (IMP). Using beta ( $\Phi$ ) values, we estimated that annual survival probabilities (Figure 3.3) of IMP increased for American Robin (0.381; se=0.217), decreased for Carolina Chickadee (0.205; se=0.117), decreased for Carolina Wren (-0.101; se=0.0966), increased for Gray Catbird (0.370; se=0.110), increased for House Wren (0.685; se=0.162), increased for Northern Cardinal (0.147; se=0.0698), and increased for Song Sparrow (0.306; se=0.112).

## **DISCUSSION**

We identified variation in survivorship along the light pollution gradient, with higher apparent survival for two of seven focal species, and lower apparent survival for two of seven species. Additionally, we identified variation in survivorship along the noise pollution gradient, with higher apparent survival for one of seven species, and lower apparent survival for two of seven species. It is possible for these species-specific responses to be a response of various environmental factors resulting from urbanization (i.e. impervious surface, food sources). Cumulatively, our results suggest that the effects of artificial light and anthropogenic sound could possibly influence avian vital rates, but that the regulatory mechanisms may be species specific.

### *Potential Influence of Artificial Light on Survival*

Differences in apparent survival among species along a light pollution gradient may relate to variation in natural history traits among species. For example light pollution has been determined to affect the singing behaviors of several species (Miller et al. 2006; Francis et al. 2009, Ortega et al. 2012). In areas with light pollution, American Robins will initiate their morning chorus earlier (Miller et al. 2006), and the increased time for daily activities such as courtship and foraging may have overall positive effects on robin survival. Light pollution, particularly skyglow, extends far beyond NN study sites, which included few rural, quiet, dark places. There could have possibly been differences seen in all species across the spatial extent if sampling was done in quiet, dark places.

### *Potential Influence of Anthropogenic Noise on Survival*

Variation in the effects of sound pollution on apparent survival of the focal species also may relate to variation in natural history traits among species. In urban environments, anthropogenic sound may mask bird song, particularly notes which occur at lower frequencies (1-2kHz). As a result, individuals that have high vocal plasticity and can alter minimum frequency during a song to minimize masking by ambient noise (Brumm & Todt 2002; Slabbekoorn & den Boer-Visser 2006). Wood et al.'s (2006) suggested that Song Sparrows singing at noisier locations exhibited higher-frequency low notes and had relatively less energy (amplitude) in the low-frequency range of their songs (1–4 kHz), where most anthropogenic noise also occurred. Seger-Fullam et al. (2011) reported that it is possible that particular species of birds learn or favor songs with higher minimum frequencies if low frequency notes are not transmitted effectively through urban noise (Hansen 1979; Podos et al. 2004). Both Song Sparrows and Gray Catbirds have been reported to alter temporal patterns as well as shift their vocal frequencies in noise, suggesting that

frequency shifting may not preclude the use of other mechanisms for enhancing vocal communication in noise (Wood and Yezerinac, 2006; Dowling et al. 2012).

Species-specific responses to urbanization may represent a trade-off between survival and reproduction (Goodman 1974; Stearns 1992; Charlesworth 1994). If artificial light and anthropogenic sound are stressors that negatively affect reproduction, then it is possible that bird populations compensate with higher survival; if artificial light and anthropogenic sound are stressors that negatively affect survival, then it is possible that birds compensate with higher reproduction. Senzaki et al. (2020) reported on reproductive success of three of our seven focal species (American Robin, Northern Cardinal, and House Wren). Considering our results in relation to Senzaki et al. (2020), we note that the negative consequences of light and noise pollution emerge within a life-history trade-off. We found American Robin survival increased with light pollution, Northern Cardinal survival decreased with noise pollution, and House Wren survival decreased with light pollution. Positive and negative consequences of noise and light pollution may be obscured from detection within narrowly focused studies due to broader life-history trade-offs.

Species-specific responses to noise and light pollution need additional study to determine whether all species that show no survival costs to noise and light pollution experience costs to their reproduction instead. Additionally, research is needed to determine whether some species occupy microhabitats (i.e. cavities, bark characteristics) that buffer their exposure to noise and light pollution. We used relatively coarse-scale geospatial maps of anthropogenic noise and urban light maps produced from models based on land-use and satellite data. Future research on avian responses to artificial light and anthropogenic sound would benefit from finer-scale data that characterizes individual bird exposures to artificial light and anthropogenic sound from location-based sampling. Additionally, our survival analyses could be expanded by including other mapped

covariates such as vegetation density or tree cover. These variables might play key roles in buffering exposure to noise and light pollution.

## **CONCLUSION**

Environmental conditions are key drivers of life-history evolution. Considering that we found negative fitness consequences for some species, positive fitness consequences for some species and no consequences for some species, noise and light pollution may produce a lot of sub-lethal effects (e.g., changes in songs and other behaviors) and affect survival. Our findings of a correlation between anthropogenic or sound and adult avian survival for five of seven focal species suggests that responses of different species urbanization may be related to how easily that species can easily adjust to local conditions, which can depend on natural history traits, life history traits, and/or behavioral plasticity. Overall, the complexity of human-dominated ecosystems leaves more questions than answers and therefore, our understanding of the demographic consequences and sensitivity of populations to extinction in urban environments is of great importance.

## LITERATURE CITED

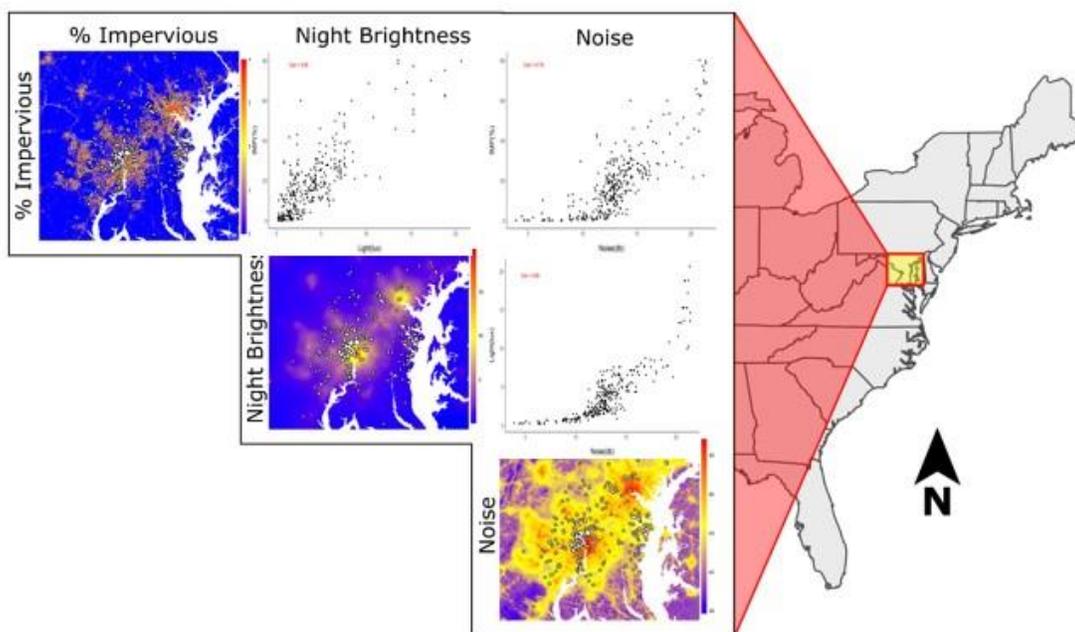
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**TABLES AND FIGURES**



**Figure 3.1** Inset maps and correlations of sampling sites of the Neighborhood Nestwatch Program in greater Washington, D.C., USA.

**Table 3.1** Correlation Table of IMP, light pollution, and noise pollution showing all three variables to be very highly correlated.

	IMP	noise	light
IMP	1.0000000	0.7922362	0.8219412
noise	0.7922362	1.0000000	0.8480927
light	0.8219412	0.8480927	1.0000000

**Table 3.2** Variables used in the development of a priori and light pollution and noise pollution models for apparent survivorship ( $\Phi$ ).

*Note:* Continuous Variables are in lowercase and factors are in uppercase.

<b>Model Set</b>	<b>Variable</b>	<b>Variable description</b>
<b>a priori</b>	Sex	binary sex (male, female)
<b>Urbanization</b>	IMP	Impervious surface cover (%)
<b>Urbanization</b>	IMP <sup>2</sup>	Impervious surface, quadratic form
<b>Light Pollution</b>	light	Anthropogenic light pollution along an urbanization gradient
<b>Noise Pollution</b>	noise	Anthropogenic noise pollution along an urbanization gradient

**Table 3.3** Counts of captured and re-encountered birds in the Neighborhood Nestwatch program across years.

<b>Species</b>	<b>Code</b>	<b><u>Captures</u></b>			<b><u>Reencounters</u></b>		
		<b>Female</b>	<b>Male</b>	<b>Total</b>	<b>Female</b>	<b>Male</b>	<b>Total</b>
<b>American Robin</b>	AMRO	343	367	710	44	43	87
<b>Carolina Chickadee</b>	CACH	378	321	699	95	125	220
<b>Carolina Wren</b>	CAWR	431	362	793	99	124	223
<b>Gray Catbird</b>	GRCA	537	1055	1592	82	290	372
<b>House Wren</b>	HOWR	321	691	1012	31	116	147
<b>Northern Cardinal</b>	NOCA	709	935	1644	131	395	526
<b>Song Sparrow</b>	SOSP	195	706	901	44	308	352
<b>Total across spp.</b>		2914	4437	7351	672	1401	1927

**Table 3.4** Model variables and corresponding abbreviations.

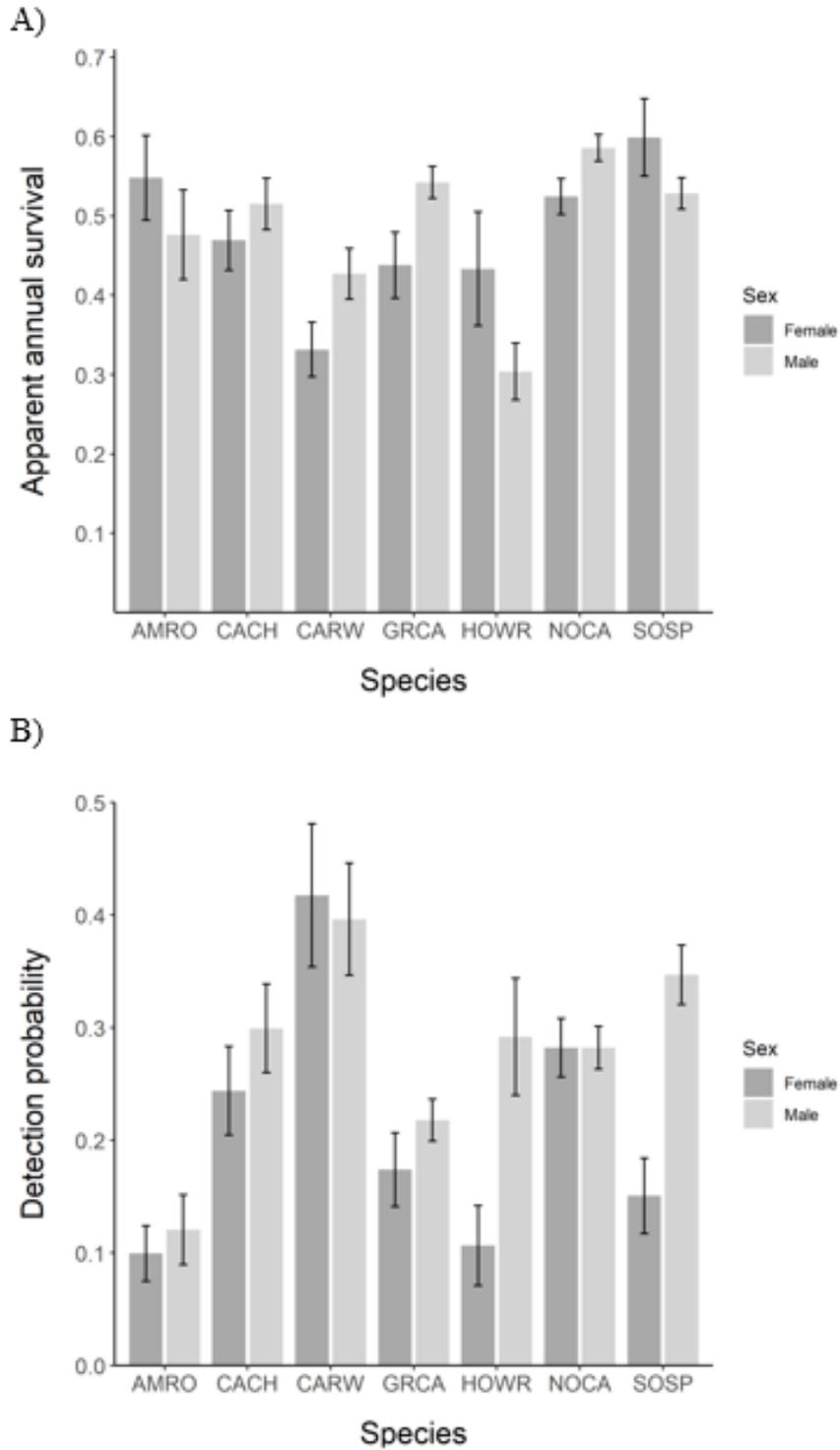
Model	Abbreviation
'~ 1'	Intercept
'~ sex'	S
'~ imp'	I
'~ imp + I(imp^2)'	I + I <sup>2</sup>
'~ sex + imp'	S + I
'~ sex + imp + I(imp^2)'	S + I + I <sup>2</sup>
'~ sex + NightBrightness'	S + light
'~ sex + SoundImpact'	S + noise
'~ imp + NightBrightness'	I + light
'~ imp + SoundImpact'	I + noise
'~ imp + I(imp^2) + NightBrightness'	I + I <sup>2</sup> + light
'~ imp + I(imp^2) + SoundImpact'	I + I <sup>2</sup> + noise
'~ sex + imp + NightBrightness'	S + I + light
'~ sex + imp + SoundImpact'	S + I + noise
'~ sex + imp + I(imp^2) + NightBrightness'	S + I + I <sup>2</sup> + light
'~ sex + imp + I(imp^2) + SoundImpact'	S + I + I <sup>2</sup> + noise
'~ imp + NightBrightness + SoundImpact'	I + NB + noise
'~ imp + I(imp^2) + NightBrightness + SoundImpact'	I + I <sup>2</sup> + light + noise
'~ sex + imp + NightBrightness + SoundImpact'	S + I + light + noise
'~ sex + imp + I(imp^2) + NightBrightness + SoundImpact'	S + I + I <sup>2</sup> + light + noise

**Table 3.5** Model variables and corresponding abbreviations.

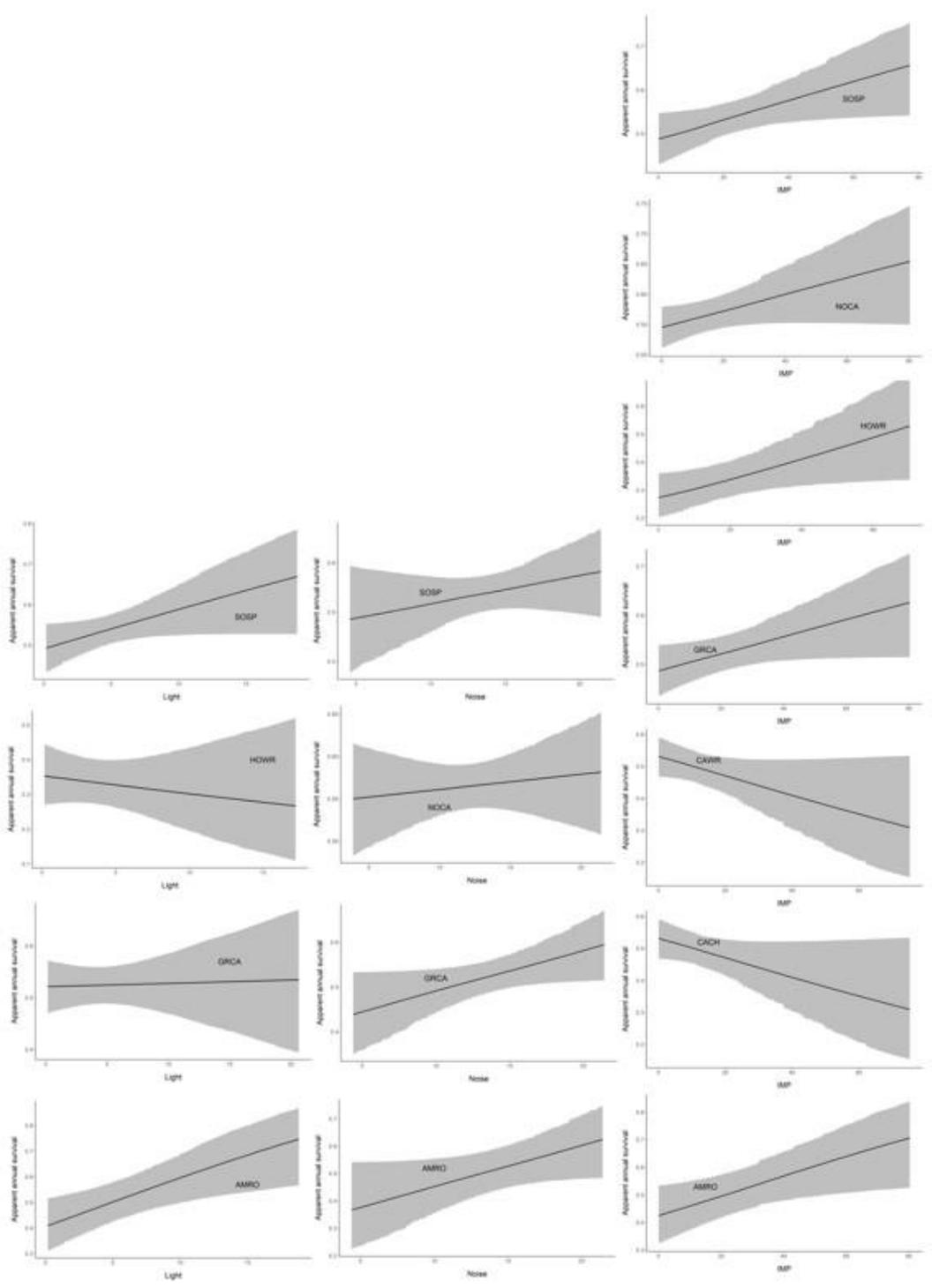
Model	Abbreviation
'~ 1'	Intercept
'~ sex'	S
'~ imp'	I
'~ imp + I(imp^2)'	$I + I^2$
'~ sex + imp'	$S + I$
'~ sex + imp + I(imp^2)'	$S + I + I^2$
'~ sex + NightBrightness'	$S + \text{light}$
'~ sex + SoundImpact'	$S + \text{noise}$
'~ imp + NightBrightness'	$I + \text{light}$
'~ imp + SoundImpact'	$I + \text{noise}$
'~ imp + I(imp^2) + NightBrightness'	$I + I^2 + \text{light}$
'~ imp + I(imp^2) + SoundImpact'	$I + I^2 + \text{noise}$
'~ sex + imp + NightBrightness'	$S + I + \text{light}$
'~ sex + imp + SoundImpact'	$S + I + \text{noise}$
'~ sex + imp + I(imp^2) + NightBrightness'	$S + I + I^2 + \text{light}$
'~ sex + imp + I(imp^2) + SoundImpact'	$S + I + I^2 + \text{noise}$
'~ imp + NightBrightness + SoundImpact'	$I + \text{NB} + \text{noise}$
'~ imp + I(imp^2) + NightBrightness + SoundImpact'	$I + I^2 + \text{light} + \text{noise}$
'~ sex + imp + NightBrightness + SoundImpact'	$S + I + \text{light} + \text{noise}$
'~ sex + imp + I(imp^2) + NightBrightness + SoundImpact'	$S + I + I^2 + \text{light} + \text{noise}$

**Table 3.6** Summary statistics of the candidate models examining the impact of anthropogenic light and anthropogenic noise on avian survival within the greater Washington, D.C., area; models are ranked by AIC<sub>c</sub> and log likelihood values are given.

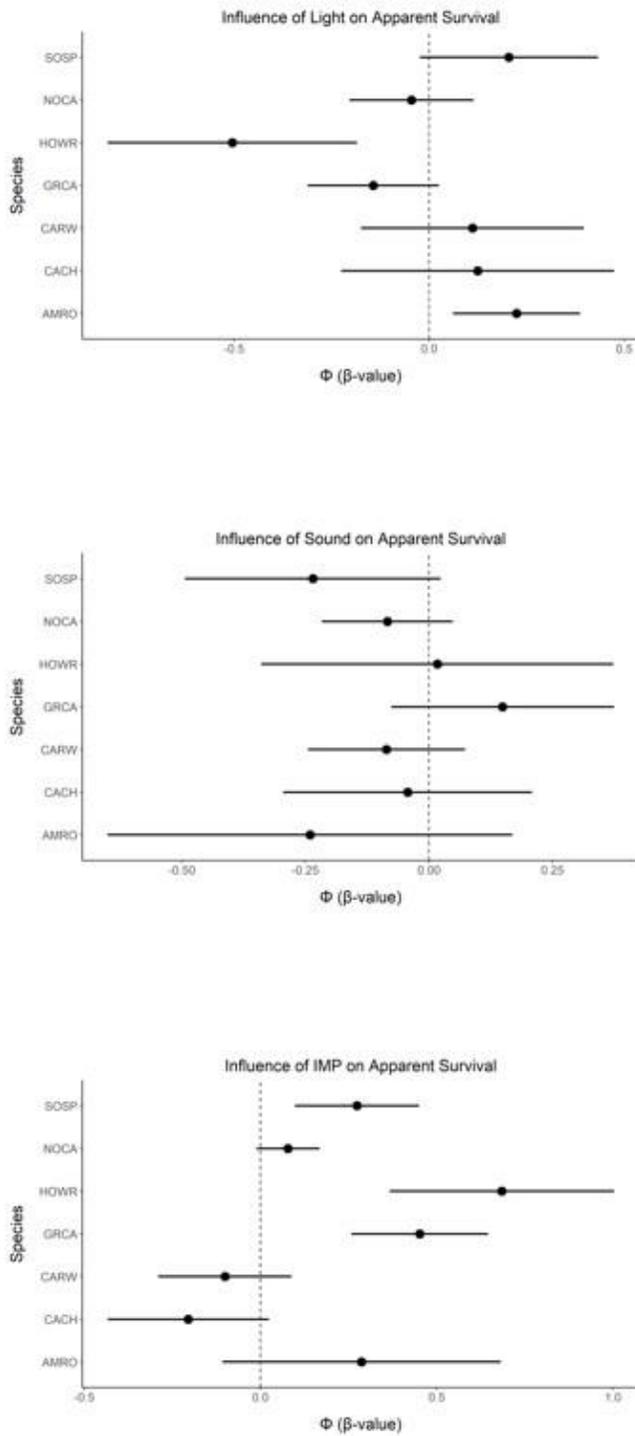
Species Code	Model $\phi$	$k$	AIC <sub>c</sub>	$\Delta$ AIC <sub>c</sub>	$w$	-2LogLik
AMRO	light	4	724.30	0.00	0.16	716.30
	IMP + IMP <sup>2</sup> + light	6	724.72	0.42	0.13	712.72
	IMP + IMP <sup>2</sup>	5	725.32	1.02	0.10	715.32
	IMP + IMP <sup>2</sup> + light + noise	7	725.40	1.11	0.09	711.40
CACH	IMP + light	5	726.24	1.94	0.06	716.24
	IMP + IMP <sup>2</sup>	5	1280.40	0.00	0.14	1270.41
	IMP	4	1280.94	0.53	0.11	1272.94
	sex + IMP + IMP <sup>2</sup>	6	1281.86	1.45	0.07	1269.86
CARW	Intercept	3	1281.87	1.46	0.06	1275.87
	IMP + IMP <sup>2</sup> + light	6	1281.92	1.51	0.07	1269.92
	sex + IMP + IMP <sup>2</sup>	6	1263.94	0.00	0.13	1251.94
	sex	4	1264.00	0.05	0.13	1256
GRCA	sex + IMP	5	1264.39	0.45	0.11	1254.39
	sex + noise	5	1264.87	0.93	0.08	1254.87
	sex + IMP + IMP <sup>2</sup> + light	7	1265.37	1.42	0.06	1251.37
	sex + IMP + IMP <sup>2</sup> + + light	7	2529.95	0.00	3.29	2515.95
HOWR	sex + IMP + IMP <sup>2</sup> + light + noise	8	2529.95	0.00	2.81	2515.95
	sex + IMP + IMP <sup>2</sup>	6	2530.77	0.82	2.17	2518.77
	sex + IMP + IMP <sup>2</sup> + noise	7	2532.74	2.79	8.80	2518.74
	IMP + IMP <sup>2</sup> + light	6	2534.53	4.59	3.3	2522.53
NOCA	IMP + IMP <sup>2</sup> + light	6	907.06	0.00	0.37	895.06
	sex + IMP + IMP <sup>2</sup> + light	7	907.72	0.65	0.27	893.72
	IMP + IMP <sup>2</sup> + light + noise	7	909.05	2.0	0.14	895.05
	sex + IMP + IMP <sup>2</sup> + light + noise	8	909.71	2.65	0.10	893.71
SOSP	IMP + light	5	912.06	5.00	0.03	902.06
	sex + IMP	5	3855.79	0.00	0.17	3845.79
	sex + IMP + light	6	3856.24	0.45	0.14	3844.24
	sex	4	3856.74	0.95	0.11	3848.74
SOSP	sex + IMP + light	6	3857.47	1.69	0.07	3845.47
	Sex + IMP + IMP <sup>2</sup>	6	3857.59	1.81	0.07	3845.59
	IMP + IMP <sup>2</sup>	5	2034.34	0.00	0.18	2024.34
	IMP + IMP <sup>2</sup> + light + noise	7	2034.58	0.24	0.16	2020.58
SOSP	sex + IMP + IMP <sup>2</sup>	6	2035.39	1.06	0.10	223.39
	sex + IMP <sup>2</sup> + noise	6	2035.65	1.32	0.09	2023.65
	IMP + IMP <sup>2</sup> + light	6	2035.74	1.41	0.09	2023.74



**Figure 3.2** Estimates (mean symbol) of (A) annual survival and (B) detection by species and sex along an urbanization gradient in greater Washington, D.C., USA. See Table 1.2 for species names by code.



**Figure 3.3** Model estimates of American Robin, Carolina Chickadee, Carolina Wren, Gray Catbird, House Wren, Northern Cardinal, and Song Sparrow annual apparent survival probabilities across a light, noise, and rural-to urban (IMP) gradients in greater Washington, D.C., USA.



**Figure 3.4** Beta ( $\Phi$ ) values showing the interaction and influence of light pollution, noise pollution, and IMP on Apparent Survival.

**APPENDICES**

## **Appendix 2.1 Cardinal Capture Project Management**

### *General Overview*

Cardinal Capture is a citizen science project aimed at studying avian health to determine whether positive or negative health readings could potentially have a correlation to urban noise and light pollution. Cardinal Capture took place in the backyards of volunteers who resided in Wake County, North Carolina; specifically in the areas of Raleigh, Durham, and Chapel Hill North Carolina. In order to participate, volunteers signed up for the project via scistarter.org, a website used to accumulate and run citizen science projects. Once joining and agreeing to the informed consent (Appendix 2.2), volunteers were contacted by a team member from a “Cardinal Capture” delegated email informing them of their successful signup and discussing possible dates that the Cardinal Capture research team could come to set up mist nets in their backyards. An Institutional Animal Care and Use Committee (IACUC) protocol (IACUC Number: 19-763) was completed, submitted, and approved before the start of the project. To collect various health measurements from separate avian individuals, Northern Cardinals (*Cardinalis cardinalis*) were captured and handled under a federal bird banding permit. Body measurements for each individual were collected and recorded using a bird banding data sheet (Appendix 2.3), additional body measurements along with volunteer location data were collected on a field datasheet (Appendix 2.5), and hematology measurements were collected, analyzed, and recorded on a lab datasheet (Appendix 2.6) by researchers. Upon successful collection of the necessary data, the bird was successfully released. To complement the light levels configured by a Geographic Information System (GIS) Noise and Light maps of the Wake County area, a Sky Quality Meter (SQM) was used by volunteers to measure the amount of brightness of the night. Volunteers recorded their readings on a light meter datasheet (Appendix 2.4) provided by the research team. Approximately 54 volunteers joined the Cardinal Capture Project from 2019 to 2020.

### *Recruitment*

From February through March of 2020, announcements for volunteer recruitment were advertised in the forms of informational fliers, listservs, university newsletters, and social media. Using the social networking site Facebook, community and event pages in the Wake County area were specifically targeted. To be sure that we had a variation of results to compare to, the goal of these targeted places was to potentially recruit volunteers in the Wake County area who resided in the different combinations of urban noise and light (high noise, high light; low noise, low light; high noise, low light; high light, low noise) as configured by our GIS maps.

### *Joining the Project*

Participants joined the project using SciStarter.org, a website used to accumulate citizen science projects. Cardinal Capture also used SciStarter’s tools to manage signups and gather other necessary information needed by the project such as physical addresses and backyard requirements. After joining the project and agreeing to the informed consent, volunteers were contacted by a team member from a “Cardinal Capture” delegated email informing them of their successful signup and discussing possible dates that research team could come to set up mist nets

in their backyards. Upon discussion, we followed up with the volunteer's submitted form to make sure that their yard was compliant with the requirements and addressed any other questions or concerns brought forward by the volunteer.

### *Termination of Project*

In the year 2020, the United States was hit with unforeseen events in relation to COVID-19, which was declared a national pandemic in March of 2020. In response, all North Carolina State University campus activities closed down, including research projects. In April of 2020, the university department gave the choice for students to seek a research exemption, which would allow for the research project to be analyzed on whether or not it was able to proceed. Due to the requirements of Cardinal Capture, including taking place in areas with people, involving research assistants, and having some field techniques that still needed to be monitored, it was decided that Cardinal Capture would end and a new research project would be pursued. All activities for Cardinal Capture ended in May of 2020 and no volunteer yard visits were made.

## **Appendix 2.2** Informed Consent for Cardinal Capture Volunteers

Cardinal Capture is a current Master's Thesis Project measuring potential effects of and light pollution on the physiology of songbirds. Because Northern Cardinals are a common bird, they are serving as our focal species.

By joining this project and registering as a project volunteer, you hereby grant faculty, staff and students of NC State who are part of the Cardinal Capture team to access your outdoor property, at mutually agreed upon times, in order to install equipment needed to capture, measure, draw blood, and release Northern Cardinals. We loan a light meter to project volunteers and ask them to take several measurements of outdoor light pollution at night.

This project combines aspects of citizen science, community curiosity, and urban ecology in order to discover the impact that anthropogenic noise and light may have on a particular species.

Cardinal Capture on SciStarter is where participants can sign up in order to enroll in the project.





## Appendix 2.5 Field Data Sheet

<b>Field Data Sheet</b>		<b>BIRD ID #</b> (band # + volunteer ID number):			
Volunteer Name:					
Volunteer Address:					
Volunteer ID Number:					
Date:					
Temperature:					
Weather:					
GPS Location (lat-long):					
Start Time:					
End Time:					
Additional Notes:					
<u>Data Sheet</u> (from banding sheet)					
BANDER		BODY MOLT		FEATHER #	
SCRIBE		FEATHER MOLT		STATUS	
DISP		WING (mm)		CAPTURE TIME	
BAND NUMBER		HEAD TO BILL (mm)		RELEASE TIME	
BAND SIZE		TARSUS (mm)		WEIGHT OF BIRD w/BAG	
SAC		TIBIOTARSUS (mm)		WEIGHT OF BAG	
AGE		TAIL (mm)		FINAL WEIGHT	
HOW AGED		CP			
HOW SEXED		BP			

### Appendix 2.6 Bird Lab Datasheet

<p><b>Lab Data Sheet</b></p> <p>Volunteer Name: Volunteer Address: Volunteer ID Number: Chemistry done by: Date: <b>Collection Time:</b> Additional Notes:</p> <p><u>Data Collection</u></p> <table border="1"><tr><td>PCV READING</td><td>REFRACTOMETER READING</td></tr></table> <p>Time Processed:                      Time Processed:</p> <p>NOTES (hematoma formation, multiple venipuncture attempts, physical abnormalities)</p> <p>BLOOD SMEAR HETEROPHIL COUNT: BLOOD SMEAR LYMPHOCYTE COUNT: BLOOD PARASITES SEEN (CHECK MARK):</p>	PCV READING	REFRACTOMETER READING	<p><b>BIRD ID #</b> (band # + volunteer ID number):</p> <table border="1"><tr><td>ABAXIS READING Time Processed:</td></tr></table>	ABAXIS READING Time Processed:
PCV READING	REFRACTOMETER READING			
ABAXIS READING Time Processed:				