

STOPOVER ECOLOGY OF MIGRATING BIRDS IN INDIANA

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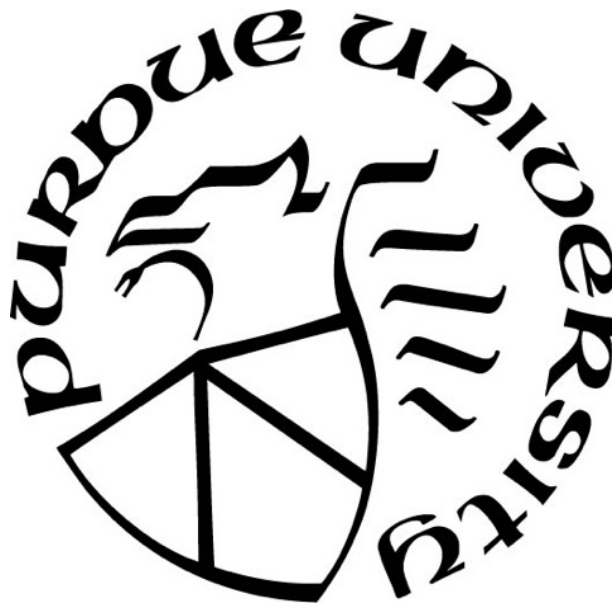
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To my family, for all the support and grace you've given me.

*To Grandma Anne, who would have been so proud of the woman and scientist I've become.
I wish you could have seen me finish this journey as I've studied how to become a better steward
of God's creation.*

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GLOSSARY AND LIST OF COMMON ABBREVIATIONS

ACS: *American Community Survey*, a product of the United States Census Bureau; this survey is sent to randomly selected households within Census block groups and asks questions related to jobs, education, housing, and other topics.

ALAN: *Anthropogenic or artificial light at night*, a form of pollution related to the amount of human-produced light sources after dark (Cabrera-Cruz et al. 2018).

BRT: *Boosted regression trees*, additive regression models in which individual terms are fitted trees (Elith et al. 2008).

CV: *Coefficient of variation* of reflectivity, a measure of daily variability in bird stopover density, measured in $\text{cm}^2 \text{ ha}^{-1}$ (Buler and Dawson 2014).

Checklist: A list of any or all species of birds observed at a given place and time by eBirders, may be classified as “complete” (all species seen are listed) or “incomplete” (only selected species are listed).

Exodus: The period of the night at which nocturnally migrating birds take off *en masse* from selected stopover sites.

HU: *Housing unit*, defined by the ACS as “a house, an apartment, a mobile home, a group of rooms or a single room that is occupied (or, if vacant, intended for occupancy) as separate living quarters” (ACS 2017).

ISA: *Impervious surface area*, artificially-created areas covered by water-resistant surfaces such as asphalt, concrete, or buildings.

NEXRAD: *Next-generation weather surveillance radars*, also referred to as WSR-88D weather surveillance radars and operated by the National Oceanic and Atmospheric Administration and the Department of Defense.

NLCD: *National Land Cover Dataset*, a product of the Multi-Resolution Land Characteristics Consortium intended to map the United States and provide information about land cover based on Landsat satellite imagery.

Migration: The predictable and seasonal movements of animals between habitats

Observation (eBird): A recording within a checklist containing at least a species designation, the estimated or exact number of individuals of that species seen, and the location at which the species was observed; observations often include measures of effort as well, though this is not required by eBird.

Sample volume: Radar sampling units, defined by the opening width of the radar transmitter in degrees and the length of the radar pulse in meters or kilometers, either $1^\circ \times 1 \text{ km}$ or $0.5^\circ \times 250 \text{ m}$ in this study (Buler and Diehl 2009).

Stopover: 1) The period of the migratory period spent on the ground between flights, or 2) the habitats used by migrating animals during the migratory period (Mehlman et al. 2005).

Reflectivity, dBZ: One of the primary measurements of radars, a measure of the reflected energy from objects in the airspace in units of decibels of reflectivity (dBZ).

ROS: Regression on order statistics, a method for estimating summary statistics of data that has been censored (Buler and Dawson 2014).

Traffic rates: The cumulative measure of airborne biomass of migrating animals across the entire night for a migration season, measured in $\text{cm}^2 \text{ km}^{-3}$.

VAD: Vertical azimuth display, radial velocity data from weather surveillance radars used to determine airborne target velocities (Buler and Diehl 2009).

VPR: Vertical profile of reflectivity, measures of reflectivity adjusted for height of radar beam, curvature of the earth, and sun angle (Buler and Diehl 2009).

WSR-88D: Weather surveillance radar 1988-Doppler, also referred to as Next-generation radar (NEXRAD) weather surveillance radars and operated by the National Oceanic and Atmospheric Administration and the Department of Defense.

ABSTRACT

Billions of birds migrate annually between breeding and wintering habitats, following transient resources. Though a majority of time is spent in breeding and wintering habitats, habitats used during the migratory periods are especially important for migrating birds. Migration and stopovers, where birds rest and refuel before continuing a migratory journey, are critical points in a bird's annual lifecycle, and are important ecologically, socially, and economically. Populations of migratory birds are declining on a global scale, however, and proper management is vital to their persistence in an urbanizing environment. Indiana in the Midwestern United States is an important area in which to study stopover ecology of migratory birds, as it is a fragmented forest-urban-agricultural matrix almost entirely managed through private ownership. In this dissertation, I studied three questions of stopover ecology within the landscape context of the Midwestern United States, primarily using weather surveillance radar and eBird citizen science data.

First, I studied spatiotemporal changes over an 11-year period (autumn 2005-2016 and spring 2006-2017) in densities of nocturnally migrating birds at two radar stations in Indiana. I found that mean density of migratory birds stopping over in Indiana declined by approximately 6.8% annually, but variability in stopover site use increased over the same period. This is consistent with other work completed on continental scales, and highlights the need for further conservation of migratory birds. Second, I studied patterns of stopover site use in Indiana during spring 2016-2017 and autumn 2015-2016, identifying landscape and local factors associated with those patterns. I used both traditional land cover characteristics and a novel approach using human socioeconomic measures to describe these patterns, and found that socioeconomics, particularly the size of a housing unit, were among the most important predictors of migratory bird density in Indiana. The results from this study suggest that migratory birds are utilizing urban habitats, which are known to contain several novel hazards for birds, but that migratory birds will benefit greatly from interdisciplinary work focusing on urban habitats. Third, I explored a novel method of using weather surveillance radar and eBird citizen science data in combination with each other, to see if both measures provided similar estimates of bird abundances during stopover. Though I found no correlation between the two, I argue that eBird and radar still provide important and complementary insights for the field of migration ecology. Finally, I provide guidelines for private landowners in Indiana on management for declining populations of migratory birds.

CHAPTER 1. INTRODUCTION

Each year, billions of birds migrate between breeding and wintering grounds to exploit transient resources around the globe. This phenomenon has long fascinated humans, making migratory birds not only important ecologically, but also economically and socially (Hutto 2000, Sekercioglu 2002). Since at least as early as 600 BCE, prophets, philosophers, and scholars have mused over the phenomenon of bird migration. The Old Testament prophet Jeremiah, for example, wrote that, “Even the stork in the heavens knows her times, and the turtledove, swallow, and crane keep the time of their coming” (Jer. 8:7, Crossway 2008). Some Greek philosophers pondered where these birds went, hypothesizing that they hibernated underground or transmuted into different species completely (Berthold 2001). As recently as three hundred and fifty years ago, some naturalists wondered if birds flew back and forth to the moon (Harrison 1954). The field of migration ecology has progressed rapidly since the time of these early naturalists, but there remains much to discover about migratory birds and their ecology.

Despite holding the attention of humans worldwide, the global system of migration is no longer pristine (Wilcove and Wikelski 2008). Since the 1980s, it has been known that populations of migratory landbirds (species occupying primarily terrestrial habitats, Rich et al. 2004) are declining significantly (Robbins et al. 1989, Terborgh 1989, Rosenberg et al. 2019). While much research has focused on the breeding season, it is likely that conditions during the wintering and migratory periods also limit migratory bird populations (Newton 2006). Conservation of migrating birds thus depends on understanding both the extent of their population declines and the habitats used throughout their annual cycle (Faaborg et al. 2010, Marra et al. 2015). In particular, stopover sites, where birds can rest and refuel along their migratory routes, play important roles in their lifecycles, and identification of these sites is an important area of study for bird conservation (Mehlman et al. 2005).

In this dissertation, I use Indiana as a case study in which to explore three distinct yet related topics. First, I seek to identify the extent of recent population declines of migrating birds, using data from two weather surveillance radars in both spring and autumn migration. Second, I aim to identify spatially explicit factors that may predict migratory bird density in both spring and autumn migration as measured by weather surveillance radar, using both traditional land cover and habitat characteristics and non-traditional socioeconomic variables as predictors in this process. Third, I aim to explore possible integration of weather surveillance radar with the citizen science

database eBird, to see if such an integration would improve the identification of individual migrant species in studies such as these, a goal not possible with weather surveillance radar data alone at present. Finally, I provide tools for land managers, particularly homeowners and residents of Indiana, for managing their properties to better conserve declining populations of migrating birds. In the remainder of this introduction, I will provide relevant background to both the foundational concepts and the methodologies used throughout this dissertation, as well as hypotheses and predictions for research topics.

1.1 Migration ecology

Migratory birds are an important part of the ecosystems in which they exist. Depending on the species, migratory landbirds operate as predators, scavengers, pollinators, or seed dispersers across their entire geographic range (Whelan et al. 2008). In addition, birds are important in the global ecosystem and economy, particularly seen through an important hobby to many people, birdwatching. Birdwatching contributes significantly to the global economy and environmental conservation efforts (Sekercioglu 2002). Furthermore, Hutto (2000) argues that the migratory period is exceptionally important for conservation efforts. Since routes and habitats are often limited during migration, their preservation is significant for protection across the entire annual cycle. Additionally, the potential of the migratory periods to fuel a conservation ethic is critical for shaping people's attitudes and actions about science and conservation of the natural world (Hutto 2000). Other ecologists have also called for increased research across migratory birds' full annual cycle, including the migratory period (Marra et al. 2015).

Many migratory birds rely on lipid-rich fruit as fuel for migration, despite often being insectivorous in the breeding season (Sherry and Holmes 1995, Narango et al. 2018). Many other migratory birds rely on arthropods, utilizing the lipids present within as a weight-efficient form of energy (McWilliams et al. 2004). Stopover site quality may thus depend on the amount and type of food available within a habitat patch (Smith et al. 2015), and food availability is a key aspect of site selection (Guglielmo et al. 2005, Buler et al. 2007, Packett and Dunning 2009, Ruhl et al. 2020). In addition, stopover site duration and departure decisions presumably are driven largely by available food resources within the framework of optimal foraging theory: animals will spend an "optimal" amount of time foraging for food within a resource patch, leaving that patch when the food resources are no longer sufficient to balance the energy spent in obtaining food in that patch (Charnov 1976, Alerstam and Hedenstrom 1998). Thus, departure from stopover sites to

continue the migratory journey may be related to the quality of those stopover sites, and therefore identification of those sites is important for migratory bird conservation.

1.2 Population trends

In the time since European settlement in North America, avian populations have seen shifts in behavior, abundance, and phenologies, and numerous drivers have been implicated in these changes. For example, Rachel Carson first drew attention to the environmental dangers of the pesticide dichlorodiphenyltrichloroethane, or DDT, in her landmark work *Silent Spring* (1962). Eng and colleagues (2019) found that a different pesticide group, neonicotinoids, reduces migrating birds' ability to refuel and delays their overall migration timing, which can have carryover effects on fecundity and survival throughout the full annual cycle. The late ornithologist Chandler Robbins, in his seminal work using Breeding Bird Survey citizen science data, suspected habitat loss and degradation were responsible for the population declines of many Neotropical migratory species (Robbins et al. 1989). Other ornithologists have identified threats to migratory bird populations from anthropogenic sources such as collisions with man-made structures or predation from domestic pets (Loss et al. 2013, 2014).

Most recently, an integrative study of multiple, independent avian monitoring networks estimated a 29% population decline since 1970 across North America (Rosenberg et al. 2019). Birds breeding in grassland and boreal forest biomes have experienced the greatest proportional net population change over that period, while wetland birds, largely through targeted management efforts, have seen a net population increase (Rosenberg et al. 2019). However, not only are the abundances of North American avian populations significantly lower in recent years, the phenology of migration has also shifted at the continental scale (Horton et al. 2019c). Over the last two and a half decades, the dates of peak spring and autumn migration have advanced among all nocturnal migrants, particularly at higher latitudes, due to global climate change (Horton et al. 2019c). Given these recent studies, continued and targeted conservation efforts for migratory species is imperative to preserve ecosystem function across North America.

1.3 Methodology

To effectively identify habitats used during migration and conserve declining populations of migratory birds, suitable methods of study and appropriate datasets are required. In this section,

I will address the data types used within this dissertation, identifying the strengths and limitations of each primary tool. My primary tool was weather surveillance radar at a broad spatial and temporal scale, used in combination with species-specific eBird citizen science data and information about habitat, land cover, and socioeconomic factors. All these data are freely available and are entirely non-invasive methods to monitor avian populations.

1.3.1 Weather surveillance radar

Radio detection and ranging, better known as *radar*, has been used for military and meteorological purposes since the 1940s, and used in ornithological applications as early as 1945 (Eastwood 1967). Radar technology functions by transmitting electromagnetic radiation, which encounters targets in the airspace and reflects back to a receiver in decibel units of reflectivity (dBZ); Doppler radars can measure, among other variables, the density and velocity of objects aloft. One of the most widespread types of Doppler radars used in the United States is the Weather Surveillance Radar-1988 Doppler (WSR-88D, also called Next Generation radar, or NEXRAD) network installed in the 1990s and operated by the National Weather Service (National Oceanic and Atmospheric Administration) and the U. S. Air Force (Department of Defense). NEXRAD data have been used in a growing number of ornithological studies in the last two decades, as this network surveys almost the entirety of the contiguous United States and provides precise information about the behaviors, abundances, and locations of migrating biomass in the airspace (Gauthreaux and Belser 2003, Bauer et al. 2019).

Among the myriad applications of weather surveillance radar for ornithological study are two that are particularly important for this study: the quantification of biomass in the airspace and the identification of frequently used stopover sites. Firstly, one early study was among the first to monitor declining avian populations using weather radar, quantifying the declining number of bird flights arriving at the Gulf of Mexico coastline in spring migration between the 1960s and 1980s (Gauthreaux 1992). Another important study recently measured biomass of migrating birds across North America and quantified seasonal survival based on differences between spring and autumn densities (Dokter et al. 2018). Secondly, identification of stopover sites using weather radar is possible due to the *en masse* departure of nocturnally migrating birds (80% of all migratory North American species, Horton et al. 2019b) after sunset. When birds take off to initiate their migratory flight, weather surveillance radars can detect these flocks and identify the sites at which they had stopped over on a fine spatial scale. Identification of stopover sites and factors driving site selection

has been done primarily in the northeastern United States, along the Gulf of Mexico coast, and around the Great Lakes (Buler et al. 2007, Bonter et al. 2009, Buler and Dawson 2014). Much work remains to be done in other landscapes, particularly within the fragmented forest-urban-agricultural matrix of the Midwestern United States.

1.3.2 eBird citizen science

Given the logistical challenges of efficiently counting and identifying birds across a large area, ornithologists have outsourced some of their work, building on social propensities towards birdwatching. Citizen science is a collaboration between professional scientists and the general public in which scientists gain valuable data from the efforts of the public, who in turn gain a role in the scientific process. Since humans continue to find birds fascinating and enjoyable to watch, citizen science in ornithology is a rapidly growing field of research. Projects such as the Breeding Bird Survey, Christmas Bird Count, Great Backyard Bird Count, and Project FeederWatch are more structured scientific projects in which citizens are given protocols to follow. Other projects such as eBird and iNaturalist are less structured but allow citizens to cultivate their own database, share their observations, and even enjoy friendly competition with other birdwatchers (Hannibal 2016).

eBird in particular, managed by the Cornell Lab of Ornithology, is a global enterprise, and is currently considered one of the largest citizen science-driven databases on biodiversity (Sullivan et al. 2014). eBird data can and have been utilized in a variety of studies regarding abundance, occupancy, or phenology (reviewed in Sullivan et al. 2009, 2014). In the field of migration ecology, some studies have used eBird occurrence data to map stopover areas for migratory songbirds (Fern and Morrison 2017), or identify areas where urban light pollution might interact with migratory behavior (La Sorte et al. 2017). eBird has also been used to test hypotheses based on optimal migration theory or even model the role of atmospheric conditions in shaping migration flyways (La Sorte et al. 2013, 2014).

More recently, an attempt has been made to integrate eBird data with weather surveillance radar data, thus addressing the individual limitations of each. Weather surveillance radar is unable to differentiate individual species in the airspace, which limits its potential to monitor species- or community-level processes. While eBird is a massive dataset with high resolution in many aspects, particularly temporal and species-level resolutions, it is far from an unbiased source (Sullivan et al. 2009). Some recent studies have attempted to address these individual weaknesses and integrate

the two datasets (Kelly et al. 2016, Horton et al. 2018). Through this integration, these studies have explored migration ecology at a continent-wide scale across species boundaries, an important advancement in the field that will create numerous opportunities for improved conservation of a declining group. The integration of radar and eBird data is by no means perfected, however, and further testing and improvement of this integration will be beneficial to the field of stopover ecology and migratory bird conservation as a whole.

1.3.3 Additional data

In addition to weather surveillance radar and eBird citizen science data, information about habitat or land cover characteristics are important predictors in many ecological studies. The National Land Cover Dataset, a product of the Multi-Resolution Land Characteristics (MRLC) Consortium, provides detailed information about the structure and type of land cover, such as forest, developed, or agricultural areas, at a spatial resolution of 30m (Homer et al. 2015). In addition, the MRLC Consortium also produces datasets describing the amount of tree canopy cover and urban imperviousness within an area (Coulston et al. 2012, Yang et al. 2018). These habitat variables have been identified as important predictors, particularly of migratory bird densities, in several studies (e.g., Rodewald and Matthews 2005, Buler et al. 2007, Pennington et al. 2008, Bonter et al. 2009, Buler and Dawson 2014, Homayoun and Blair 2016). In addition, anthropogenic light at night has been identified as an important determinate of migratory bird densities in several studies (La Sorte et al. 2017, Van Doren et al. 2017, McLaren et al. 2018, Horton et al. 2019b).

While the importance of natural habitat for migrating birds cannot be understated, there are other factors that may drive bird abundances or community structure than simply the relative amount of forest or urbanization in a landscape. While not typically studied in most ecological work, socioeconomic factors such as income, race, or housing structures can operate on a landscape scale. One study in Chicago, IL (USA), found that socioeconomic status predicted bird biodiversity across some census tracts (Davis et al. 2012). Typically, socioeconomic drivers have been studied in conjunction with vegetation patterns or breeding bird species assemblages (Kinzig et al. 2005, Mennis 2006, Luck et al. 2009). However, the study of these factors in the field of stopover ecology will likely have implications for migratory bird conservation, allowing for improved management strategies and targeted efforts for private landowner education.

1.4 Current knowledge gap

Indiana in the Midwestern United States is a fragmented forest-urban-agricultural landscape, almost entirely managed through private ownership. This balance of factors creates an important area in which to observe patterns of migratory bird behavior and abundances. While some studies of stopover ecology have been completed in this system (e.g., Packett and Dunning 2009), work remains to be completed at a large spatial and temporal scale. In addition, the extent of avian population declines has been quantified at a continental scale using weather surveillance radar (Rosenberg et al. 2019), but continued monitoring of migratory bird abundances during migration itself, particularly within highly altered landscapes, remains a priority (Bauer et al. 2019). Identification of suitable stopover sites within this landscape is a logical “next step,” combined with identification of any land cover or socioeconomic factors associated with highly used sites, in order to effectively conserve migrating birds. While identification of stopover sites using weather surveillance radar has been done in several landscapes such as the Northeastern United States or the Gulf of Mexico coastline (Buler and Diehl 2009, Buler and Dawson 2014), mapping of stopover sites within the Midwestern United States has not been completed (but see Diehl et al. 2003, Bonter et al. 2009, Archibald et al. 2017 for work in the Great Lakes region). In addition, to our knowledge, no studies have explored the relationship between socioeconomic structures and migratory bird densities. Furthermore, the integration of weather surveillance radar with species-level data from sources such as eBird, if possible, would allow for more information regarding species- or taxa-specific population changes or stopover site use. Finally, our case study, Indiana, is dominated by private ownership: over 95% of the state is privately owned (Indiana Department of Natural Resources 2020). Conservation in this context will largely depend on management decisions made by landowners; thus, the provision of resources with which to manage lands effectively has great potential to improve habitat for migratory birds.

1.5 Hypotheses and predictions

My goals in this dissertation were to 1) describe spatiotemporal patterns of migratory bird ecology during stopover in a fragmented forest-agricultural-urban system, 2) test hypotheses regarding factors driving those patterns, 3) test new methodology for integrating two big data sources used to study migratory bird ecology, and 4) provide tools for private landowners within Indiana to manage their lands effectively for conservation of migrating birds. The primary tools with which I accomplished these goals were weather surveillance radar, also called NEXRAD, and

eBird citizen science data. I also used data from the U. S. Census Bureau, the National Land Cover Dataset and related products, and satellite imagery of anthropogenic light at night as covariates and predictors in this project. As mentioned previously, these data are all freely available and non-invasive methods of study. My hypotheses and associated predictions for my three primary research topics are as follows:

- 1) Migratory bird populations have declined over recent decades due to multiple factors such as habitat loss and climate change (Rosenberg et al. 2019). Conservation of these species depends on understanding how and where their populations are changing, and weather surveillance radar provides a unique opportunity to measure biomass of migrating birds on a large spatial and temporal scale. I predict that changes seen on a continental scale (Rosenberg et al. 2019) will be seen on a local scale in Indiana as declines in overall bird densities during migration in Indiana. Additionally, Indiana's fragmented landscape may influence migratory behavior within distinct habitats, so I predict differential rates of declines among habitat types, particularly given habitat-specific patterns of population change observed on a continental scale (Rosenberg et al. 2019).
- 2) Migratory bird densities are driven by habitat types (i.e., hardwood forest; Buler et al. 2007) on a landscape scale, but other factors such as anthropogenic light at night, impervious surface area, tree canopy cover, and socioeconomic factors have been identified as drivers of bird abundance or biodiversity in previous studies (Rodewald and Matthews 2005, Luck et al. 2009, McLaren et al. 2018, Van Doren et al. 2017). Based on previous research, I predict that migratory bird density at exodus in Indiana will be positively associated with greater amounts of forest cover (and thus lower amounts of urban or agricultural land cover types), higher levels of anthropogenic light at night, lower levels of impervious surface, and possibly areas of higher socioeconomic status when measured at a landscape scale.
- 3) The degree to which weather surveillance radar and citizen science data are corroborated by one another has implications for many areas of stopover ecology (i.e., Horton et al. 2018). In particular, using eBird data to validate radar-determined stopover distributions and identify species communities utilizing distinct habitats would be an important step forward in this field. The integration of these two datasets would, if possible, broaden the scope at which each is individually able to address the conservation and management of migratory birds. This type of integration assumes that citizen science efforts measure bird migration intensity similarly to weather surveillance radar at broad scales. Therefore, I

predict that relative counts of birds from each data source will be positively correlated with one another, an important first step in the aforementioned integration process.

CHAPTER 2. SPATIOTEMPORAL CHANGES IN SPRING AND AUTUMN DENSITIES OF NOCTURNALLY MIGRATING BIRDS IN INDIANA OVER AN 11-YEAR PERIOD

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2.1 Abstract

Migratory bird populations, often monitored during breeding and wintering season surveys, have been declining in North America for decades. The use of weather surveillance radar to monitor population-level trends during migration is an important approach that allows for better understanding of the magnitude of these declines. We used weather surveillance radar data collected during spring (2006–2007, 2011–2012, and 2016–2017) and autumn (2005–2006, 2010–2011, and 2015–2016) migration from two stations in Indiana to identify spatiotemporal trends in migratory bird abundances. Specifically, we measured trends in densities of birds leaving stopover sites within three distinct habitat types (forest, urban, and agriculture), daily variability in stopover site use, and traffic rates of birds in migratory flight aloft near radar stations. We used two-way interactive linear models with year, habitat, season, and radar as covariates to evaluate presence or absence of trends in bird densities. In both spring and autumn migration, the mean density of migratory birds leaving stopover sites declined by approximately 6.8% annually across the 11-year study period ($t = -4.702$, $p < 0.001$). Conversely, daily variability in bird stopover site use within seasons increased over the same period across all habitat types ($t = 5.792$, $p < 0.001$). Traffic rates of migrating birds aloft over Indiana declined by approximately 2% annually in autumn ($t = 1.707$, $p < 0.1$). These results highlight the importance of continued conservation in forested and other high-quality migratory bird habitats, but also highlight an increasing importance of conservation within urban and other highly altered landscapes, especially as these areas continue to increase in the Anthropocene Era.

2.2 Introduction

Populations of migratory birds have been declining worldwide in the last several decades, with declines largely attributed to global climate change, habitat loss, and habitat degradation throughout their entire range (Robbins et al. 1989, Rappole and McDonald 1994, Both et al. 2006, Bairlein 2016, Bauer et al. 2018, Rosenberg et al. 2019). While many studies have focused on breeding and wintering periods, the migratory period is also an important portion of the annual cycle (Newton 2006). Migration is energetically expensive and dangerous; mortality during this period can be up to 15 times higher than during breeding or wintering periods for Neotropical long-distance migrating songbirds (Sillett and Holmes 2002, Paxton et al. 2017). Expanding beyond these single species examinations presents a number of challenges. However, monitoring population-level trends during the migratory period is a unique approach that can greatly benefit conservation strategies. For example, a recent study used a continent-wide network of weather surveillance radars to assess changes in biomass of migrating birds throughout their annual cycle (Dokter et al. 2018). By monitoring bird densities during spring and autumn, it is possible to assess precise information about the magnitude of continued declines in North American birds.

Several novel hazards to birds have arisen in the modern era. Rachel Carson's landmark *Silent Spring* (1962) first drew attention to the detrimental hazards of certain pesticides, which continue to negatively affect birds, particularly birds migrating through agricultural areas (Hallmann et al. 2014, Eng et al. 2019). In addition, introduced predators such as domestic cats within human-dominated landscapes kill billions of birds every year (Loss et al. 2013). Even the structures humans have built are a significant source of bird mortality, both directly through window collisions (Winger et al. 2019) and indirectly through artificial light at night (ALAN), which disorients birds and draws them into low-quality habitats in urban areas (La Sorte et al. 2017, Van Doren et al. 2017, Cabrera-Cruz et al. 2018, McLaren et al. 2018).

Many of these novel anthropogenic factors are particularly important in the Midwestern United States. For instance, many cities in the Midwest generally, and Indiana specifically, expose migratory birds to high levels of ALAN (Horton et al. 2019b). Chicago, Indianapolis, and Cincinnati are among the top 20 cities in the United States exposing migratory birds to ALAN, while Fort Wayne and South Bend in Indiana are among the top 125 cities (Horton et al. 2019b). The increase of urban and agricultural habitats throughout the Midwest in the modern era further introduces hazards to migrating birds.

Indiana, once covered in 9.3 million hectares of forest (over 95% of its total area) before European settlement, is now dominated by urbanized and agricultural land, with less than 20% forest cover remaining (Indiana Department of Natural Resources 2017). While many patches of forest remain, the new makeup of the state as a fragmented forest-agricultural-urban matrix makes it an important case study of trends in migratory bird activity. For example, small forest woodlots within an agricultural landscape matrix are heavily used by migrating birds, making them important conservation targets, a point corroborated by a recent global synthesis of conservation studies (Packett and Dunning 2009, Wintle et al. 2018). This, coupled with the state's central location along the eastern migratory flyway (La Sorte et al. 2013, La Sorte et al. 2014, Cabrera-Cruz et al. 2018), provide an opportunity to study the complex interactions between agriculture, urbanization, and their associations with migratory bird abundances and distributions.

Radar has been used for military and meteorological purposes for over 75 years, with nearly as many years in biological study. Radar aeroecology and the study of the airspace as wildlife habitat is an emerging field, but has progressed rapidly over the last several decades (Bruderer 1997b, Diehl 2013). Weather radars documented a significant decline in number of birds arriving along the Gulf of Mexico coastline between the 1960s and 1980s (Gauthreaux 1992, Gauthreaux and Belser 2003), a pattern of decline that continues to concern ornithologists and conservationists. Weather radar can also measure biomass of migratory birds across North America, quantifying seasonal survival based on differences in spring and autumn abundances, as well as population declines of North American birds (Dokter et al. 2018, Rosenberg et al. 2019). Other researchers have even used archived weather radar data in combination with weather forecasts to predict bird migration intensity across North America, much like meteorologists predict weather patterns (Van Doren and Horton 2018). These studies have all focused on migration traffic rates during flight, but weather radar can also quantify the biomass of birds emerging from stopover sites at night (Buler and Diehl 2009, Buler and Dawson 2014). The departure of birds from stopover habitats is termed the *exodus* period of migratory flight (Buler and Dawson 2014). This *en masse* emergence allows for identification of terrestrial stopover sites that nocturnal migrants use during the day and spatially explicit measures of bird biomass within different habitats.

Understanding where and how migratory bird populations are changing is imperative to their continued conservation. Weather surveillance radar provides a unique opportunity to monitor biomass of birds travelling through Indiana in a spatially and temporally explicit design. Our primary objective was to use radar to quantify how migrating bird abundances aloft and near the

ground have changed across space and time in Indiana, and to identify possible factors related to those changes. Changes in overall population size of migrating birds may affect ecology within a specific portion of their migration cycle, altering spatial patterns and overall densities in Indiana. Based on previous studies, we expected to see a decline in overall migratory bird density over time during migration, both near the ground and aloft. Additionally, given the fragmented landscape patterns within Indiana and the dependence on even small forest woodlots by migrating birds, we expected declines in overall density would differ among habitats. We also expected to see differences in seasonal abundances of migrating birds due to reproductive output in the breeding season (Dokter et al. 2018).

2.3 Methods

The Weather Surveillance Radar-1988 Doppler (WSR-88D, hereafter referred to as NEXRAD; Crum et al. 1993) is a national radar network installed in 1991 and operated by the National Weather Service (National Oceanic and Atmospheric Administration, NOAA) and the U.S. Air Force (Department of Defense). We used two NEXRAD radars operated by NOAA whose surveillance areas cover most of the northern and central portions of Indiana, USA (Figure 2.1). The KIWX (hereafter IWX) radar in North Webster (41.359°N, 85.700°W) covers much of northern Indiana, while the KIND (hereafter IND) radar in Indianapolis (39.707°N, 86.280°W) covers almost the entirety of central Indiana. We obtained archived Level II NEXRAD data for both spring and autumn migration at both the IND and IWX radars from Amazon Web Services (AWS; <https://s3.amazonaws.com/noaa-nexrad-level2/index.html>). We sampled data from six years within an eleven-year time period in Indiana, reducing the amount of radar data to process while providing an indication of population changes over time. Each season (i.e., spring 2005) took between 50-150 hours to process. Specifically, we processed data for nights during autumn (September–October) 2005–2006, 2010–2011, and 2015–2016, and springs (April–May) 2006–2007, 2011–2012, and 2016–2017.

NEXRAD and other surveillance radars operate by emitting a series of electromagnetic pulses, which are scattered upon meeting a target in the airspace. Scattered waves are reflected back to the radar receiver, from which several different quantities are measured. A primary measurement is reflectivity, in decibel units (dBZ), which is related to the total amount of reflected energy (Bruderer 1997a). In addition to the magnitude of reflectivity, NEXRAD collects measures of radial velocity. Spatially, radar data are measured within *sample volumes*, defined by the length

of the pulse and the angle of the radar beam, 0.5° or 1° in the case of NEXRAD data (Crum et al. 1993). NEXRAD sample volumes in our study were of both coarser “legacy” (1 km x 1° ; 2005–2007 data) and finer “super-resolution” (250 m x 0.5° ; 2010–2017) spatial resolutions. Data are recorded almost continuously throughout the day at 5- or 10-minute intervals, depending on the amount of precipitation in the air (Buler and Dawson 2014). We utilized this abundance of data to quantify migration densities at two periods during the night: the period of *exodus* immediately after take-off to identify number of nocturnally migrating birds leaving stopover sites in Indiana, and nightly integration of migration *traffic rates* of birds flying over Indiana.

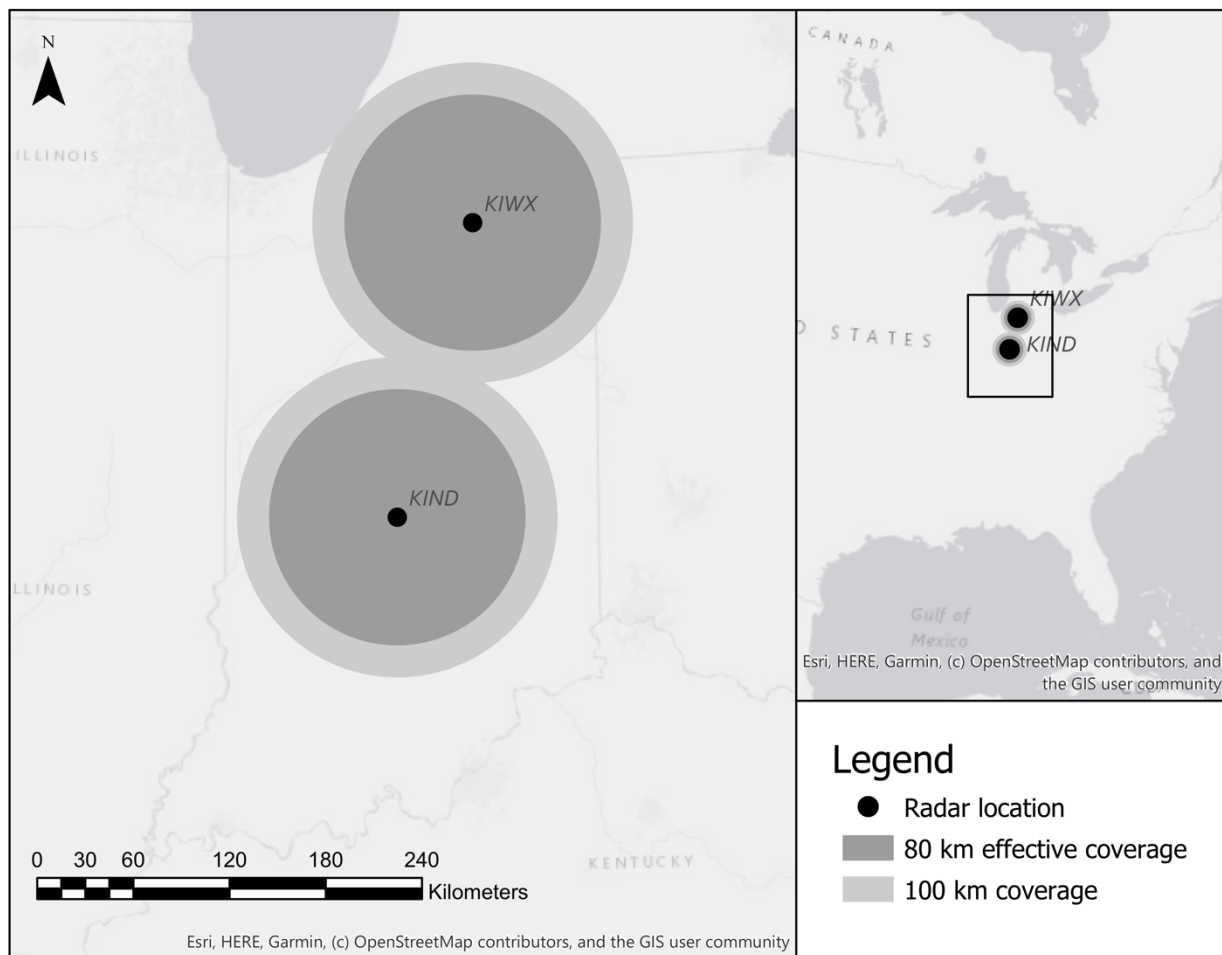


Figure 2.1. Study area and approximate coverage of two radars, IWX and IND (also called KIWX and KIND) in Indiana, USA, used to monitor spatial and temporal trends in migratory bird densities.

2.3.1 Stopover exodus

To standardize the biomass of birds leaving stopover sites among nights, we sampled NEXRAD data at the instant of peak exodus (i.e., maximum rate of increase of reflectivity) as birds took off each night following McLaren et al (2018). Migrating birds depart stopover areas *en masse* in relation to the elevation of the sun, usually around the end of civil twilight. However, their departure timing on any given evening can vary both across and within seasons based on several factors such as sun elevation, night length, wind conditions, and body condition (Sjöberg et al. 2017). After filtering NEXRAD data to remove nights contaminated with precipitation ($n = 700$ nights, 47.8% of possible 1,464 nights over the study), nights dominated by insect activity ($n = 91$ nights, 6.2%), beam refraction under certain atmospheric conditions (also called anomalous propagation; $n = 191$ nights, 13.1%), unknown contaminants or lack of data ($n = 66$ nights, 4.5%), pixels of consistent clutter, and radials with extensive beam blockage, we spatiotemporally interpolated data to the instant of maximum rate of increase in reflectivity for each night in our study (McLaren et al. 2018). Data were then summarized across each season by year and radar using a regression on order statistics (ROS) for multiply censored data (Buler and Dawson 2014), which outputs estimates of arithmetic mean and coefficient of variation (CV, a measure of within-season variability in stopover site use) of vertically integrated reflectivity (VIR) of aggregate bird density aloft at the time of peak exodus each night, in units of $\text{cm}^2 \text{ha}^{-1}$. Full details of our radar processing methods for quantifying exodus from stopover sites can be found in Appendix A.

2.3.2 Spatial analysis

To identify trends in density of birds leaving different habitats, we classified radar sample volumes based on land cover information from the National Land Cover Dataset (NLCD 2011; Homer et al. 2015). The proportion of forest (NLCD forest categories 41, 42, 43, and woody wetlands 90), urban (NLCD developed categories 21, 22, 23, and 24), and agriculture (NLCD pasture and cultivated crop categories 81 and 82) were calculated for each sample volume. Sample volumes with greater than 75% cover of each respective category were labeled as *forest* ($n_{\text{spring}} = 21,454$ sample volumes, area = 188,383 ha; $n_{\text{autumn}} = 22,747$, area = 198,116 ha), *urban* ($n_{\text{spring}} = 35,758$, area = 175,343 ha; $n_{\text{autumn}} = 38,342$, area = 185,736 ha), or *agriculture* ($n_{\text{spring}} = 155,688$, area = 1,186,154 ha; $n_{\text{autumn}} = 160,943$, area = 1,234,045 ha). Only those sample volumes with greater than 75% cover were selected to lessen variation due to interannual changes in land cover composition. Variable areas sampled between spring and autumn were due to filtering of data,

particularly removal of within-season censored sample volumes as described in Appendix A. After this classification, the IND radar site was 13% forest, 10% urban, and 52% agriculture and the IWX radar site was 4% forest, 6% urban, and 58% agriculture. This process was repeated for spring and autumn seasons at both radars in all years.

2.3.3 Migration traffic rates

We also gathered data on passage of total cumulative biomass of birds flying over Indiana, or traffic rates of birds (Horton et al. 2019a). These data were summarized for both spring (March 1 to June 15) and autumn (August 1 to November 15) in 2005–2007, 2010–2012, and 2015–2017. Due to fewer time constraints with processing these data compared to exodus data, we included both seasons from all years in this study. We subsampled scans every 30 minutes between local sunset and sunrise, sampling data from 5–37.5 km from the radar at 0.5–4.5° elevation sweeps to construct vertical profiles of reflectivity (VPR) from 0 to 3 km above ground level at 100 m intervals (Farnsworth et al. 2016, Newcombe et al. 2019). Velocity azimuth displays (VAD) were generated to calculate migrant track and groundspeed (Browning and Wexler 1968). Radial velocity measures were de-aliased using the methods of Sheldon et al. (2013). Prior to VPR and VAD construction, precipitation was identified and set to zero on a per-sample volume basis using MISTNET, a deep-learning classification algorithm (Lin et al. 2019). VPRs and VADs were constructed using WSR-LIB (Sheldon 2015).

To calculate total nightly migrant biomass passage, we first converted reflectivity factor (dBZ) to reflectivity (η), resulting in units of $\text{cm}^2 \text{ km}^{-3}$ (Chilson et al. 2012). We multiplied this value by the northward (spring) and southward (autumn) components of biomass groundspeed (km hr^{-1}) and multiplied by the altitudinal resolution (0.1 km) of each height bin, resulting in $\text{cm}^2 \text{ km}^{-1} \text{ hr}^{-1}$. We integrated through the night using linear interpolation for area under the curve, resulting in $\text{cm}^2 \text{ km}^{-1} \text{ night}^{-1}$ (Horton et al. 2019a). Lastly, we summed these values across each season at each radar to obtain a measure of total seasonal biomass passage at each radar.

2.3.4 Statistical analysis

For both spring and autumn migration, we quantified trends in mean reflectivity and coefficient of variation (CV) at exodus within each habitat type and trends in total traffic rates of migrating birds. We calculated mean reflectivity (area weighted mean, to account for variable areas

of each radar sample volume) and mean CV at exodus each year within each habitat type at both radars in both seasons, then used analysis of variance (ANOVA) models to quantify spatiotemporal changes in bird density and variability in stopover site use from autumn 2005–2016 and spring 2006–2017. Analyses were restricted to only those sample volumes where data were available every year to eliminate possibility of sampling bias.

We log10-transformed mean reflectivity to meet assumptions of a linear model; CV did not exhibit a non-normal distribution of residuals. Factors such as radar (IND and IWX), habitat (forest, urban, and agriculture), and season (spring and autumn) were included as covariates in this analysis, and a single model where mean reflectivity or CV were predicted to be a function of year, habitat, season, and radar was run. For mean reflectivity, we used a model containing two-way interactions between radar and habitat and radar and season, as Akaike's Information Criterion was lowest when only these interactions were included but not all possible two-way interactions ($AICc_{subset} = 118.9$, $AICc_{full} = 130.3$, $AICc_{all} = 128.4$). For CV, we used a model containing a two-way interaction between year and radar ($AICc_{subset} = -22.88$, $AICc_{full} = -20.53$, $AICc_{all} = -5.22$). We used post-hoc Tukey Honest Significant Difference (HSD) tests with 95% confidence levels to identify presence of significant interactive effects.

We also used an ANOVA to estimate magnitude of trends in traffic rates from spring and autumn 2005–2017 at both radars, using year, season, and radar as covariates in a two-way interactive model. A two-way interaction between season and radar was not included in this model as Akaike's Information Criterion was lower when this interaction was not included ($AICc_{full} = 1193.0$, $AICc_{subset} = 1196.3$). Interaction plots for continuous variables were generated using R package *interactions* (Long 2019). Annual percentage changes, where applicable, were calculated as the percentage change in fitted values of dependent variables between first and last years. Spatial mapping, data parsing, processing, and statistical analyses were completed in ArcMap version 10.3, ArcGIS Pro version 2.3, and R software version 3.6 (R Core Team 2019).

2.4 Results

Between autumn 2005–2016 and spring 2006–2017, density estimates of migrating birds leaving stopover sites at exodus in Indiana declined annually by a rate of -0.06753 , or $-0.856 \text{ cm}^2 \text{ ha}^{-1} \text{ yr}^{-1}$ (s.e. ± 0.014 ; $t = -4.702$, $p < 0.001$, Figures 2.2-2.3). This was approximately a 6.8% annual decline over our study period. Density estimates were lower at the IND radar, particularly in autumn ($t = -1.874$, $p = 0.066$, Figure 2.4a). In addition, density estimates were lowest in

agricultural areas around the IND radar when compared to other habitat types at both radars (Figure 2.4b). This model had an adjusted R^2 of 0.529, explaining over 50% of the variability in stopover densities of migratory birds. Results from all linear models are shown in Table 2.1.

Daily variability in stopover site use, CV, was higher in spring than autumn and was higher in agricultural and urban areas than in forest habitats (Figure 2.4c-d). CV also increased by a rate of $0.044 \text{ cm}^2 \text{ ha}^{-1} \text{ yr}^{-1}$ over the study period (s.e. ± 0.0077 , $t = 5.792$, $p < 0.001$), though this rate of increase was slower at the IWX radar (Figure 2.4e). In other words, migrating birds often utilized stopover sites more variably in agricultural and urban areas and in spring, and are using stopover sites more variably in recent years. This model had an adjusted R^2 of 0.518.

Traffic rates of migrating birds aloft in autumn declined over time by approximately 1.93% annually when measured by a significant interaction ($-3.80\text{E}+05 \pm 2.25\text{E}+05 \text{ cm}^2 \text{ km}^{-1} \text{ yr}^{-1}$, $t = 1.707$, $p = 0.098$). Outside this interaction, traffic rates of birds aloft were higher in autumn than in spring ($t = -1.721$, $p = 0.096$). In other words, densities of birds aloft were more similar in spring and autumn of recent years than in the earlier years of the study (Figure 2.4f). We also observed no difference in traffic rates between the two radars. Our model for migrating bird traffic rates explained 62% of the variance in the data (adjusted $R^2 = 0.621$).

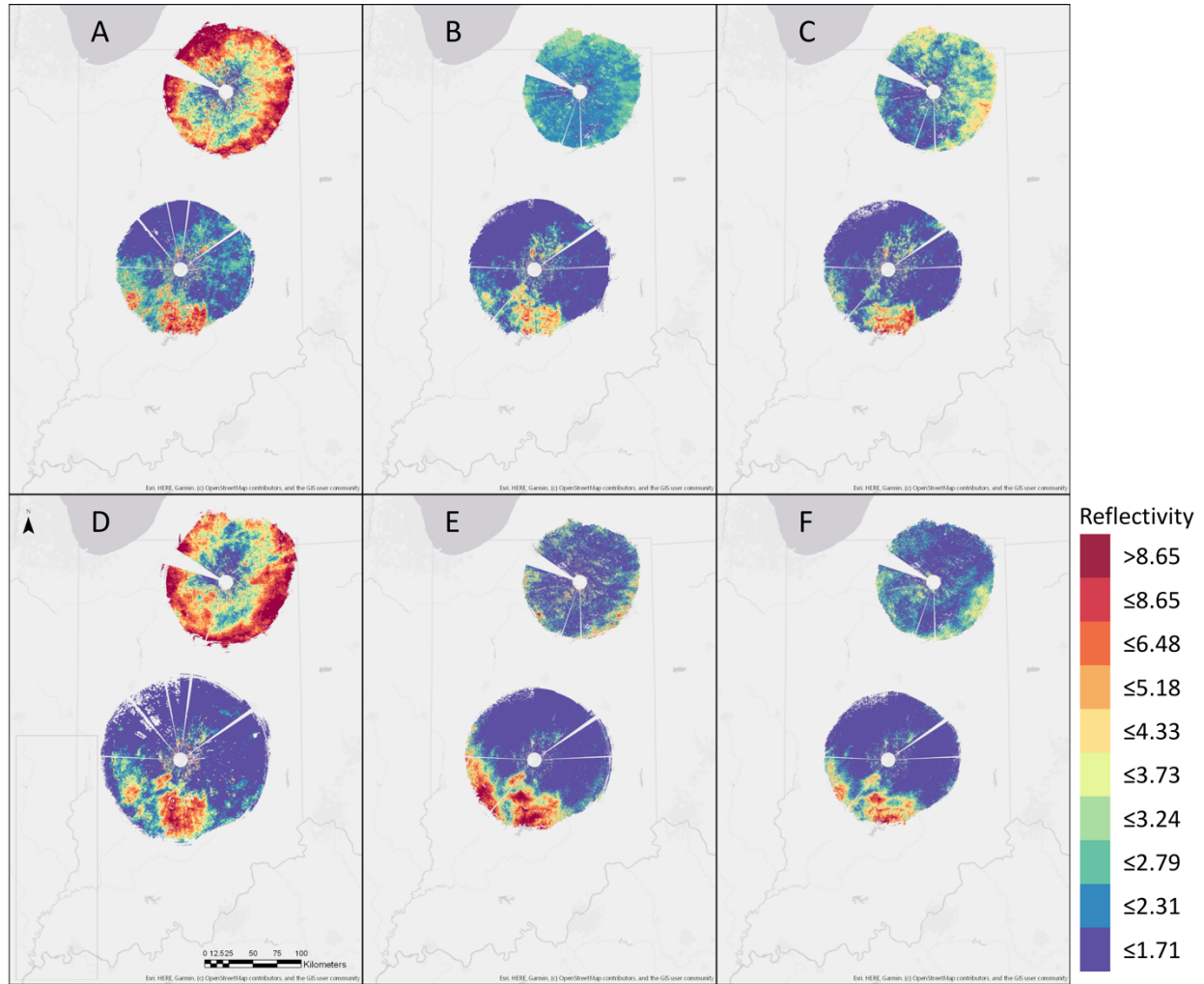


Figure 2.2. Autumn (September–October, A–C) and spring (April–May, D–F) radar imagery showing temporal patterns of migratory bird abundances and spatial patterns of stopover in three time periods: early, 2005–2007 (A and D); middle, 2010–2012 (B and E); and late, 2015–2017 (C and F). Reflectivity in $\text{cm}^2 \text{ha}^{-1}$ is shown on the same scale between all images to allow comparison of spatial and temporal patterns of migratory bird distributions. Radials with no data indicate filtered areas based on persistent clutter.

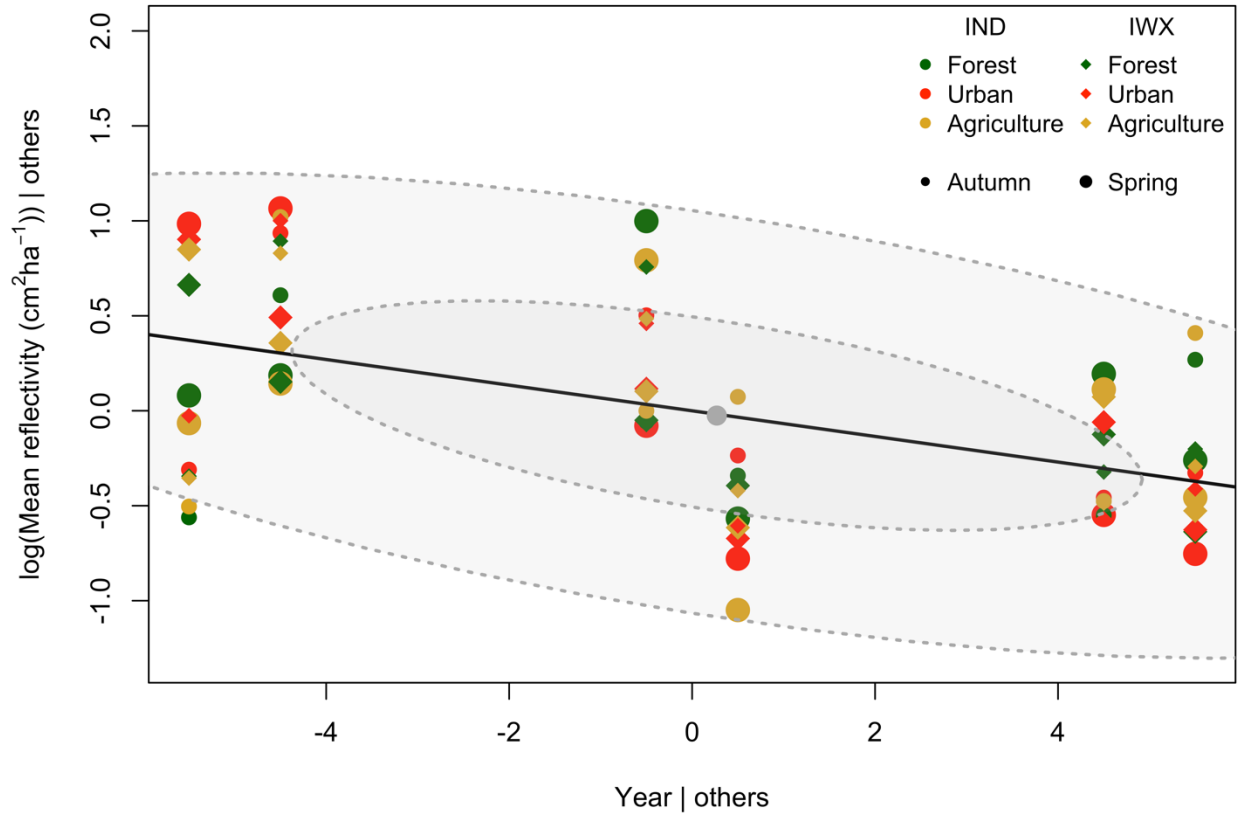


Figure 2.3. Partial regression plot describing patterns of migratory bird density at stopover (mean reflectivity) over time while controlling for effects of other variables. Bird density was measured by weather surveillance radar during autumn and spring migration across an 11-year period at two radars (IND and IWX) in Indiana, USA, within three habitat types: forest, urban or developed, and agriculture. Values shown are log10-transformed, and ellipses are 50% and 95% data concentration ellipses.

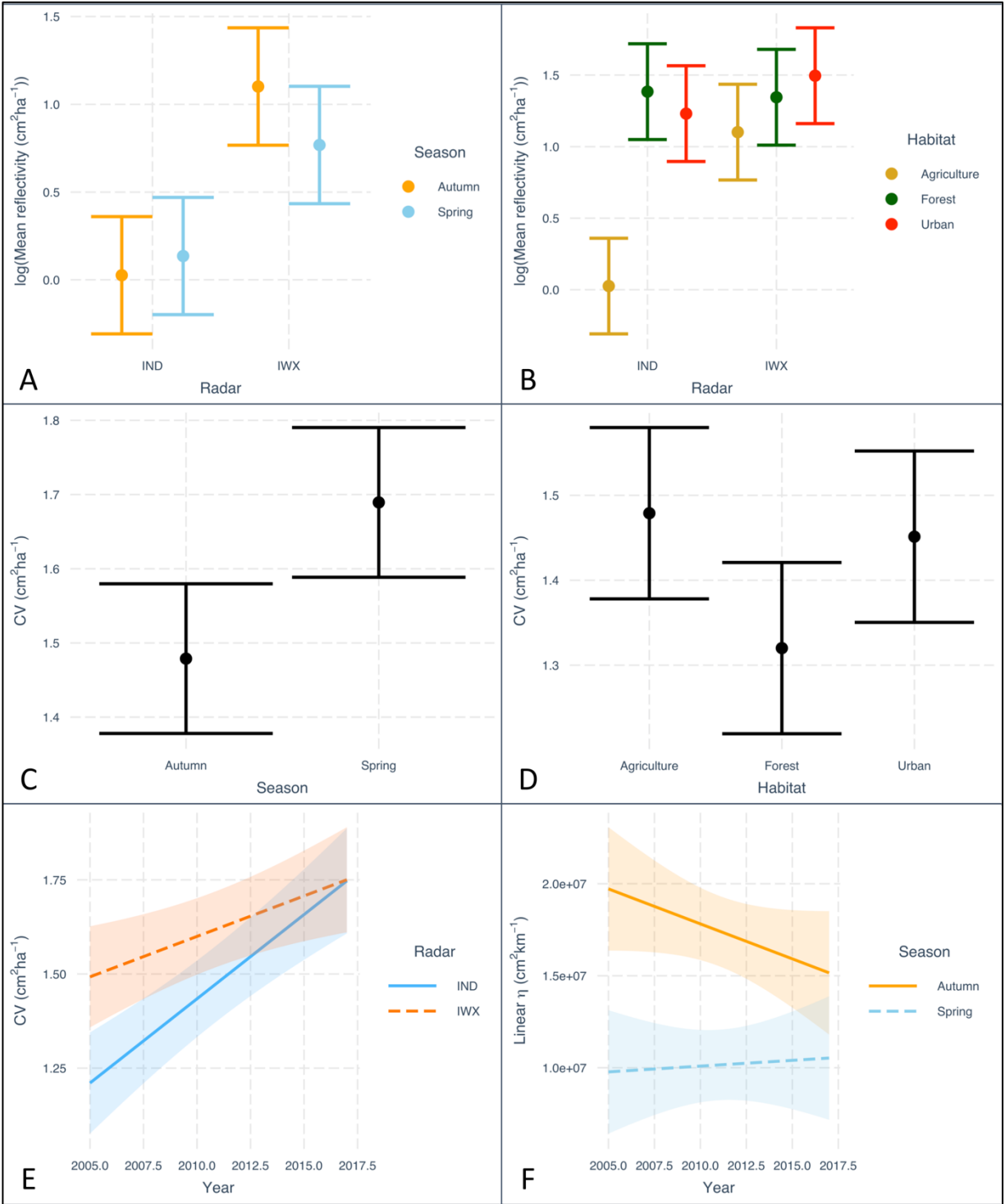


Figure 2.4. Interaction and effects plots for categorical and continuous covariates in linear models testing effects of year, season (autumn and spring), habitat (forest, urban, or agriculture), and radar (IND and IWX) on migratory bird density during stopover (A-B), daily variability in stopover site use (C-E), and traffic rates of birds aloft (F) in Indiana, USA, over an 11-year period. Only statistically significant ($\alpha = 0.10$) interactions (A-B, E-F) or main effects (C-D) are shown, and shaded areas or bars are 95% confidence intervals.

Table 2.1. Linear model results describing relationships between year, season, habitat type, and radar and bird density (mean reflectivity, log10-transformed), coefficient of variation (CV, daily variability in stopover site use), and traffic rates of birds aloft during spring and autumn migration across an 11-year period in Indiana, USA. Habitat was not included in the traffic rate model, as bird use of specific habitats cannot be determined using traffic rate data. (*) indicate $p < 0.10$, (**) indicate $p < 0.05$.

Formula	Coefficients	Estimate	Standard error	t value	p value
<i>density ~ year + season + habitat + radar + radar:season + radar:habitat</i> Adjusted R ² = 0.529 F (df) = 10.97 (8, 63), $p < 0.001$	Intercept	135.832	28.874	4.704	1.44E-05**
	Year	-0.06753	0.014	-4.702	1.45E-05**
	Season (spring)	0.110	0.168	0.655	0.515
	Habitat (forest)	1.358	0.205	6.637	8.54E-09**
	Habitat (urban)	1.205	0.205	5.887	1.65E-07**
	Radar (IWX)	1.076	0.236	4.552	2.48E-05**
	Radar (IWX) : season (spring)	-0.443	0.236	-1.874	0.066*
	Radar (IWX) : habitat (forest)	-1.115	0.289	-3.852	0.00028**
	Radar (IWX) : habitat (urban)	-0.811	0.289	-2.802	0.0066**
	Residual		0.501		
<i>CV ~ year + season + habitat + radar + radar:year</i> Adjusted R ² = 0.541 F (df) = 14.94 (6, 65), $p < 0.001$	Intercept	-88.502	15.534	-5.697	3.18E-07**
	Year	0.044	0.008	5.792	2.20E-07**
	Season (spring)	0.211	0.045	4.634	1.78E-05**
	Habitat (forest)	-0.159	0.055	-2.876	0.0055**
	Habitat (urban)	-0.028	0.055	-0.500	0.619
	Radar (IWX)	46.905	21.890	2.143	0.036**
	Year : radar (IWX)	-0.023	0.011	-2.136	0.036**
	Residual		0.191		
<i>traffic ~ year + season + radar + year:season + year:radar</i> Adjusted R ² = 0.621 F (df) = 12.47 (5, 30), $p < 0.001$	Intercept	7.82E+08	4.52E+08	1.730	0.094*
	Year	-3.80E+05	2.25E+05	-1.692	0.101
	Season (spring)	-8.98E+08	5.22E+08	-1.721	0.096*
	Radar (IWX)	8.31E+08	5.22E+08	1.592	0.122
	Year : season (spring)	4.43E+05	2.60E+05	1.707	0.098*
	Year : radar (IWX)	-4.14E+05	2.60E+05	-1.596	0.121
	Residual		3.24E+06		

2.5 Discussion

When measured both aloft and near the ground, our study revealed declines in migratory bird stopover densities across Indiana between 2005–2017. Between autumn 2005–2016 and spring 2006–2017, densities of migrating birds leaving stopover sites at exodus declined by approximately 6.8% annually, and seasonal traffic rates of migrating birds aloft declined during autumn migration by approximately 1.9% annually. Daily variability in stopover site use, however, increased over our study period, particularly in agricultural and urban areas and at the IND radar in southern and central Indiana. Populations of migratory birds have been declining for decades across North America (Robbins et al. 1989, Terborgh 1989, Wilcove and Wikelski 2008, Bairlein

2016, Rosenberg et al. 2019). Our results measuring migrating bird densities within Indiana specifically are consistent with these studies, which is especially concerning given the previously observed decreases from as early as the 1960s (Carson 1962, Gauthreaux 1992, Robbins et al. 1989). While Horton et al. (2018) found little change in annual numbers of migrants in the Gulf of Mexico coastal region over the same time period (2007–2015) using weather surveillance radar, Rosenberg et al. (2019) found overall declines in bird abundances across the entire North American continent between 2007–2017. Local, regional, or seasonal factors may thus be shaping patterns of population abundances, and future studies could examine these patterns across both continental and local scales to ascertain further where and how migratory bird populations are changing.

Declines in North American birds have been attributed to a myriad of factors operating on a global or continental scale such as habitat loss, climate change, and urbanization (Rosenberg et al. 2019). In the agricultural Midwestern United States, evidence from birdwatchers has indicated fewer birds seen during organized counts over the decades (JBD, unpublished data, Big May Day Bird Count program by Indiana Audubon Society), declines which also could be attributed to local factors such as artificial light pollution at night or pesticide use. Consistently identified as an important factor influencing migratory bird ecology in the eastern United States, artificial light pollution was cited as a threat to migrating birds in several Midwestern cities including Indianapolis, Fort Wayne, and South Bend, IN (Horton et al. 2019b). Additionally, pesticide use is correlated with grassland bird declines and neonicotinoid-treated seeds can have significant negative impacts on migrating bird physiology (Meehan et al. 2010, Mineau and Whiteside 2013, Eng et al. 2019).

In the early years of our study period, traffic rates of migrating birds aloft were higher in autumn than spring and declined over the course of our study so that autumn densities became more similar to spring densities. It was expected that densities of migrating birds would be higher during autumn migration, given previously observed estimates due to breeding season fecundity (Dokter et al. 2018). Thus, our observation of declines in traffic rates in autumn relative to spring such that traffic rates were similar between seasons in later years is concerning from a conservation perspective. These trends could be due to several factors, such as declining reproductive output in the breeding season, increased mortality or decreased fueling rates due to factors such as pesticide use, or shifting migration routes such that birds are increasingly avoiding the Midwestern United States.

Several factors could be contributing to changes in abundances of autumn migrants. Reproductive success has been shown in one species (Veery, *Catharus fuscescens*) to have carry-over effects in subsequent seasons, particularly on arrival on wintering grounds (Heckscher et al. 2017). Another study found that mercury exposure during the breeding season could have carry-over effects to influence autumn migration survival (Ma et al. 2018). Neonicotinoid insecticides also have negative effects on migrating birds, reducing their ability to refuel which likely delays migration, and can persist in plant tissues throughout a growing season (Budge et al. 2015); given the high number of younger birds in autumn and that younger birds are thought to be less efficient migrants, factors influencing migratory efficiency may have disproportionately negative effects on younger birds in autumn migration (Eng et al. 2019, Schmaljohann et al. 2018). Finally, migration routes are often different between spring and autumn seasons, and some species have shown flexibility in migration routes in response to habitat change (Dolman and Sutherland 1995, Sutherland 1998). Observed declines in abundances of birds aloft during autumn migration in Indiana could thus be due to some species exhibiting flexibility in their migration routes, particularly since autumn migration is often less time-constrained (Alerstam and Hedenstrom 1998).

We found faster rates of decline of bird densities leaving stopover sites compared to traffic rates of birds migrating through Indiana. Though this trend could be due to methodological or sampling bias, as data from stopover eliminated all nights with precipitation while traffic rates were derived by removing precipitation on a per-sample volume basis, an alternative interpretation of this trend is that there are now fewer birds stopping over in Indiana relative to the number of birds migrating over Indiana. This interpretation is consistent with our observation that the within-season daily variability with which birds utilized stopover sites within Indiana (CV) increased over our study period and was higher in agricultural and urban areas. First, this consistency of habitat use in forested areas is indicative of some preference for forest habitats during migration. In addition, it is possible that migrating birds are treating habitat patches within these highly altered urban and agricultural landscapes as emergency stopover sites or “fire escapes,” which are defined as sites that are used infrequently and typically near barriers or intensively altered landscapes such as the Midwestern United States (Mehlman et al. 2005). Our findings are in contrast to observed patterns of variation in areas along major barriers such as coastlines, where fire escapes may be used more consistently, albeit in low densities, after oceanic crossings (Buler and Dawson 2014). However, given the increase in variability of stopover site use in the Midwest, our work suggests

the disproportionately important role of small, isolated woodlots, city parks, and other small forest patches for migratory bird conservation (Wintle et al. 2018).

Given our results, the role of suitable habitat patches within developed and agricultural land cover types is an important one for migrating birds. Small patches like urban parks or woodlots may create less interior breeding habitat for mature forest specialists and can result in increases in predation rates and cowbird (*Molothrus* spp.) nest parasitism (Robinson 1996, Finch 1991). However, migrating birds have been known to use such small, forested patches as stopover habitat (Bonter et al. 2009, Packett and Dunning 2009, Buler and Dawson 2014). Mehlman and colleagues (2005) suggest small patches that are not beneficial for breeding birds may still be important stopover sites for migrating birds. In particular, urban parks and other developed areas (e.g., Buler and Dawson 2014), while likely not as productive for breeding birds and containing novel risks such as predation from domestic cats or building collisions (Loss et al. 2013, 2014), may be disproportionately important stopover sites for declining populations of migrants.

Studies using weather surveillance radar to map stopover densities are somewhat limited in part because of the inability to sample all nights within a season due to contaminants such as precipitation and insects, as well as the current inability of radar technology to differentiate among species. We were unable to ascertain, for example, which groups of species utilized different habitats, or how distinct groups of species are changing in abundance and habitat use relative to others. To fully understand bird migration and its relationship with a rapidly changing environment, the utilization of other sources of data such as point counts, field surveys, or citizen science databases such as eBird will be imperative (Sullivan et al. 2014). Future research should explore how migrant community composition in the Midwestern United States is changing over time, what factors may be driving those changes, and what efforts can be made to mitigate those changes.

2.5.1 Conclusion

We observed declines in abundances of birds stopping over during migration in Indiana, a fragmented forest-agricultural-urban system, between 2005–2017 at an annual rate of approximately 6.8%. In addition, we observed declines in traffic rates of birds aloft during autumn migration over the same period at an annual rate of approximately 1.9%. This suggests that fewer birds may be stopping over in Indiana in recent years, and may be treating Midwestern United States as barriers to be crossed rather than consistent stopover areas. Given the declines of bird densities and increased variability of stopover site use particularly in agricultural and urban

habitats, it is important to continue management of Indiana and other Midwestern forests and forest patches to protect migratory birds, particularly focusing on small, isolated patches near developed areas such as woodlots, urban parks, or local backyards. These small patches may become disproportionately important in the future as more birds depend on emergency stopover sites for resting and refueling during migration through fragmented and urbanized systems.

CHAPTER 3. SOCIOECONOMICS AND LAND COVER PREDICT STOPOVER HABITAT USE BY MIGRATORY BIRDS IN A FRAGMENTED LANDSCAPE

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3.1 Introduction

The migratory period is among the most dangerous and risk-prone phases in a bird's lifecycle, with higher mortality during this period than at any other time (Silllett and Holmes 2002, Paxton et al. 2017). Identification of suitable habitat during migration has been and continues to be an important area of study for bird conservation (Mehlman et al. 2005). Populations of migratory birds have been declining significantly and continue to decline over recent decades (Robbins et al. 1989, Terborgh 1989, Wilcove and Wikelski 2008, Rosenberg et al. 2019). It is likely that conditions experienced during migration are important in limiting migratory bird populations, despite much research historically focusing on the breeding season (Newton 2006). Thus, it is imperative to understand habitats used during migration and factors driving that habitat selection to better protect migratory birds.

Studies of land cover characteristics driving stopover habitat selection have provided invaluable information to managers and conservationists. One study in particular explored factors driving migratory bird distributions at multiple scales, finding that proximity to coastlines at a regional scale, hardwood forest at a landscape scale, and arthropod abundance and plant communities at a patch scale were important drivers of migrant abundances (Buler et al. 2007). Another study found small woodlots and early-successional forests containing fruiting trees and shrubs were important for migratory birds in autumn (Packett and Dunning 2009). Radar analysis in particular has provided precise quantification of spatial distributions during migration on a landscape scale in some regions (Buler and Dawson 2014, Lafleur et al. 2016, Zenzal et al. 2018). Landscape-level processes interact to influence bird ecology. In the modern era, fragmentation and urbanization at the landscape scale have shaped bird biology in a myriad of ways (Donovan and Flather 2002, McKinney 2002, Fahrig 2003, Alberti 2005, Proppe et al. 2013, Hager et al. 2017). It is now known that migrating birds utilize small habitat patches, the result of fragmentation and

urbanization, that are otherwise unsuitable for breeding birds (Packett and Dunning 2009). These small patches may thus have disproportionate conservation value for their size as migrating birds concentrate within them (Mehlman et al. 2005, Pennington et al. 2008, McCabe and Olsen 2015, Wintle et al. 2018).

Much research on stopover habitat selection has focused primarily on habitats outside of anthropogenic influences. When urbanization is included in studies, the focus often is on single components such as anthropogenic light at night (ALAN), urban-to-rural gradients, or fragmentation due to agriculture (Cabrera-Cruz et al. 2018, Pennington et al. 2008, Packett and Dunning 2009). These studies have identified several risks associated with anthropogenic factors, such as increased probabilities of window collisions, predation from domestic cats, or disorientation from artificial light (Loss et al. 2013, Hager et al. 2017, Van Doren et al. 2017). ALAN has been identified as a disruption and disturbance for nocturnally migrating birds (Van Doren et al. 2017, La Sorte et al. 2017, Cabrera-Cruz et al. 2018). Migrating birds are attracted to ALAN, which often draws them into smaller patches of lower habitat quality (McLaren et al. 2018). In addition, many areas with higher amounts of light pollution are found in areas with high concentrations of migrating birds (Cabrera-Cruz et al. 2018, Horton et al. 2019b). Proximity to bright lights has been shown to increase migratory bird stopover densities (McLaren et al. 2018), which is of conservation concern as this may elevate risks of collision- or predation-related mortality due to urbanization (Loss et al. 2013, Hager et al. 2017).

Not all urban areas are homogenous, however. Urban systems have complex patch dynamics and increased spatial heterogeneity (Alberti 2005), which may influence migratory bird distributions. One recent study found that forest-dwelling migratory birds utilized urban tree canopies and residential areas in Latin America during migration and winter (Amaya-Espinel and Hostetler 2019). Urban parks and green spaces in the northern United States have also been shown to provide stopover habitat for migrating birds (Homayoun and Blair 2016). In addition, migratory birds can use urban habitats for stopovers of multiple days, possibly searching for and occupying suitable habitat within urban landscapes (Seewagen et al. 2010).

Socioeconomic factors such as income and housing density can predict vegetation cover patterns; in one study, models combining socioeconomic and biophysical variables were better predictors of vegetation cover than biophysical variables alone (Luck et al. 2009). Thus, simply monitoring biophysical variables can miss an important set of factors driving changes that may influence migratory bird distributions. Several studies have explored avian diversity trends across

socioeconomic gradients or within cities (Kinzig et al. 2005, Davis et al. 2012, Lepczyk et al. 2017). In one, higher socioeconomic status was associated with higher levels of biodiversity (Kinzig et al. 2005). However, very few studies have been done to explore whether socioeconomics may help explain patterns of bird densities during migration.

It remains unknown how socioeconomic factors interact with landscape-level factors such as land cover to influence migratory bird stopover behavior. Here, we utilized big data sets to answer this question (La Sorte et al. 2018). Weather surveillance radar can answer questions of migratory bird stopover densities and distributions, providing detailed information on a landscape-level scale (Buler and Dawson 2014, Bauer et al. 2019). In addition, detailed socioeconomic data are collected on regular bases through the United States Census Bureau (USCB), providing a spatially explicit, relatively fine-scale source of information (American Community Survey; USCB 2017). We used Indiana, USA, in the Midwestern United States as a case study in which to address this question, since the Midwest is a unique matrix of agriculture, urban areas, forest fragments, and large, protected forests.

In this study, we hypothesized that migratory bird stopover site use in Indiana could be explained by socioeconomics and land cover characteristics. Higher socioeconomic status (Kinzig et al. 2005), older and more valuable houses (Luck et al. 2009, but see Loss et al. 2009), and lower human population densities were predicted to be positively associated with migratory bird density as measured by weather surveillance radar at exodus, when birds initiate their migratory flight. We believed bird densities in wealthier, older, and less dense neighborhoods would be higher in part given increased vegetation cover, higher proportions of native vegetation supporting higher arthropod densities (Burghardt et al. 2009), and larger lot sizes in these areas. In addition, based on previously published work we predicted a positive relationship between bird density and proximity to ALAN due to the disorienting and attractive effect of light at night (Van Doren et al. 2017), a positive relationship with amount of forest and tree canopy cover since these habitats provide food and shelter for migrating birds (Buler et al. 2007), and a negative relationship with agriculture and impervious surface area at the landscape scale, as these habitat types provide little to no food or shelter for migrants. These landscape characteristics have been studied in depth during breeding seasons, and to a lesser extent migration seasons, but the interactions between landscape characteristics and socioeconomics have not been studied in depth to our knowledge, especially during migration. We anticipate that our results will be informative to conservationists, land managers, and land-use planners, particularly within urban and developing areas.

3.2 Methods

3.2.1 Weather surveillance radar

To map stopover density of migrating birds in Indiana, we obtained reflectivity data from two Weather Surveillance Radar-1988 Doppler (WSR-88D) radars, also called Next Generation or NEXRAD radars, operated by the National Oceanic and Atmospheric Administration (NOAA). Weather surveillance radars, including NEXRAD, operate by emitting a series of electromagnetic pulses, which are scattered after meeting an entity in the airspace. These scattered waves are reflected back to the receiver in decibel units (dBZ) related to the total amount of energy; measures of radial velocity of objects in the airspace are also recorded (Crum et al. 1993, Bruderer 1997a). These data are measured within *sample volumes*, defined by the length of the pulse and the opening angle of the radar beam, a resolution of 250m x 0.5° in recent NEXRAD data. Data are recorded almost continuously throughout the day at 5- or 10-minute intervals, depending on the amount of precipitation in the air (Buler and Dawson 2014). We used data from two radars in Indiana, the KIWX radar in North Webster near Fort Wayne (41°21'31"N, 85°42'00"W) and the KIND radar in Indianapolis (39°42'27"N, 86° 16'49"W). Level II NEXRAD data from the lowest tilt-angle elevation (0.5°) were downloaded using Amazon Web Services (AWS; <https://s3.amazonaws.com/noaa-nexrad-level2/index.html>) for peak autumn and spring migration dates at both radars, using nights from September to October 2015-2016 and April to May 2016-2017.

We developed a basegrid shapefile centered on each radar's location with polygons corresponding to sample volume resolution on which to geo-reference our data, adding land cover information from the National Land Cover Dataset (NLCD 2011; Homer et al. 2015). We calculated the proportion of each land cover type within a given sample volume, which allowed us to generate a water filter over large bodies of water (i.e., Lake Michigan near the KIWX radar) by removing sample volumes with greater than 75% water. We also developed digital elevation models using elevation from The National Map (<http://viewer.nationalmap.gov/basic>) and calculating mean ground elevation within each sample volume. Additionally, we removed areas with persistent clutter from topographic interference or anthropogenic features such as large buildings or wind farms by selecting a series of scans (>1500 scans) in summer 2016 and determining sample volumes with mean reflectivity >30 dbz. These sample volumes were eliminated from further analysis, along with radials containing extensive beam blockage (Buler and Dawson 2014).

In addition to removing these sample volumes, nights containing contamination from precipitation, insects, consistent clutter, or anomalous propagation (beam refraction resulting under certain atmospheric conditions; Buler and Dawson 2014) are not suitable for analysis, as these factors can confound bird migration patterns. Therefore, we visually screened nights for precipitation within 100 km of both radars using archived Level III imagery available from NOAA (<https://gis.ncdc.noaa.gov/maps/ncei/radar>). Data from clear nights were then downloaded and Level II imagery was visually screened to remove nights contaminated by consistent clutter or anomalous propagation. Because insects fly at slower speeds than birds, we could distinguish nights dominated by birds from insect-dominated nights by measuring mean target speeds at peak migration (approximately three hours after sunset). We obtained wind speeds from the North American Regional Reanalysis (NARR) project provided by NOAA (Mesinger et al. 2006). We distinguished bird-dominated nights from insect-dominated nights by determining the horizontal velocity of radar-detected targets through measuring the difference between wind velocity vectors and target velocity vectors following Buler and Diehl (2009). Nights with mean target airspeeds of >5 m/s were considered bird-dominated nights.

Most nocturnally migrating birds take off *en masse* at approximately civil twilight, or half an hour after sunset. However, departure timing can vary significantly both across and within seasons based on several factors besides sun elevation such as night length, wind conditions, and body condition (Sjöberg et al. 2017). Therefore, we fit cubic spline functions to reflectivity data for each night and interpolated reflectivity to the time of maximum increase in reflectivity (i.e., when most birds were taking off each evening). This interpolation was done using *w2birddensity*, a program developed in part by the Aeroecology Program at the University of Delaware using the Warning Decision Support System – Integrated Information (WDSS-II) which was jointly developed by the National Severe Storms Laboratory (NOAA) and the University of Oklahoma. This program outputs a measure of interpolated bird densities for times of peak exodus each night, using algorithms developed by Buler and Diehl (2009) and Buler et al. (2012) to adjust for range and spatiotemporal sun elevation angle biases. To ensure that all remaining nights following this analysis were suitable for final analysis, we plotted a vertical profile of reflectivity (VPR) for each night. If most reflectivity occurred below 500m, we assumed these nights were dominated by birds, as reflectivity occurring above this threshold may be indicative of precipitation.

To summarize data, we used a regression on order statistics (ROS) approach to estimate summary statistics for multiply censored data (Buler and Dawson 2014), using R package NADA

version 1.6-1 (Lee 2017). Following Buler and Dawson's (2014) methodology, minimum observed reflectivity values among sampling volumes at a given range were used to determine range-specific censoring limit values in the ROS algorithm for each sampling day. The ROS algorithm outputs summarized data containing estimates of arithmetic mean reflectivity and coefficient of variation for each sample volume. We used arithmetic mean reflectivity as our dependent variable in both spring and autumn, as this is a more appropriate approximation of the total number of migrating birds within a season, while the geometric mean is related to the mean daily stopover intensity (Buler and Dawson 2014).

3.2.2 Land cover and socioeconomic covariates

Distribution of migratory birds during stopover is often driven by the landscape through which they are migrating (Buler et al. 2007). Thus, we utilized land cover information from the National Land Cover Dataset (NLCD 2011; Homer et al. 2015) as explanatory variables in our dataset. First, a basegrid using United States Census Bureau block groups as the cell size was created for Indiana using ArcMap version 10.6. NLCD variables were reclassified into this basegrid using the spatial join function, and the proportion of each landcover type in each cell was quantified. We counted NLCD categories 41 (deciduous forest), 42 (evergreen forest), 43 (mixed forest), and 90 (woody wetlands) as *forest* habitats. All developed categories (21-24) were considered *urban*, and categories 81 (pasture/hay) and 82 (cultivated crops) were considered *agriculture*. These three categories accounted for over 95% of the total area in Indiana. We also included tree canopy cover and impervious surface area (ISA) as covariates in our data (Coulston et al. 2012, Yang et al. 2018), as these have been identified in several studies as predictors of bird abundance (Homayoun and Blair 2016, Evans et al. 2018, Archer et al. 2019).

Finally, ALAN has been recently identified as a driving factor for migratory bird stopover distributions (La Sorte et al. 2017, Cabrera-Cruz et al. 2018, McLaren et al. 2018). Following the methodology of Cabrera-Cruz et al. (2018), we used mean annual radiance from composited nighttime images from the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB), taken by the Suomi National Polar-orbiting Partnership (NPP) satellite in 2015. The data, provided by NOAA and the National Geophysical Data Center (NOAA/NGDC 2019), are available in three products, with varying levels of filtering. We chose the annual composite “vcm-orm-ntl” product, which has had clouds masked, outliers and ephemeral lights removed, and background or moonlight reflections set to zero. Thus, this product leaves primarily electrical

sources of ALAN. Radiance values, measured in nanoWatts per square centimeter per steradian ($\text{nW}/\text{cm}^2/\text{sr}$) and multiplied by $1\text{E}9$, were \log_{10} -transformed before analysis, adding 1 to preserve all values (Cabrera-Cruz et al. 2018). We also measured the geodesic distance to areas of bright light, classified as areas with a digital number >55 , where this number is a measure of nocturnal brightness within each pixel on a scale of 0 to 63 (Cabrera-Cruz et al. 2019).

Socioeconomic variables were obtained from the American Community Survey (ACS), a product of the United States Census Bureau (USCB). This survey randomly samples addresses across the United States, producing information for 1- and 5-year periods (USCB 2017). In this project, we used the 5-year estimates from 2013-2017, as these are calculated for all geographic areas at the block group scale, the smallest geographic unit used by the Census Bureau. Data were downloaded using American FactFinder (<https://factfinder.census.gov>). We selected five ACS variables for use in explaining migratory bird distributions in Indiana. Total population was selected as an estimate of human abundance across the state and converted into a measure of density by calculating persons per square kilometer, as block groups are variable in size (mean area = 19.6 km^2). One study in Australia found that socioeconomic factors such as age of a neighborhood and housing unit value influenced vegetation density (Luck et al. 2009). Thus, we also selected three variables related to housing: median value of owner-occupied housing units (HUs), the median year a structure was built, and the median number of rooms in HUs, to quantify information related to value, age, and size of HUs. Housing units are defined by the ACS as “a house, an apartment, a mobile home, a group of rooms or a single room that is occupied (or, if vacant, intended for occupancy) as separate living quarters” (USCB 2017). Finally, we selected median household income as an additional explanatory variable; very few studies have explored the relationship between socioeconomic status and migratory bird abundances.

We used the block group as the final spatial scale for analysis, as this was the coarsest resolution of all datasets. All variables were reclassified into this spatial scale using the *spatial join* function in ArcGIS Pro version 2.3. In total, we used approximately 2,100 individual block groups sampling over $30,000 \text{ km}^2$, just over 30% of Indiana’s total area. All socioeconomic variables were standardized with a mean of zero and standard deviation of 1 to lessen variation due to scales on which variables were quantified (i.e., income with a range of 5,789 to 250,000 USD and number of rooms with a range of 2.6 to 9).

3.2.3 Statistical analysis

In summary, we measured twelve total covariates: proportion of forest, urban, and agriculture land cover types, tree canopy cover, impervious surface area (ISA), log-transformed ALAN, distance to bright lights, human population density, median HU value, median year HUs were built, median number of rooms in HUs, and median household income. We also included distance from radar to control for any additional spatial variation and range bias unaccounted for by other variables on a landscape scale. All thirteen variables were measured at the U.S. Census block group spatial scale (Figure 3.1); summary statistics for these variables are presented in Table 3.1. To assess the degree to which these covariates were correlated, we quantified Pearson's r correlation coefficients between all covariates and selectively removed variables with $r > |0.75|$ (Table 3.2). Through this process we removed proportion of developed land cover, proportion of forest land cover, log-transformed ALAN, and median HU value from consideration in our final models predicting migratory bird densities (arithmetic mean reflectivity) during spring and autumn migration. This left us with nine explanatory variables representing habitat (proportion of agricultural land cover, tree canopy cover, and impervious surface area), socioeconomics (standardized human population density, median year HUs were built, median number of rooms in HUs, and median household income), distance to bright lights at night, and distance from radars as a way to control for bias in data. We also removed outliers, considered as census blocks where average reflectivity was $>50 \text{ cm}^2 \text{ ha}^{-1}$ ($n_{\text{spring}} = 4$, $n_{\text{autumn}} = 5$).

Boosted regression trees (BRTs), additive regression models where individual terms are simple fitted trees, have several advantages in ecological studies, particularly their ability to fit complex or nonlinear relationships and automatically estimate interactions between predictors (Elith et al. 2008). The tree complexity of the model specifies the number of terms in an interaction, the learning rate determines the contribution of each tree to the model, and the bag fraction specifies the proportion of data randomly selected at each iteration of the model (Elith et al. 2008). To find the optimal levels for these parameters, we used the train function in R package *caret* (Kuhn et al. 2019), iteratively finding the best model using a series of increasingly narrow tuning parameters. In spring, our best model based on an R^2 metric used a tree complexity of 7, learning rate of 0.004, a bag fraction of 0.5, and 1,000 trees. In autumn, the best model used a tree complexity of 7, learning rate of 0.003, bag fraction of 0.5, and 1,000 trees. Both models used a Gaussian error distribution. These analyses were completed in R version 3.6 using packages *dismo* and *gbm* (R Core Team 2019, Hijmans et al. 2017, Greenwell et al. 2019).

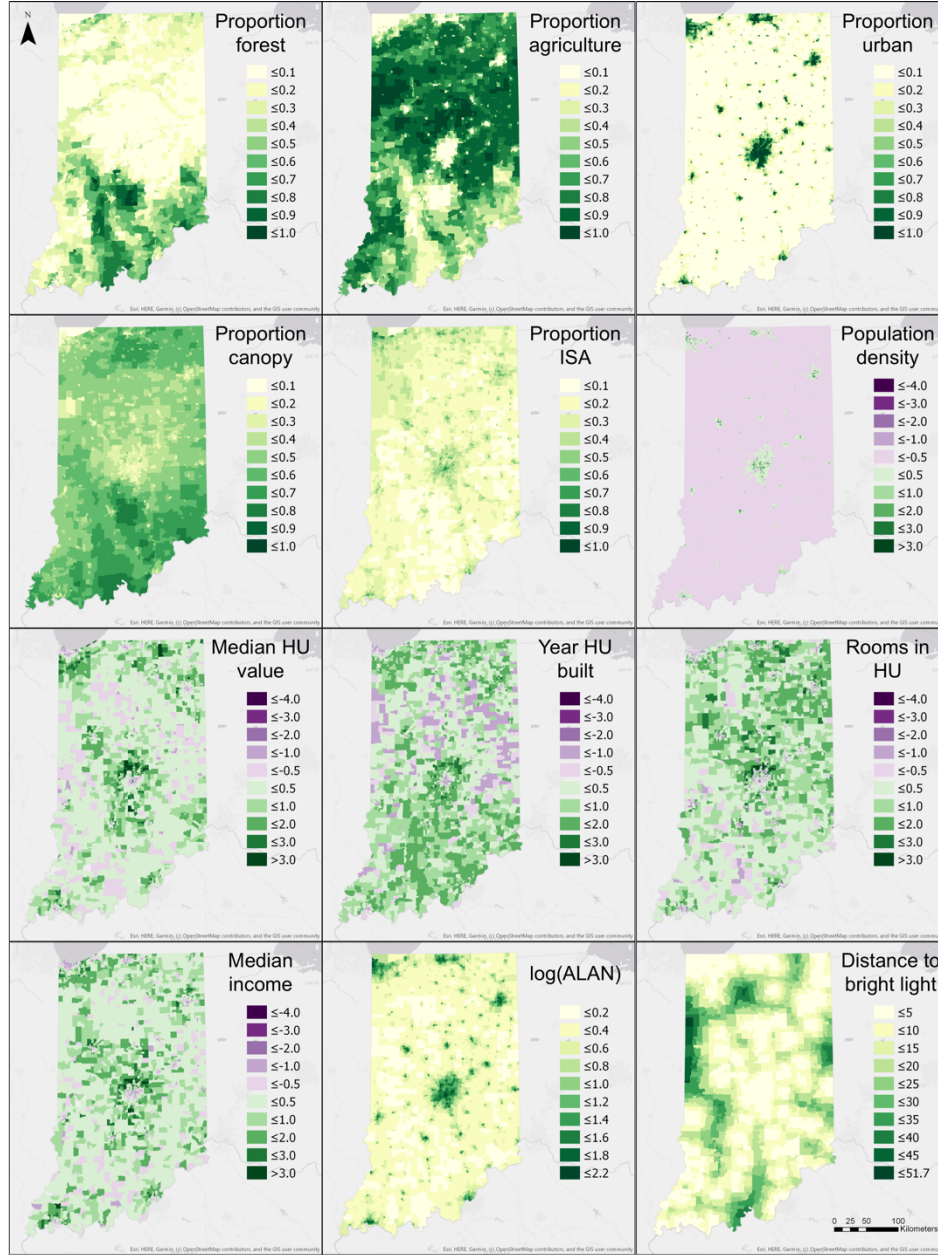


Figure 3.1. Covariates used in boosted regression tree models to explain arithmetic mean reflectivity, a measure of bird density, during spring and autumn migration in Indiana, USA, at the United States Census Bureau (USCB) block group scale. Land cover, tree canopy cover, and impervious surface area are derived from the National Land Cover Dataset (NLCD 2011, full citations in text) and shown as proportions of total block group area. Human population density (persons/km²), median housing unit (HU) value, year HU built, rooms in HUs, and median income are derived from the American Community Survey (USCB 2017); these variables were standardized to a mean of zero and standard deviation of 1 and units shown are \pm standard deviations. Log-transformed radiance at night (ALAN) is calculated from VIIRS DNB satellite imagery (NOAA/NGDC 2019). Bright lights are classified as a digital number of >55 , and distance to bright lights displayed in km.

Table 3.1. Descriptive statistics for covariates derived from the American Community Survey (USCB 2017), the VIIRS DNB (NOAA/NGDC 2019), and the National Land Cover Dataset (NLCD 2011).

Covariate	Range (units)	Mean	Standard deviation
Human population density	0 – 8,386 (people/km ²)	847	± 987
Median household income	5,789 – 250,000 (USD)	53,138	± 22,896
Median HU value	10,000 – 898,300 (USD)	122,977	± 63,237
Median year HU built	1939 – 2008*	1967	± 18.1
Median number of rooms in HU	2.6 – 9	5.81	± 0.98
log ALAN	0.125 – 2.182 (log nW/cm ² /sr)	0.975	± 0.53
Proportion forest	0 – 0.935	0.126	± 0.17
Proportion agriculture	0 – 0.949	0.275	± 0.32
Proportion developed	0 – 1.0	0.568	± 0.39
Tree canopy cover (proportion)	0 – 0.8	0.331	± 0.17
Impervious surface area (proportion)	0 – 0.84	0.325	± 0.15
Distance to bright lights (m)	0 – 51,693.6	5,892.5	± 8,558.4
Distance to radars (m)	0 – 242,099.0	82,115.3	± 53,802.6

* 1939 was the oldest year for which data was recorded; all years labeled 1939 also include HUs built before this year.

Table 3.2. Correlations among covariates derived from the American Community Survey (USCB 2017), the VIIRS DNB (NOAA/NGDC 2019), and the National Land Cover Dataset (NLCD 2011). Only correlations of $r > |0.5|$ are shown, and correlations of $r > |0.75|$ are italicized. Log-transformed ALAN, median HU value, proportion of developed, and proportion of forest land cover types were removed from further analysis due to correlations of $r > |0.75|$.

Covariate 1	Covariate 2	Pearson's r
log-transformed ALAN	Distance to bright light	-0.544
<i>log-transformed ALAN</i>	<i>Impervious surface area</i>	<i>0.856</i>
log-transformed ALAN	Human population density	0.721
<i>log-transformed ALAN</i>	<i>Proportion agriculture</i>	<i>-0.835</i>
<i>log-transformed ALAN</i>	<i>Proportion developed</i>	<i>0.940</i>
log-transformed ALAN	Proportion forest	-0.544
<i>log-transformed ALAN</i>	<i>Tree canopy cover</i>	<i>-0.784</i>
Median household income	Median number of rooms	0.734
<i>Median HU value</i>	<i>Median household income</i>	<i>0.782</i>
Median HU value	Median number of rooms	0.561
Median HU value	Median year HU built	0.517
Human population density	Impervious surface area	0.617
Human population density	Proportion agriculture	-0.624
Human population density	Proportion developed	0.727
Human population density	Tree canopy cover	-0.659
Proportion agriculture	Impervious surface area	-0.636
Proportion agriculture	Tree canopy cover	0.556
<i>Proportion developed</i>	<i>Impervious surface area</i>	<i>0.765</i>
<i>Proportion developed</i>	<i>Proportion agriculture</i>	<i>-0.872</i>
Proportion developed	Proportion forest	-0.590
<i>Proportion developed</i>	<i>Tree canopy cover</i>	<i>-0.809</i>
Proportion forest	Impervious surface area	-0.546
<i>Proportion forest</i>	<i>Tree canopy cover</i>	<i>0.764</i>
Tree canopy cover	Impervious surface area	-0.728

3.3 Results

The final BRT model in autumn migration using 2,176 observations and 9 predictors had a mean total deviance of 3.811 and mean cross-validated residual deviance of 3.371 (s.e. = 0.802), explaining 11.5% of the total deviance; the training data correlation was 0.604, and the cross-validation correlation was 0.39 with a standard error of 0.041. For spring migration, the final BRT model using 2,106 observations and 9 predictors had a mean total deviance of 2.607 and mean cross-validated residual deviance of 2.052 (s.e. = 0.653), explaining 21.3% of the total deviance;

the training data correlation was 0.684, and cross-validation correlation was 0.533 with a standard error of 0.044.

In both models, all predictors had non-zero influence, and the three most influential predictors had combined relative influences of greater than 50%. Distance from radars was the most important predictor of migratory bird density in spring and autumn (relative variable influence = 27.5% and 22%, respectively; Figures 3.3-3.4) and was considered a nuisance variable used to control for any remaining range bias in radar data. Several socioeconomic factors were next in importance in describing patterns of migratory bird densities. The size of an HU—median number of rooms—was the second most important predictor in autumn and fifth in spring (relative variable influence = 16.6% and 9.2%, respectively). In autumn, there were two important interactions between HU size and median income and tree canopy cover (Figure 3.5). In spring, there was an interaction between HU size and median income (Figure 3.6). There was a negative relationship between bird density and HU size, such that HUs with fewer rooms predicted the presence of more birds during both spring and autumn migration, particularly at low levels of tree canopy cover and areas of higher income. The median age of HUs at a location also predicted migratory bird density, in that more birds were predicted to be in areas with newer HUs, especially at higher income levels in autumn (Figure 3.5). In addition, household income had a positive relationship with migrating bird density in autumn, and bird density was lowest in areas of low income (0-2 standard deviations below the mean) in spring. Finally, human population density showed a positive relationship with bird density during both spring and autumn, with a peak between 3-4 standard deviations above the mean.

Tree canopy cover was the most important predictor in spring and second most in autumn, after distance from radars (relative variable influence = 16.3% and 15.2%, respectively). There were generally more birds at increased levels of tree canopy, though there was an additional peak at <10% canopy cover. In autumn, there was an important interaction between tree canopy cover and size of an HU, where the most birds were observed in areas that combined low canopy cover and small HUs (Figure 3.5). In spring, impervious surface was an important predictor (relative variable influence = 12.5%), but there was generally a positive trend such that bird density was predicted to be highest at >60% impervious surface (Figure 3.4). Proportion of agriculture within a census block was another important predictor (10.9% in spring and 9.5% in autumn), and showed a negative relationship with bird density. Finally, distance to bright lights at night was one of the

least important predictors (relative variable influence of 4.7% in spring and 3.1% in autumn), but more birds were predicted to occur in areas with nocturnal bright lights, primarily city centers.

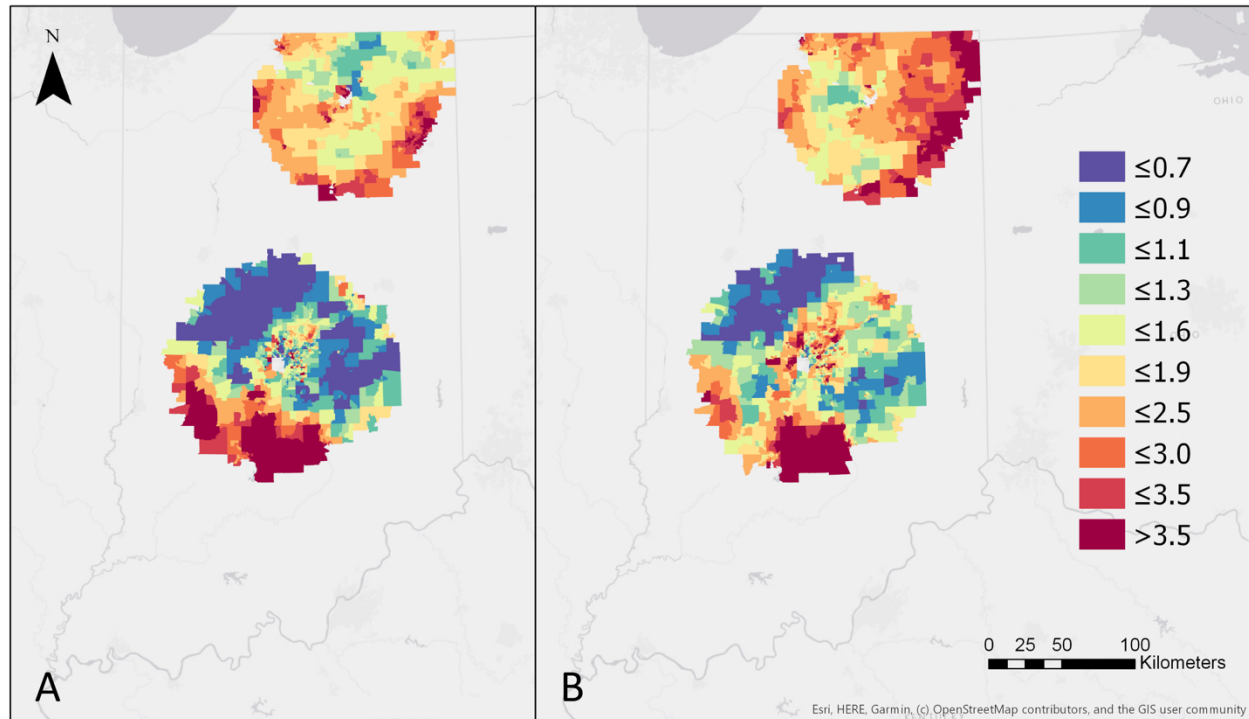


Figure 3.2. NEXRAD-derived measures of migratory bird densities at two radars, southern KIND and northern KIWX, in Indiana, USA, during spring (A) and autumn (B) migration 2015-2017. Reflectivity estimates are shown in units of $\text{cm}^2/\text{hectare}$ and have been averaged within each census block group.

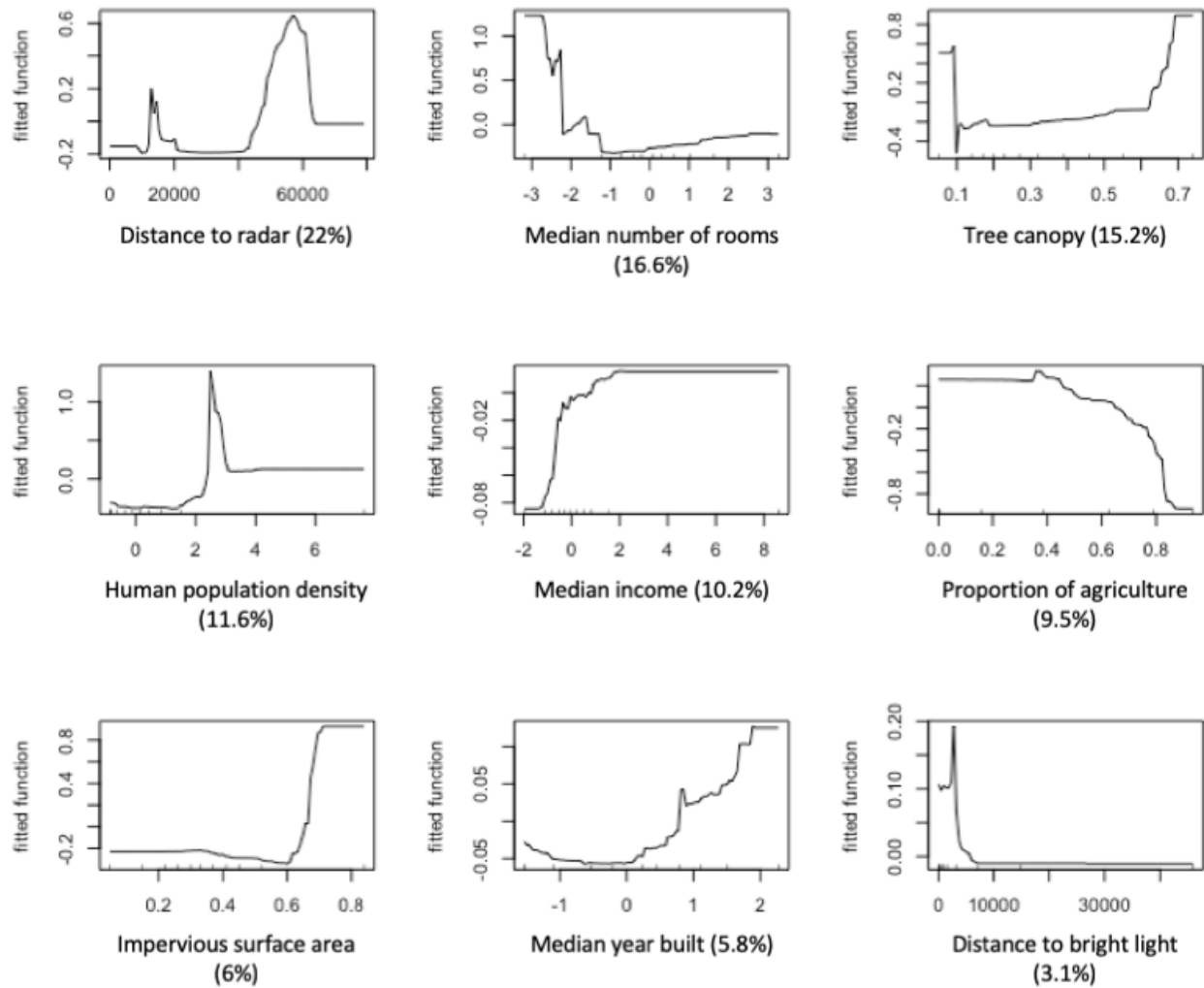


Figure 3.3. Partial dependence plots of variables predicting arithmetic mean reflectivity, a radar-derived measure of migratory bird density, during autumn migration in Indiana, USA in a boosted regression tree model. Unless otherwise noted or listed as proportions, variables have been standardized to a mean of zero and standard deviation of 1. Values in parentheses indicate percent relative influence of each predictor. Y-axes are units of reflectivity ($\text{cm}^2/\text{hectare}$).

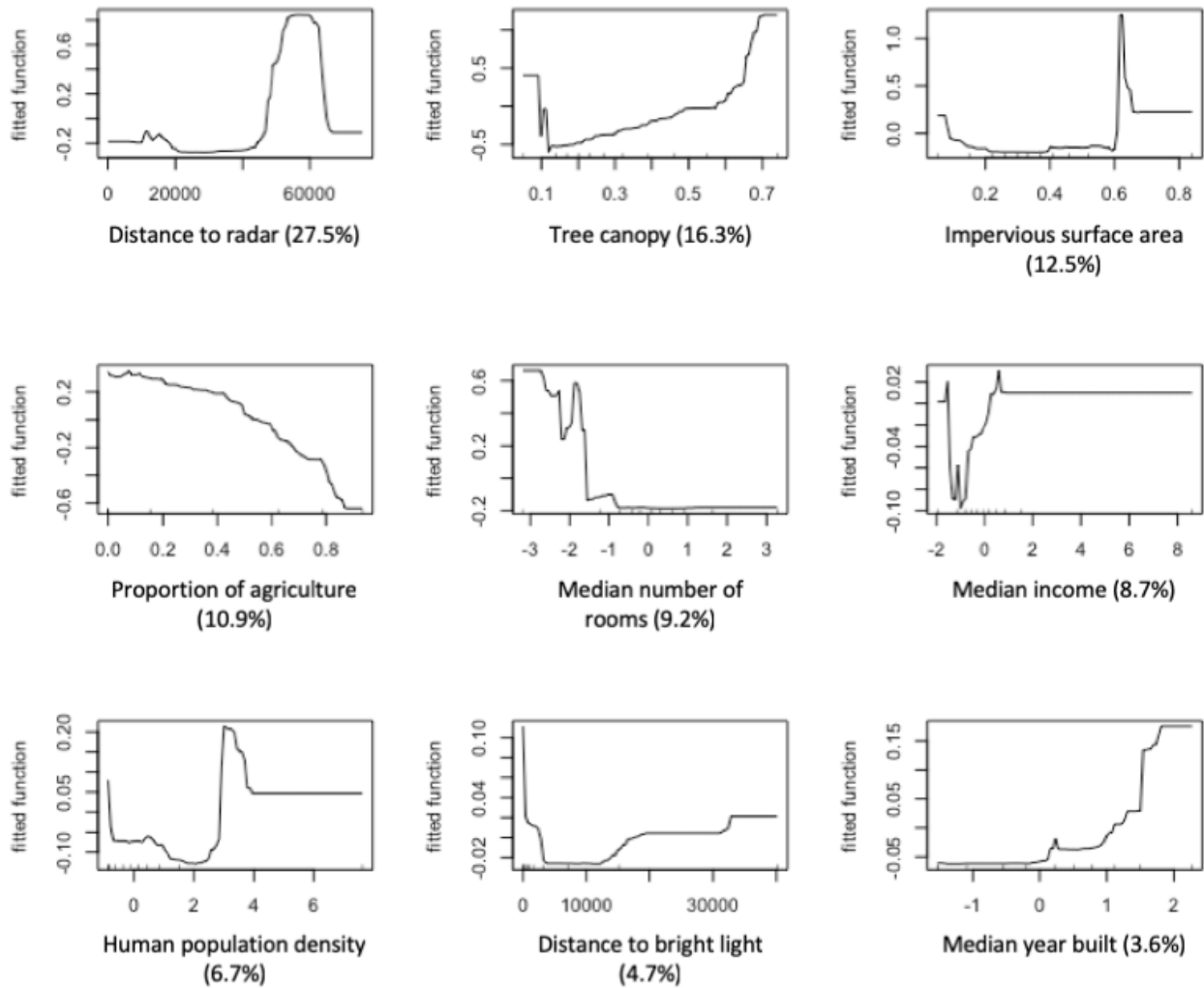


Figure 3.4. Partial dependence plots of variables predicting arithmetic mean reflectivity, a radar-derived measure of migratory bird density, during spring migration in Indiana, USA in a boosted regression tree model. Unless otherwise noted or listed as proportions, variables have been standardized to a mean of zero and standard deviation of 1. Values in parentheses indicate percent relative influence of each predictor. Y-axes are units of reflectivity ($\text{cm}^2/\text{hectare}$).

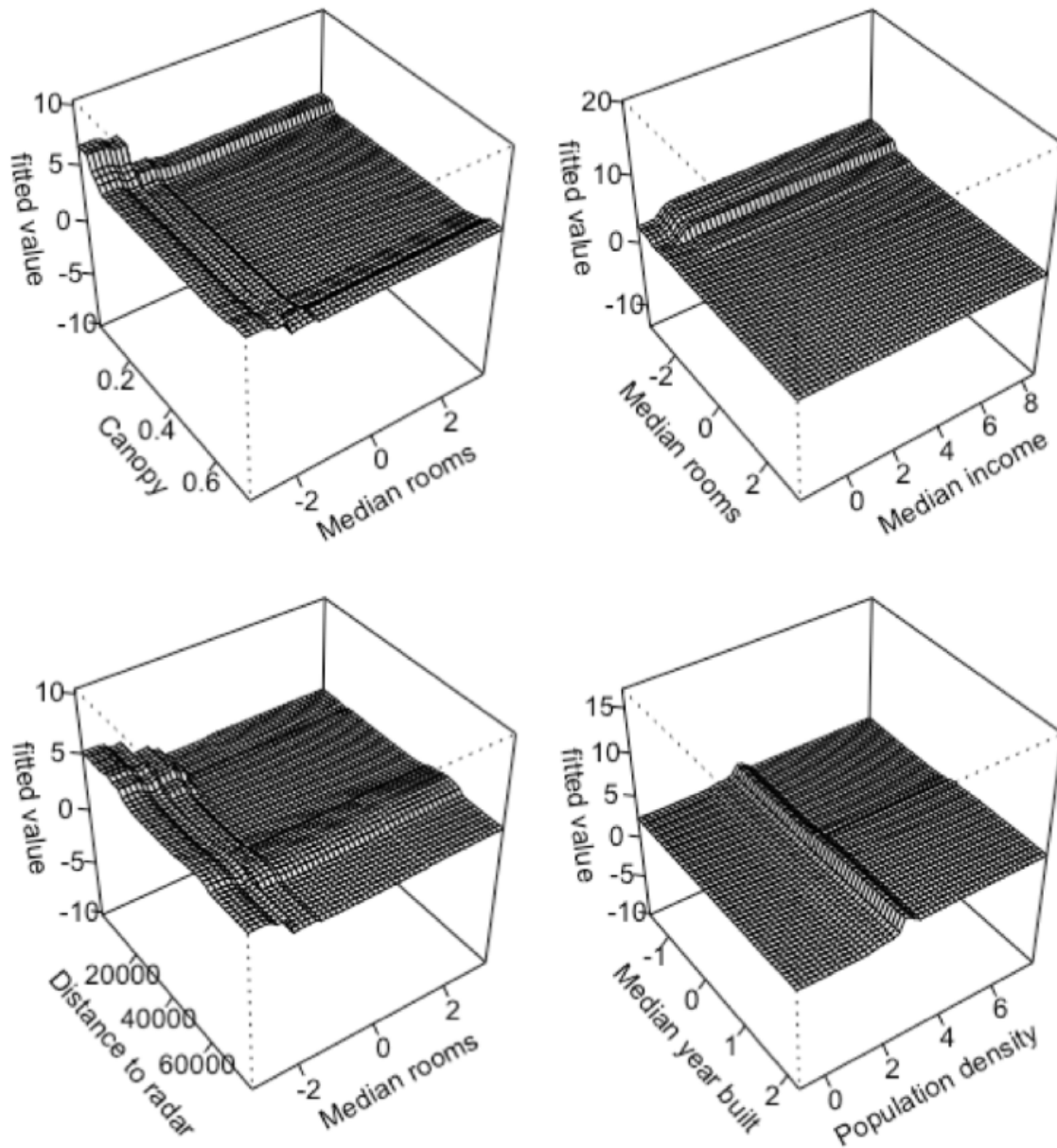


Figure 3.5. Partial dependence plots from a boosted regression tree model for interactions between predictors and influence on arithmetic mean reflectivity, a measure of migratory bird density, during autumn migration in Indiana, USA. Plots are provided in order of decreasing interaction size from top left to bottom right. Distances are provided in meters, median year HUs were built was standardized to a mean of 0 and standard deviation of 1, and all other variables are listed as proportions. Z-axes are units of reflectivity (cm²/hectare).

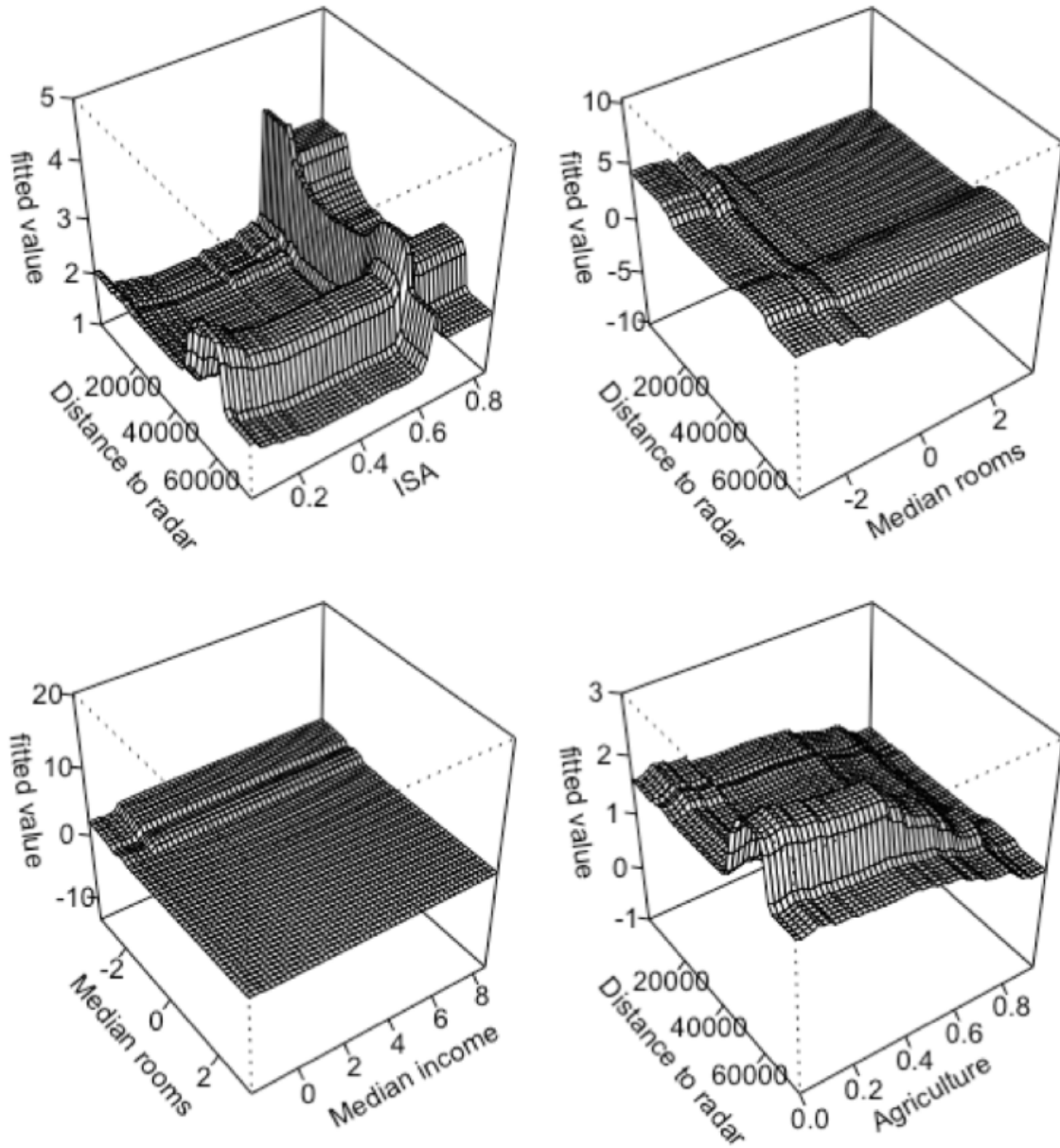


Figure 3.6. Partial dependence plots from a boosted regression tree model for interactions between predictors and influence on arithmetic mean reflectivity, a measure of migratory bird density, during spring migration in Indiana, USA. Plots are provided in order of decreasing interaction size from top left to bottom right. Distances are provided in meters, median number of rooms in HUs and human population density were standardized to a mean of 0 and standard deviation of 1, and all other variables are listed as proportions. Z-axes are units of reflectivity ($\text{cm}^2/\text{hectare}$).

3.4 Discussion

Socioeconomic factors, particularly the size of a housing unit, were among the most important predictors of migratory bird density, especially during autumn migration in Indiana in 2015-2017. While several variables related to land cover characteristics were also important as expected, especially in spring, the high relative importance of U.S. Census-derived data is a novel result highlighting a previously obscure aspect of migratory bird ecology: human socioeconomic status along flyways may influence stopover site selection for migrating birds. More specifically, migratory bird densities were predicted to be highest when median number of rooms in HUs were low, particularly in neighborhoods with above average household incomes in spring. In addition, there were more birds predicted to occur in areas with extreme levels of tree canopy cover (<10% and >75%), high levels of impervious surface (>60%), smaller HUs in autumn, and in areas of higher human population density. These results were unexpected and raise some conservation and management suggestions, addressed below. On a landscape scale, we found that migrating birds are utilizing urbanized and developing habitats during stopover and suggest that future management efforts should aim to incorporate strategies to address factors operating within urban systems for effective conservation.

Migratory bird densities were highest at low distances to bright lights at night, which is consistent with several studies measuring effects of ALAN on migrating birds, though this variable was relatively less important than most (Van Doren et al. 2017, Cabrera-Cruz et al. 2018). A landscape-level effect of ALAN attracting migrating birds into urban and developing habitats could explain the curvilinear trend between bird densities and canopy cover, such that bird densities were higher than expected at <10% canopy cover and at high levels of impervious surface (>60%). Therefore, as birds select stopover sites at a landscape scale within this urban and developing context, finer site-level factors within urban areas such as size and age of HUs, human population density, or household income may become more important.

The high importance of distance from the radars in both spring and autumn (relative variable influence of 27.5% and 22%, respectively) was an unexpected result, suggesting range bias from weather surveillance radars may be present in our data. In part, this was unexpected given the location of both radars in distinct landscapes, one being centered in an urban center of central Indiana (KIND in Indianapolis) and one located in a rural area of northern Indiana (KIWX outside North Webster). Spatially, distance from radars was positively correlated with proportion of forest cover (Pearson's $r = 0.24$) and negatively correlated with proportion of developed land

cover (Pearson's $r = -0.13$), though these correlations were weak. As shown in Figure 3.2, bird densities at the KIWX radar were considerably higher when observed farther away from that radar. Given our observed interaction between distance from radar and agriculture in spring (Figure 3.6), it is possible this variable is describing patterns of spatial variation related to human land use. At both radars, high densities of forest cover are located further from the radar's location, which may further explain these trends at a landscape scale (Buler et al. 2007). In other words, increased amounts of tree canopy or forest cover may operate on a landscape or state-wide scale (Buler et al. 2007, Buler and Dawson 2014), while more local factors such as impervious surface and neighborhood characteristics further serve to influence migratory bird densities. The strength of this predictor, however, suggests that residual range bias may be remaining in these data. Future research could explore these factors at multiple scales, as our research was limited by the spatial resolution of census block groups and limited to two radars within Indiana.

Housing unit size, quantified by the number of rooms in an HU, was significantly and negatively associated with migratory bird density in Indiana, particularly at above-average household income levels, low canopy cover levels, and during autumn migration. The high importance of this predictor during autumn was unexpected, as was the direction of the trend. Housing units, which are specifically defined as separate living quarters as small as a single occupied room or as large as a single-family home, are a unique measure and have not been studied in the context of avian migration to our knowledge. Small HUs are typically apartment units or subunits within stand-alone dwellings, which is consistent with our observed patterns of increased bird densities in areas of higher human population density; these types of HUs may be associated with increased landscaping or the presence of water features that might explain these patterns of bird densities, particularly if these HUs are in wealthier areas.

Median household income was positively associated with migratory bird density in Indiana; one consequence of this pattern was that during migration, middle- to upper-class households would be more likely to see birds around their houses than lower-class households. One study in the Chicago, IL area found that some lower income households were further away from open space with less tree canopy cover (Davis et al. 2012). In addition, lower income households are disproportionately found within cities rather than suburban or rural areas, particularly in the Midwest (Glaeser et al. 2008). Income elasticity of demand for land has been suggested as an explanation for this spatial pattern of income brackets across a landscape; in other words, wealthier households may choose to live on larger lots or in less-dense communities, while poorer

households may not have that option (Glaeser et al. 2008). However, some apartment communities may be an exception to this pattern, as low income apartment complexes often have large areas of green space acting as habitat (B. S. Hardiman, *pers. comm.*).

More specifically, bird migration intensity in autumn was highest above mean income, approximately 53,000 USD in Indiana, and was lowest below mean income levels in spring in a step function-like pattern. Thus, middle-class households would be most likely to see migrating birds during stopover around their houses. This raises concerns of environmental justice within Indiana: low income households, which may already experience lower biodiversity and less green space (Davis et al. 2012), have fewer opportunities to see migrating birds on stopover. If a conservation ethic can be jumpstarted with stories of migration (Hutto 2000) and a myriad of benefits come from being in nature (Dinnie et al. 2013), it is concerning that lower income households may not have access to these benefits and their ability to develop a conservation ethic is restricted (Dunn et al. 2006). The phenomenon of bird migration should be accessible to every person, and development of a positive attitude towards conservation not limited by socioeconomic status.

Increased human population density was also associated with higher bird densities during migration in Indiana, primarily in newer neighborhoods in autumn. This was unexpected, as areas of high human population density are found in urbanized habitats in Indiana (Figure 3.1). These results could be due to several factors, such as ALAN drawing birds into urbanized habitats, agricultural habitats having low human population densities, or the presence of landscaping such as large trees and water features in high human population-dense areas such as university campuses. Proximity to bright light had a non-zero influence on bird density in our models, such that there were higher bird densities at low distances to bright light, so ALAN is likely responsible for a portion of our observed trends. Additionally, agriculture was negatively associated with migratory bird densities, which corroborates our findings of higher bird densities in areas of higher human population densities. Supplemental feeding of birds in areas of higher human population densities could also be an explanatory factor in this pattern (Tryjanowski et al. 2015).

While the relationships between neighborhood characteristics measured by socioeconomics and bird densities were stronger than expected, we observed relationships between bird densities and land cover characteristics that are consistent with other studies on stopover ecology. Most birds were predicted to occur at high levels of tree canopy cover, which is consistent with a large body of work highlighting the importance of forested habitats for migrating birds (e.g.,

Mehlman et al. 2005, Buler et al. 2007, Packett and Dunning 2009). In addition, we observed negative relationships between bird densities and amount of agricultural land within census blocks, which is again consistent with other studies (e.g., Buler and Dawson 2014). While these results were consistent with what was expected, we also observed high densities of migrating birds in urban habitats, which raises concerns and implications for conservation and management of declining migratory bird populations.

3.4.1 Conservation and management implications

Our observations of higher densities of migrating birds in urbanized and developing areas lead to several important implications for management and conservation. It is well known that urban areas contain several novel hazards for birds, and migratory species are often disproportionately affected (Loss et al. 2014). High ALAN levels from urban areas are found disproportionately within migratory passages, a finding which has implications for long-term fitness and potential carryover effects on breeding and wintering grounds (Cabrera-Cruz et al. 2018). In addition, ALAN may make birds more susceptible to collisions with built structures (Parkins et al. 2015). Building collisions are responsible for mortality of up to a billion birds per year, and migratory species make up a disproportionately high number of those deaths (Loss et al. 2014, Hager et al. 2017). The surrounding landscape also influences risk of building collisions. Buildings such as university campus apartments containing small HUs and office buildings in areas of low urbanization showed higher mortality rates than single-family houses (Hager et al. 2017). However, building characteristics also drive collision risk: large buildings with higher amounts of glass on façades were responsible for more collisions in a recent study (Riding et al. 2019). Given our results showing higher bird densities in more human population-dense areas, building collision risk is an important consideration for conservationists.

Birds within urban and developing areas are also at risk of predation by human-associated predators such as domestic cats; cat predation is responsible for mortality of up to 4 billion birds per year (Loss et al. 2013). In particular, un-owned cats such as barn cats and strays were responsible for the greatest proportion of mortality and depredated primarily native species, including many migratory species such as American Robins (*Turdus migratorius*), Red-winged Blackbirds (*Agelaius phoeniceus*), and Gray Catbirds (*Dumetella carolinensis*, Loss et al. 2013). Domestic cats have been shown to make bird populations less likely to persist in urban habitats than in fragmented forest patches, possibly creating population sinks (Baker et al. 2005, van

Heezik et al. 2010). Thus, effective conservation of migrating birds must incorporate ways to reduce domestic cat predation to prevent urban stopover sites, particularly those in denser, higher socioeconomic status areas, from becoming more hazardous.

Anthropogenic factors operating in urban landscapes are not always negative or positive, however, and we would emphasize that our results be considered carefully in the greater context of conservation biology. For example, though the urban heat island effect could provide refugia in urban habitats by extending the growing season—thus allowing birds to find fuel where there might otherwise be ecological mismatches between fruit or insect phenology and migration (Alberti 2005, Both et al. 2006, Horton et al. 2019c)—climate change on a global scale has great potential to negatively influence many aspects of migratory bird ecology. Furthermore, we found increased densities of birds in urban habitats, though we have also observed declining densities of birds in urban habitats in recent years (Outcalt et al. *in prep*). Recognizing the limitations of using density as a measure of habitat quality (Van Horne 1983), it is important to acknowledge that urban stopover sites, though used in high densities, may be acting as sinks, rather than sources, for migratory birds. Future research should examine effects of urban stopover site use on fitness throughout the full annual cycle to clarify these aspects.

Given our results, conservation of migrating birds at stopover sites in the Midwest will be greatly benefitted from programs such as Lights Out (National Audubon Society, <https://www.audubon.org/conservation/project/lights-out>), efforts to contain free-ranging domestic cats, and sustainable economic development and improvement, particularly in low-income neighborhoods. Green space in urban areas has been shown to have numerous, wide-ranging benefits (Fuller et al. 2007, Dinnie et al. 2013), but often is unavailable to many groups (Barbosa et al. 2007). Continued emphasis on increasing green spaces and decreasing impervious surfaces in cities, particularly if those green spaces are planted with native species which provide food for birds (Burghardt et al. 2009), will benefit both birds and people. If urban areas can benefit birds in some aspects but not others, management to improve those aspects that benefit birds while mitigating the negative ones can help conserve migratory birds.

3.4.2 Conclusion

The results of this study illustrate an important aspect of migration ecology that has been as of yet poorly understood. While the effects of urbanization as a whole on migration behavior have been extensively studied in recent years, socioeconomic status of given areas within cities

has not. The social sciences are often considered a separate field of study from traditional ecology, but our results suggest this distinction is unnecessary and may be obscuring some important trends. Size and age of HUs, median household income, and human population density were important predictors of migratory bird density during both spring and autumn migration in Indiana, results that have implications for bird conservation, land management, and issues of environmental justice. We suggest future studies continue to explore these trends at finer spatial scales and over broader geographic regions. Interdisciplinary research between social scientists and ecologists benefits both fields and allows researchers to study ecological and societal relationships that may previously have been obscured.

CHAPTER 4. A NOVEL INTEGRATION OF CITIZEN SCIENCE AND WEATHER SURVEILLANCE RADAR TO COUNT BIRDS – A CASE STUDY IN INDIANA

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4.1 Introduction

Migrating birds are among the most well-studied migrating animals and attract the attention of millions of people (Hutto 2000), but are also facing significant population declines in recent decades due to factors such as habitat loss and global climate change (Robbins et al. 1989, Terborgh 1989, Bairlein 2016, Rosenberg et al. 2019). Serving a dual purpose in today's environments, migratory birds both provide valuable ecosystem services (Whelan et al. 2008) and engage the public in conservation initiatives, particularly through birdwatching (Hutto 2000, Sekercioglu 2002). Continued study and conservation of these species is thus important for future preservation of entire ecosystems and public engagement in conservation and the scientific process.

To protect habitats for migratory species more effectively, it is important to understand patterns of habitat use throughout species' full annual cycle (Faaborg et al. 2010, Marra et al. 2015). Migration, though which mobile species access seasonally and spatially transient resources, is a period of disproportionately high mortality for many of those species (Sillett and Holmes 2002, Paxton et al. 2017). Thus, stopover sites that provide fuel and shelter during the migratory period play important roles that resonate throughout a bird's lifetime (Hutto 1998). Quantifying bird densities across a variety of highly used sites during migration is vital for continued conservation and prevention of further declines (Mehlman et al. 2005).

Techniques used to monitor and identify highly used stopover sites are varied, and in recent decades, have expanded to include sources not originally designed for ornithological study of migration ecology. The current network of WSR-88D weather surveillance radars across the United States, also called NEXRAD, has proven to be an invaluable remote sensing tool for studying bird migration. Since the mid-twentieth century, radar has been used to quantify migration phenology, measure density of migrating animals, identify important stopover locations, and even predict bird migration intensities across North America (Gauthreaux 1970, 1971, Diehl

2013, Buler and Dawson 2014, Dokter et al. 2018, Van Doren and Horton 2018). NEXRAD data are freely available and archived since the mid 1990s, allowing for identification of important stopover sites and estimation of density of nocturnally active biomass across broad spatial and temporal scales.

Other emerging tools used for ornithological research are citizen science databases such as eBird. Originally designed by the Cornell Lab of Ornithology as a tool for birdwatchers to record their sightings and for scientists to measure diversity and spatiotemporal species distributions, eBird has since become the world's largest database related to biodiversity that is driven by citizen science (www.eBird.org, Sullivan et al. 2009). With over 100 million bird sightings contributed annually, this resource is becoming another invaluable tool for migration ecologists. It is a semi-structured dataset that allows users to collect data in a checklist format and include measures of effort (La Sorte et al. 2018). These measures of effort can help lessen some variability and error in sampling, and the ability of eBirders to mark submitted checklists as “complete” can remove presence-only data, keeping more scientifically rigorous presence-absence and abundance data (Fletcher et al. 2019). Due to the high number of checklists submitted annually and the data quality control built into the user interface, bird sightings can be used to monitor aspects of migration ecology such as habitat use, abundance, and community composition. One landmark study recently used both eBird and weather surveillance radar to measure how bird body masses and wind patterns shape flight behaviors and strategies across North America (Horton et al. 2018, see also Horton et al. 2019a).

The integration of NEXRAD and eBird, two massive datasets that have each individually contributed much to the field of migration ecology, has only recently been initiated, and much work remains to be done. In particular, validating radar-determined stopover distributions using eBird data is an important and as-of-yet unstudied area. If this validation were possible, we could use eBird descriptions of species assemblages to identify communities utilizing distinct habitats, for example. Assessing the degree to which these datasets corroborate each other will strengthen the findings of research using these methods individually and provide valuable insights for land managers and conservation agencies. Though eBird data are sparsely sampled across space, the wealth of information about community composition is something which radar data, continuously sampled across space and time, are missing. If possible, integration of these two datasets would broaden the scope at which they are individually able to address issues of conservation and management of migratory birds.

Our objective was to assess corroboration between NEXRAD and eBird data, investigating patterns of migratory bird abundance using both datasets within a fragmented forest-agricultural-urban landscape in the Midwestern United States. Indiana, once primarily forested, has been transformed by agriculture and urbanization in the last century (Indiana Department of Natural Resources 2017). Thus, identification of remaining high-use stopover sites is important to maintain sites along a bird's entire migratory pathway (Mehlman et al. 2005). We studied the relationship between eBird and NEXRAD data in this landscape context as a case study, identifying both high-use stopover areas during spring and autumn migration and the degree to which weather surveillance radar data are correlated with eBird-derived observations of nocturnally migrating birds. Our primary hypothesis was that NEXRAD-derived measures of total bird stopover densities and eBird-derived observations of migratory bird abundances counted over a given period are positively correlated with one another, as both techniques measure counts or densities of migrating birds on temporally and spatially explicit scales.

4.2 Methods

4.2.1 Weather surveillance radar

The Weather Surveillance Radar-1988 Doppler (WSR-88D, or NEXRAD) is a national network installed around 1990 and operated by the National Weather Service (National Oceanic and Atmospheric Administration, NOAA) and the U.S. Air Force (Department of Defense). We used two NEXRAD radars operated by NOAA whose surveillance areas cover most of the northern and central portions of Indiana, USA. The KIWX radar in North Webster (41.359°N, 85.700°W) covers much of northern Indiana, while the KIND radar in Indianapolis (39.707°N, 86.280°W) covers almost the entirety of central Indiana. We obtained archived Level II NEXRAD data for both spring and autumn migration at both the KIND and KIWX radars from Amazon Web Services (AWS; <https://s3.amazonaws.com/noaa-nexrad-level2/index.html>). We analyzed data for 6 years spread over an 11-year period in Indiana, minimizing both the amount of radar data to process and inter-annual variation in bird densities. Specifically, we processed data for nights during autumn (September–October) 2005–2006, 2010–2011, and 2015–2016, and spring (April–May) 2006–2007, 2011–2012, and 2016–2017.

NEXRAD surveillance radars operate by emitting electromagnetic pulses and measuring the reflected waves in decibel units (dBZ) of reflectivity, measured within *pulse volumes*, defined as the length of the pulse and opening angle of the radar beam, usually 0.5° or 1° (Crum et al. 1993,

Bruderer 1997a). NEXRAD pulse volumes in our study were of both coarser “legacy” (1 km x 1°; 2005–2007 data) and finer “super-resolution” (250 m x 0.5°; 2010–2017) spatial resolutions. Data are recorded at 5- or 10- minute intervals throughout the day, dependent on precipitation levels (Buler and Dawson 2014). We sampled NEXRAD data at the instant of peak exodus (maximum rate of increase of reflectivity) as migrating birds took off each night, given the *en masse* departure of birds in relation to sun elevation. We filtered NEXRAD data to remove nights contaminated with precipitation ($n = 700$ nights, 47.8% of possible 1,464 nights over the study), nights dominated by insect activity ($n = 91$ nights, 6.2%), beam refraction under certain atmospheric conditions (also called anomalous propagation; $n = 191$ nights, 13.1%), unknown contaminants or lack of data ($n = 66$ nights, 4.5%), pixels of consistent clutter, and radials with extensive beam blockage. We then spatiotemporally interpolated data to the instant of maximum increase for each night in our study (McLaren et al. 2018), and summarized data across each season by year and radar using a regression on order statistics (ROS) for multiply censored data (Buler and Dawson 2014), resulting in estimates of arithmetic mean and coefficient of variation (CV) of vertically integrated reflectivity (VIR). These variables are measures of aggregate bird density aloft at the time of peak exodus nightly in units of $\text{cm}^2 \text{ ha}^{-1}$, as well as the daily variability in bird densities. Full details of radar processing methods are found in Appendix A.

4.2.2 eBird citizen science

While eBird data are often used to obtain spatially and temporally explicit models of distribution and abundance for specific species (Sullivan et al. 2009), our goal was to summarize abundances across all nocturnally migrating species. We used the eBird Basic Dataset, which is the complete set of observations for a given range of dates or locations (eBird Basic Dataset 2017). We downloaded observations from autumn (September–October) 2005–2006, 2010–2011, and 2015–2016, and spring (April–May) 2006–2007, 2011–2012, and 2016–2017 for the state of Indiana; these dates were chosen to align temporally with the aforementioned radar data. There were 796,531 observations submitted in spring and 229,681 in autumn over our study period.

To differentiate species based on life history, we classified all species recorded in Indiana as migratory or non-migratory using Brock’s Birds of Indiana (Brock 2006), supplemented by information from the Birds of North America about incidental or uncommon species (Rodewald 2015). Of 409 species that have occurred in Indiana (Brock 2006), 273 are classified as partial or complete migrants. While most of these species are nocturnal migrants, groups such as raptors,

swallows, and hummingbirds are diurnal migrants only. We thus separated species based on these natural history traits (Brock 2006, Rodewald 2015, JBD, *unpublished data*), and removed species from eBird datasets that were classified as non-migratory resident species ($n = 27$), diurnal migrants ($n = 36$), and domesticated ducks and geese (Table A1). After isolating only nocturnal migrants, we further filtered the data based on county, in order to spatially align eBird and radar data (Figure 4.1).

Our goal was then to measure relative abundance of birds counted by eBirders. We accomplished this by converting observations from the Basic Dataset into an index of abundance using duration (minutes) as a measure of effort. This provided a measure of birds of any given species counted per minute at each location (birds/min). We used minutes instead of distance as time is often used to measure effort in similar studies using sources such as Audubon’s Christmas Bird Count (party-hours, Butcher et al. 1990); in addition, this allowed us to use more data as fewer eBirders report distance travelled, and time may be more accurately recorded than distance estimates. To use eBird data as presence-absence data and not presence-only data (Fletcher et al. 2019), we selected only “complete” checklists—checklists where eBirders mark “yes” in response to the question, “Are you submitting a complete checklist of the birds you were able to identify?” In addition, we also removed all checklists with non-numeric, “X” counts of birds to eliminate bias in reported abundances. All observations that provided no measure of effort, such as historical or incidental records, were also removed.



Figure 4.1. Study area showing approximate spatial coverage of two NEXRAD weather surveillance radar stations (KIND and KIWX) in Indiana, USA, and overlapping counties used to filter eBird citizen science data.

4.2.3 Integration and analysis

Our objective was to assess the degree to which weather surveillance radar data and eBird citizen science counts provide similar relative estimates of bird density during migration and stopover. To achieve this goal, we paired eBird-derived estimates of birds counted per minute with radar-derived estimates of bird density via a 5 km by 5 km grid created across the study areas

within Indiana; this scale was chosen to estimate counts of birds on a landscape scale. eBird and radar points were grouped by season (spring and autumn) and time period (“early”—2005-2007, “mid”—2010-2012, and “late”—2015-2017) to account for variation in number of eBird sightings reported over time and between seasons. We used a final sample size of 37,658 eBird observations (number of birds per minute of a given species) in autumn and 153,913 observations in spring. After processing weather surveillance radar data and removing contaminants, we used a final sample size of 181 nights at the KIND radar and 235 nights at the KIWX radar, 28.4% of the total possible 1,464 nights. The approximately 27,700 km² area sampled by both radars covers 29% of the total land area in Indiana.

After quantifying mean birds counted per minute and mean reflectivity in each 5 km x 5 km grid cell ($n = 5,162$), we used a natural logarithm to transform both measures of relative abundance to normalize the data before analysis. Mean counts with associated standard deviations are shown in Table 4.1. We then used a randomization approach to estimate correlation between eBird and weather radar counts. We calculated Pearson’s r correlation coefficients between eBird and radar counts, then randomized the data 9,999 times to generate a null distribution for test statistics. We then calculated the probability of obtaining our observed test statistic under the null distribution. Spatial analyses and data processing were completed using ArcMap version 10.3, ArcGIS Pro version 2.4, and R software version 3.6.1 (R Core Team 2019).

Table 4.1. Mean number of birds of given species counted by citizen science (eBird, birds per minute) and average densities of migrating birds measured by weather surveillance radar (mean reflectivity, cm² ha⁻¹) around two radar stations in Indiana, USA, during spring and autumn migration in three time periods (early, 2005-2007; middle, 2010-2012; and late, 2015-2017).

Values shown are mean \pm standard deviation.

Period	Season	eBird	Radar
Early	Autumn	2.71 (\pm 2.28)	1.12 (\pm 0.84)
	Spring	3.82 (\pm 4.12)	1.38 (\pm 0.85)
Mid	Autumn	4.34 (\pm 6.54)	0.40 (\pm 0.33)
	Spring	6.40 (\pm 15.01)	1.16 (\pm 1.50)
Late	Autumn	8.27 (\pm 23.42)	0.37 (\pm 0.45)
	Spring	11.27 (\pm 30.15)	0.53 (\pm 0.44)

4.3 Results and discussion

We observed patterns of spatial overlap between locations of eBird sightings and radar-observed hotspots in Indiana during both autumn (Figure 4.2) and spring migration (Figure 4.3). This suggests that birders often select sites rich in migratory bird density, as measured by NEXRAD. However, we did not observe the positive associations hypothesized to exist between the number of birds counted by eBirders and the densities of birds measured by radar in each 5 x 5 km grid cell (Pearson's r range = -0.13 to 0.04; Table 4.2). Despite significant increases in eBird sample sizes over time ($n_{early\ autumn} = 41$, $n_{late\ spring} = 516$; $F_{1,4} = 14.37$, $p < 0.05$), we found no correlation between the number of birds counted by the two tools (Figure 4.4). NEXRAD data showed an apparent decline in densities of migratory birds in our study area between 2005–2017, which is consistent with other studies using radar (Rosenberg et al. 2019), while eBird-derived counts did not change (Figure 4.5).

Given our analytical approach, we were unable to find a positive correlation between eBird citizen science and weather surveillance radar data in terms of the number of birds counted by each, with no observed Pearson's $r > |0.2|$. Despite increases in sample sizes over time and between spring and autumn, the average relative numbers of birds counted by eBird were not similar to the densities of birds measured by radar. Only a few recent studies, to our knowledge, have explicitly integrated eBird counts and weather surveillance radar (Horton et al. 2018, 2019a). These studies utilized spatiotemporal exploratory models (STEM) that estimate probability of species occurrence instead of raw counts, however, and monitored broad-scale migratory patterns across North America rather than specific stopover sites. Thus, our study is one of the first to attempt the integration of eBird counts across all species with weather surveillance radar estimates of bird density during stopover. Despite the lack of strong correlation between counts, we believe these data nonetheless tell an important story.

Each of these “big data” sources, eBird and weather radar, have individually been used in many migration ecology studies. eBird is a semi-structured type of data with high volume of data but few methodological standards (La Sorte et al. 2018), and has been used in several studies of migration to understand habitat associations, changes in behavior due to anthropogenic light at night, and even previously untested concepts such as the relationship between body mass and wind compensation (reviewed in La Sorte et al. 2018; Horton et al. 2018). Weather surveillance radar, which can be considered less structured than eBird due to its continuously collected abundance of data (La Sorte et al. 2018), has been widely used in migration ecology since at least the 1980s and

has provided invaluable information about migratory behavior, important stopover sites, and numbers of migrants during migration (e.g. Horton et al. 2018, Buler and Dawson 2014, Horton et al. 2019a).

The lack of observed overlap in eBird and radar counts of abundance or density could be due to spatial sampling bias. NEXRAD data are collected almost continuously across time and geographic area, while eBirders are more selective in that they often visit sites known or suspected to have high densities of birds. In addition, eBirders exhibit a variety of sampling strategies, such as bird feeder watching from interior rooms, walking trails, or searching a larger area. This variability in sampling coverage, in contrast to the evenly and continuously sampled radar data across each 5x5 km grid cell, could thus contribute to a lack of correlation in number of birds counted. In addition, this sampling bias by eBirders could be due simply to lack of access to some locations, potentially forcing them to select sites used less frequently by migratory birds. Radar data show consistent bird use of large patches of hardwood forests (Buler and Dawson 2014), while eBird checklists are often located near urban areas or places with higher human densities due to ease of access (Sullivan et al. 2009). Our results in particular highlight these spatial discrepancies, as grid cells containing eBird data were often located near urban centers or high-density stopover sites measured by radar (Figures 4.2-4.3).

Our observed discrepancies between eBird and weather radar could also be due to the presence of year-round resident birds or birds that have not yet initiated their migratory journey in eBird checklists. Some abundant species such as the Blue Jay (*Cyanocitta cristata*) or Canada Goose (*Branta canadensis*) have both migratory and resident populations in Indiana; separating these populations is difficult if not impossible given the semi-structured methodologies and volunteer efforts that eBird employs. However, when we tested the removal of those species considered both migratory and year-round residents ($n = 10$ species, $n_{\text{obs}} = 121,641$ in spring and 40,845 in autumn), we still found no correlation between eBird and radar, suggesting this is not contributing to our observed discrepancies (Table A.2). Another possibility for the discrepancies between eBird and radar is the removal of all observations with “X” counts, which are often large flocks too big to count or estimate. It is therefore possible that eBird-derived counts are underestimating true abundances.

Another possible explanation could be due to the variability of quality in eBird data. We did not discriminate based on relative experience of observers in our analyses, but observer skill may influence factors such as species identification or number of species counted (Kelling et al.

2015). Perhaps observer skill also influences the number of birds counted, introducing increased variability into our analyses. Time of year also influences the number of observations recorded in eBird, as we saw over four times as many observations during spring migration than during autumn migration. While we did not observe differences in patterns of correlation or lack thereof between spring and autumn migration, observer bias and skill could have an influence on variability between seasons. It is possible that more experienced birders record observations during autumn migration, given the notorious difficulty of identifying small songbirds in non-breeding plumage.

Finally, recent studies have described the phenomenon of dawn ascent or reorientation, commonly observed over the Great Lakes (Wiedner et al. 1992, Diehl et al. 2003, Archibald et al. 2016, Heist et al. 2018). Migratory animals have also been shown to depart original stopover sites and relocate across the landscape; these landscape-level movements likely allow birds to find more suitable habitat over the course of their stopover (Mills et al. 2011, Taylor et al. 2011). eBird-derived observations of migrating birds are frequently sampled in the morning, while radar-derived measures of birds were sampled just after sunset in our study. However, the displacement of migrating birds across the landscape is often less than 1 km (Mills et al. 2011), making this phenomenon an unlikely explanatory factor for our observed disparities between counts.

In conclusion, we believe these results, though contrary to our expectations, highlight an important aspect of migration ecology. Landbird migration is a complex, global system. eBird and weather radar both describe a portion of this phenomenon, but likely fail to identify the full magnitude and scope individually. Radar data inform ornithologists about the abundance of birds aloft, locations of important stopover sites, and patterns of flight behavior (Buler and Diehl 2009, Buler and Dawson 2014, Dokter et al. 2018, Horton et al. 2018, Rosenberg et al. 2019). eBird, in contrast, provides information about which species are migrating, where migrants intersect with human activity, and life history patterns of migrant species (reviewed in Sullivan et al. 2009, La Sorte et al. 2018). eBird is selective by location and season, but provides information continuously operative weather radar currently is lacking on community composition and structure. In addition, eBird is continuously improving methods of analysis; next-generation spatially and temporally explicit abundance models are now available for many species (Fink et al. 2020), and future research could explore ways to integrate these with weather radar. The use of these two datasets likely complement each other, particularly when identifying important stopover sites, studying species-level patterns, and seeking to inform the public about the fascinating and important phenomenon of bird migration.

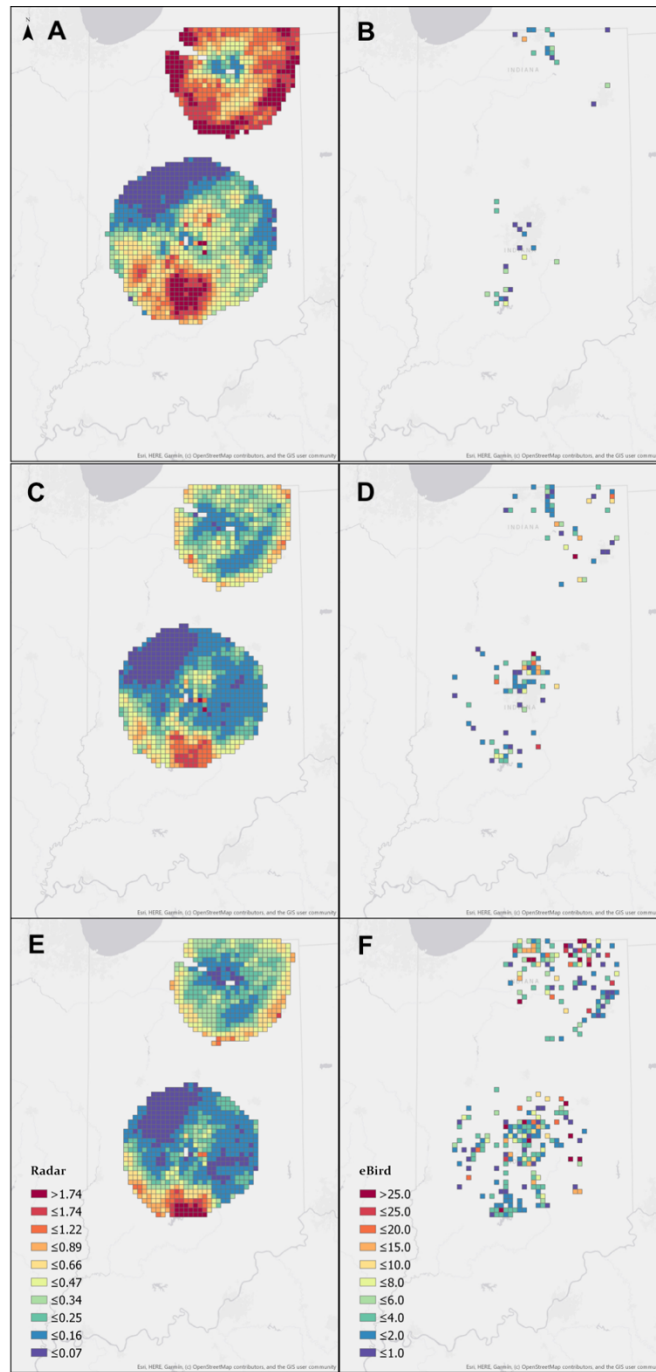


Figure 4.2. Average counts of migrating birds as measured by weather surveillance radar (left, mean reflectivity, $\text{cm}^2 \text{ha}^{-1}$) at two stations and eBird citizen science data (right, birds of a given species counted per minute) during autumn migration in three time periods (early, 2005-2006, A-B; middle, 2010-2011, C-D; and late, 2015-2016, E-F) in Indiana, USA. Values have been averaged within 5 x 5 km grid cells to account for spatial variation.

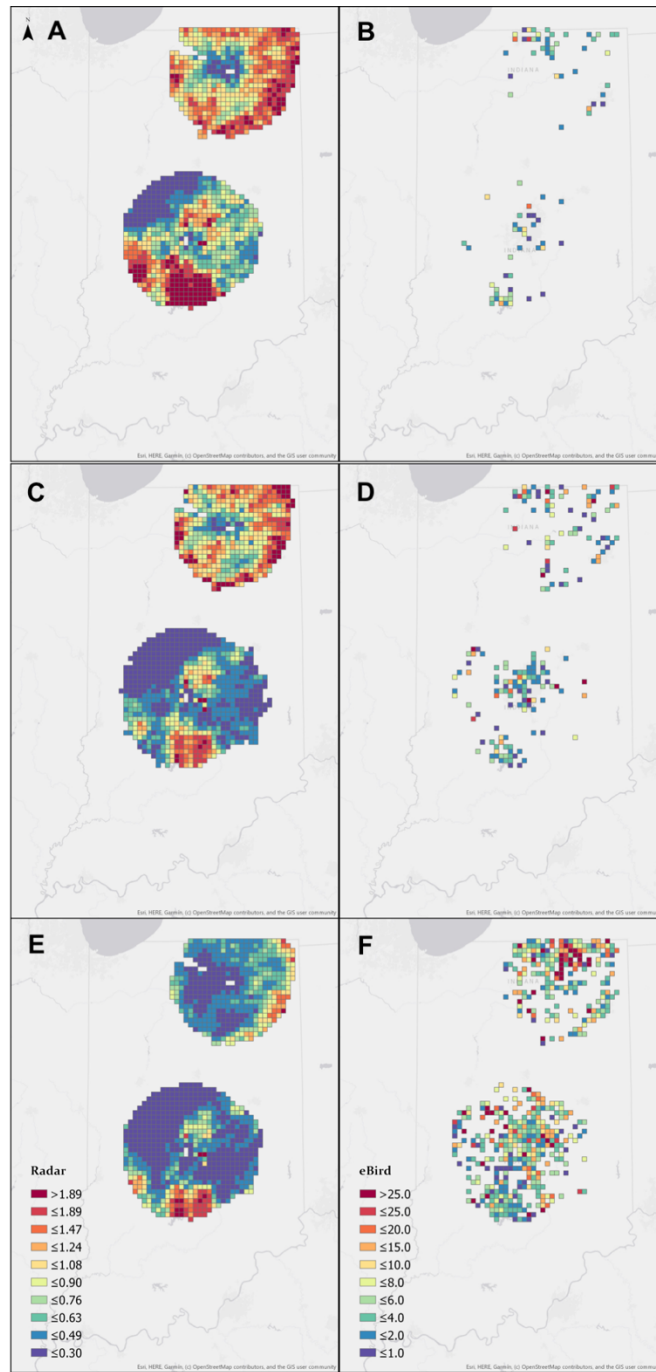


Figure 4.3. Average counts of migrating birds as measured by weather surveillance radar (left, mean reflectivity, $\text{cm}^2 \text{ha}^{-1}$) at two stations and eBird citizen science data (right, birds of a given species counted per minute) during spring migration in three time periods (early, 2006-2007, A-B; middle, 2011-2012, C-D; and late, 2016-2017, E-F) in Indiana, USA. Values have been averaged within 5 x 5 km grid cells to account for spatial variation.

Table 4.2. Correlations between number of birds of given species counted by citizen science (eBird, birds per minute) and densities of migrating birds measured by weather surveillance radar (mean reflectivity, $\text{cm}^2 \text{ha}^{-1}$) around two radar stations in Indiana, USA, during spring and autumn migration in three time periods (early, 2005-2007; middle, 2010-2012; and late, 2015-2017).

Period	Season	Pearson's r	95% confidence interval	T statistic	df	Bootstrap p value
Early	Autumn	0.0205	[-0.289, 0.326]	0.128	39	0.447
	Spring	-0.0793	[-0.284, 0.132]	-0.738	86	0.240
Mid	Autumn	-0.1259	[-0.308, 0.066]	-1.300	105	0.079
	Spring	0.0406	[-0.104, 0.184]	0.550	183	0.161
Late	Autumn	-0.0969	[-0.214, 0.023]	-1.591	267	0.0014
	Spring	-0.0677	[-0.153, 0.019]	-1.539	514	0.0263

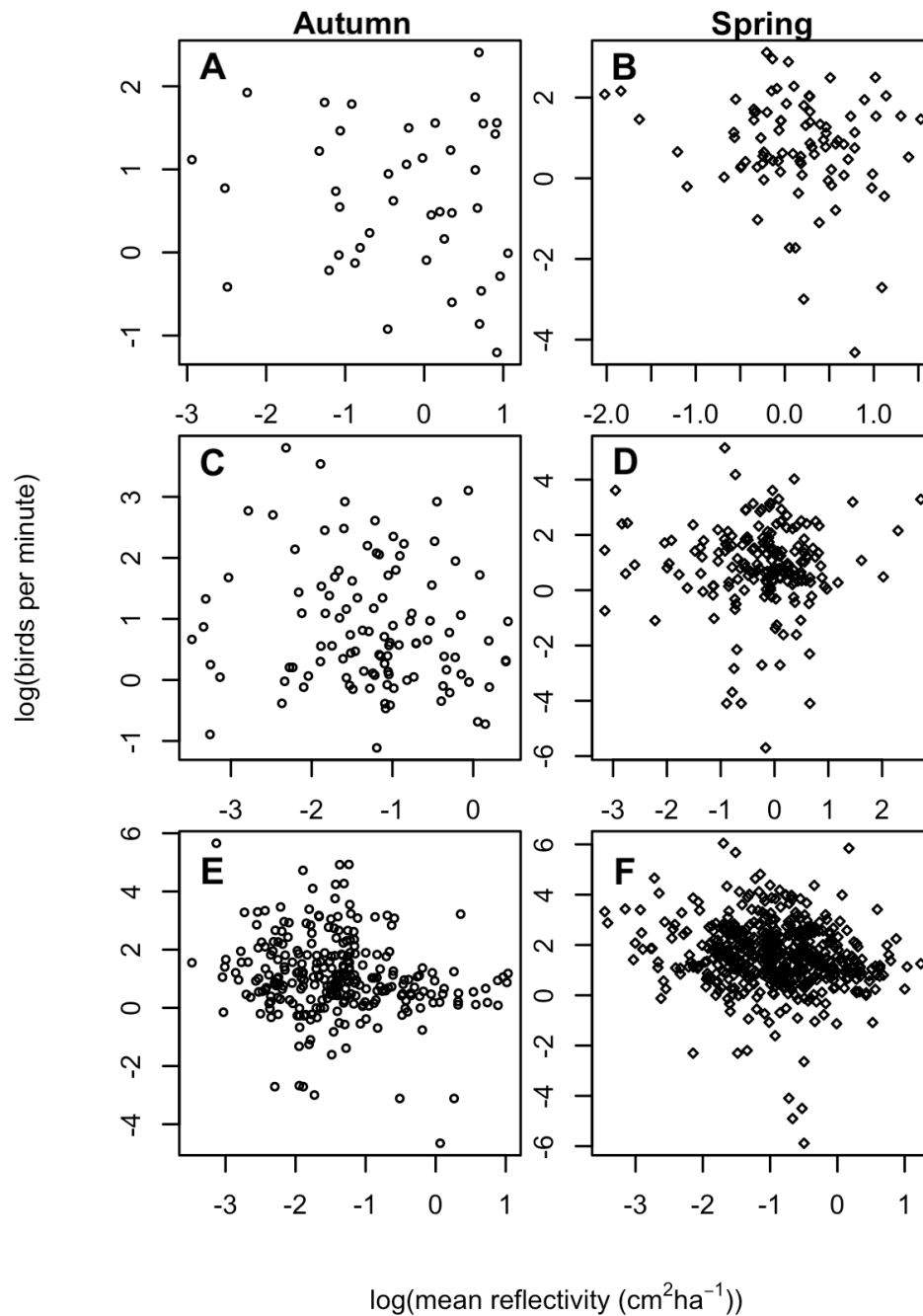


Figure 4.4. Citizen science (eBird)-derived counts of migrating birds (birds of a given species counted per minute) compared to weather surveillance radar measures of bird density (mean reflectivity) during both autumn and spring migration, in three time periods (early, 2005-2007, A-B; middle, 2010-2012, C-D; and late, 2015-2017, E-F) around two radar stations in Indiana, USA. All values have been log-transformed.

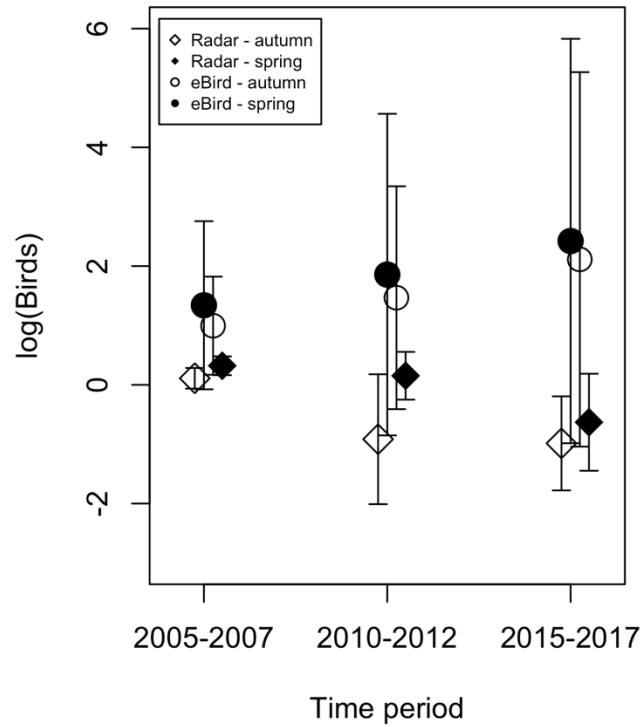


Figure 4.5. Average measures (\pm standard deviation) of bird abundances as measured by both eBird (birds of a given species counted per minute) and weather surveillance radar (mean reflectivity in $\text{cm}^2 \text{ha}^{-1}$) during three time periods in autumn and spring migration around two radar stations in Indiana, USA. Values have been log-transformed.

CHAPTER 5. NO ROOM AT THE INN – SUBURBAN BACKYARDS AND MIGRATORY BIRDS

You’ve probably noticed geese flying back and forth in spring and fall, or robins and bluebirds coming back in the spring to make nests around your home or in your birdhouse. Bird migration is one of the greatest phenomena of the natural world, and these birds in your yard are just a snapshot of it. Yearly, billions of birds migrate between breeding grounds in North America and wintering grounds in the Caribbean, Mexico, and Central and South America, and many fly through Indiana during their journey. Some migratory songbirds weigh no more than a few ounces but fly non-stop across oceans to find food in the winter and nesting sites in the summer. During migration, birds depend on suitable habitats to rest and refuel, just as we need to rest and fill up on long hikes or road trips. These “stopover sites,” as they’re called, can be compared to *full-service hotels* providing plenty of food and shelter, *convenience stores* providing adequate amounts of food and shelter, or *fire escapes* used primarily in emergency situations for shelter, without adequate food levels.

In Indiana, many of the “hotel” sites for forest and grassland birds have been lost over the last century to agriculture or development—the “inn” is smaller now than it used to be, and room in it is limited. However, urban and suburban parks and backyard trees can function as convenience stores or fire escapes, providing important habitat for migratory birds when hotel stopover sites may be limited. There are several ways to manage your backyard for bird conservation, particularly through planting trees and native plants. Numerous species migrate through Indiana every spring and fall, and conservation of these beautiful animals will ensure that you and your family can enjoy them for generations to come (Figure 5.1).



Figure 5.1. Some migratory songbirds in Indiana. Clockwise from upper left, Scarlet Tanager, Baltimore Oriole, Rose-Breasted Grosbeak, and Blackburnian Warbler. Painting courtesy Jessica Outcalt.

5.1 Migration – a global phenomenon

Migration occurs all over the world, between North and South America, Europe and Africa, and even the Arctic and Antarctic for a few extreme long-distance migratory birds. Centuries ago, before modern technology allowed us to see where migratory birds went and came from, some ancient Greek philosophers wondered if birds hibernated in holes in the ground or even transformed into other species. However, we now know that migrants can travel extreme distances, enduring dangerous conditions such as storms or predators (Figure 5.2). In fact, migration is one of the most dangerous times for songbirds, and therefore migratory stopover sites are vitally important for birds' protection and conservation. Most songbirds migrate at night, spending the days feeding or resting in shrubs, trees, or other habitats. Birds depend on insects and fruit for food, and trees for resting spots, during migration, so it is important to set aside areas where they can get these resources.



Figure 5.2. Major migratory pathways, or “flyways,” of North America. Image courtesy Jessica Outcalt, derived from La Sorte et al. 2014.

5.2 Where are the birds going?

Ornithologists have long known that migratory bird populations are declining. If we do nothing, many species are on the road to endangerment or extinction. A study that Purdue University researchers are currently working on suggests that birds migrating through Indiana are still declining, even over the last decade. To make matters worse, birds’ habitat has disappeared in this state. Less than 5 million acres of Indiana’s original 23 million acres of forest remain today, according to the Indiana Department of Natural Resources, though this is an increase from a low point of 1.5 million acres in 1900. Many migrating birds need forest patches, however small, to find insects, fruit, and shelter. In fact, many birds will use suburban trees and small city parks as places to snack on insects and berries before continuing on their journey.

5.3 Think like a bird – creating backyards for migrants

One of the most important aspects of backyard design is the overall structure, because that is what a bird first looks for when it's flying. Try to create several layers within your yard. If you have big trees on your property, that is a good start. Even if you don't have large trees, fill in spaces with smaller trees, shrubs, and grasses. While we might find the typical park layout—big trees with open space in between—visually appealing, birds do not. They want places for shelter, access to water, and a chance to scavenge for berries or insects.

Think like a bird—they just need a few basic things for survival. If you have access to a stream or pond, make that a focal area. It will draw birds in, providing water and insects in the process. If you don't, a birdbath makes a great addition to any yard, as long as you keep it clean so algae doesn't grow. While providing thick cover near feeders and water sources can provide shelter to unwanted predators such as domestic cats, providing water sources in open areas of your yard can attract several species of birds, such as Song Sparrows (Figure 5.3). Keep domestic cats indoors, as cats are among the biggest sources of mortality for birds.



Figure 5.3. Another common backyard bird, the Song Sparrow. Drawing courtesy Jessica Outcalt.

Wildflowers are beautiful and wonderful additions to a backyard, especially in a sunny area. Purple coneflowers, showy goldenrod, or white asters provide nectar for insects, which in turn attracts birds like Eastern Bluebirds, Yellow-rumped Warblers (Figure 5.4), and Indigo

Buntings (Figure 5.5). American Goldfinches and similar species feed on the seeds of many plants like these as well. Native viburnums, serviceberry, elderberry, and winterberry provide plenty of berries throughout the year for fruit-eating birds, such as Swainson's Thrushes or Cedar Waxwings.



Figure 5.4. Yellow-rumped Warbler. Image courtesy Dave Menke, United States Fish and Wildlife Service (public domain image ID: 9F3CE7FD-65B8-D693-7FB334FB2E162290.jpg).



Figure 5.5. Indigo Bunting. Image courtesy Jim Hudgins, United States Fish and Wildlife Service (public domain image ID: 128_8_02_20648363093_16fff232b1_o.jpg).

Finally, native trees will attract a great number of birds. The type of yard you have will determine the trees you select. Red oaks, for example, are versatile trees that can grow quickly in almost any size yard. Shagbark hickories, on the other hand, are slow-growers but are attractive to

a high number of species. Hemlocks and cedars usually prefer shade, while red maples prefer sun. In general, native plants attract birds in large part because they can provide habitat for a larger abundance and diversity of some types of insects than non-native plants do.

In conclusion, a few simple decisions about your backyard can attract birds of all types. Take your available time and resources into account, ask for advice (see suggested resources below, or visit Purdue Extension at www.extension.purdue.edu), and transform your yard into a beautiful wildlife habitat.

5.4 Suggested resources

Branhagen, Alan. 2016. *Native Plants of the Midwest: A Comprehensive Guide to the Best 500 Species for the Garden*. Portland, Oregon: Timber Press. Print.

Cornell Lab of Ornithology. 2019. "Which Birds, Which Plants?" Habitat Network. Web. <<http://content.yardmap.org/learn/which-birds-which-plants/>>.

Dunn, Jon L., and Jonathan Alderfer. 2011. *National Geographic Field Guide to the Birds of North America*, 6th Edition. Washington, D.C.: National Geographic. Print.

Indiana Audubon Society. 2019. "Official IBRC Bird Checklist – Indiana Audubon Society." Web. <<https://indianaaudubon.org/official-ibrc-bird-checklist/>>.

Indiana Wildlife Federation. "Native Plants of Indiana." 2019. <<http://www.indianawildlife.org/wildlife/native-plants/>>.

Miller, Brian K., and Brian J. MacGowan. "Putting a Little Wildlife in Your Backyard This Spring." Department of Forestry and Natural Resources, Purdue University, FNR-247-W. <<https://www.extension.purdue.edu/extmedia/FNR/FNR-247-W.pdf>>.

National Audubon Society. "Birding in Indiana." Audubon. 28 Apr. 2016. Web. <<http://www.audubon.org/news/birding-indiana>>.

-----, "Plants for Birds." 2019. <<http://www.audubon.org/plantsforbirds>>.

Nowak, Mariette, and Peter H. Raven. 2012. *Birdscaping in the Midwest: A Guide to Gardening with Native Plants to Attract Birds*. Madison: University of Wisconsin Press. Print.

Weeks, Sally S., Harmon P. Weeks, Jr., and George R. Parker. 2010. *Native Trees of the Midwest: Identification, Wildlife Value, and Landscaping Use*, 2nd edition. West Lafayette, Ind: Purdue University Press. Print.

CHAPTER 6. CONCLUSION

6.1 Summary of findings

In this dissertation, I used weather surveillance radar data from spring and autumn 2005–2007, 2010–2012, and 2015–2017 to identify 1) trends in migrating bird densities leaving stopover sites and aloft, 2) stopover sites used throughout the migration season, and 3) whether eBird citizen science data from the same periods could be used to corroborate radar estimates of densities within the context of a fragmented forest-agricultural-urban system in Indiana, USA. First, I explored patterns of migrating bird densities leaving stopover sites in three distinct habitat types (forest, urban, and agriculture) and measured densities of birds aloft, seeking to identify whether these densities had changed over the 11-year period. Second, I studied patterns of stopover site use, using both socioeconomics and habitat characteristics to explain these patterns. Finally, I sought to understand the degree to which eBird and weather surveillance radar provide similar metrics of bird densities during migration.

In my first project, I measured bird abundances over time and habitat types and observed approximately 6.8% annual declines in populations of migrating birds leaving stopover sites, and approximately 1.9% annual declines in traffic rates of birds aloft during autumn migration, but not during spring. The declines observed in this study, while somewhat variable between habitats and seasons, are consistent with other studies that have measured significant declines across all major biomes in North America (Rosenberg et al. 2019). Local factors may thus be shaping patterns of population abundances during migration among habitats and between seasons. In contrast, I observed an increase in daily variability in stopover site use over the study period and higher variability within agricultural and urban areas, which is distinct from patterns seen in other landscapes (Buler and Dawson 2014). Stopover sites in these highly altered landscapes in the Midwestern United States are likely small forest patches, isolated woodlots, or urban parks and backyards used as emergency stopover sites or “fire escapes,” which suggests a disproportionately important role of these types of sites for migratory bird conservation (Mehlman et al. 2005, Wintle et al. 2018).

Given the patterns within urban and other altered landscapes observed in my first project, I sought to understand these patterns on a finer scale. In autumn 2015–2016 and spring 2016–2017, I used both land cover information—impervious surface area, tree canopy cover, proportions of

forest, urban, and agriculture land cover types, and relative amount of bright anthropogenic light at night—and socioeconomic factors—human population density, median household income, and age, size, and value of housing units—to explain migratory bird stopover site use in Indiana. Using a series of boosted regression trees, I found that socioeconomic factors were important predictors of migratory bird density during both spring and autumn migration, with as much or more predictive power than other habitat variables. One consequence was that lower income households in Indiana were less likely to see migrating birds near their residences, which raises concerns of environmental justice for low income households and neighborhoods (Hutto 2000, Dunn et al. 2006, Dinnie et al. 2013). I also found patterns consistent with previous studies of increased bird densities at higher proportions of tree canopy cover and lower proportions of agriculture. I believe this study illustrates two important aspects of migration ecology that have been previously understudied. First, characteristics of human neighborhoods, as estimated by socioeconomic variables, were associated with densities of migratory birds in those neighborhoods, which highlights the importance of interdisciplinary work integrating social science and ecology. Second, migrating birds in the Midwestern United States often use urbanized areas as stopover sites and are declining within those habitat types, which highlights the need for improved conservation within urban and developed systems.

Finally, I wished to investigate patterns of migratory bird abundances using both weather surveillance radar and eBird citizen science data, potentially using both datasets to identify species-level patterns of abundances and habitat use during migration in Indiana. After pairing eBird-derived estimates of birds of a given species counted per minute with radar-derived estimates of bird densities across my study area, I observed patterns of spatial overlap between locations of eBird sightings and radar-observed hotspots of migratory activity. However, I found no correlation between the relative abundances of birds counted by either dataset. This could be due to variation in sampling coverage between the methods, in that radar data are collected continuously across an entire area while eBirders are selective, typically visiting sites with known or suspected high densities of birds and recording sightings more frequently in spring than autumn, or to other potential biological mechanisms. These results, while different from what was expected, suggest that eBird and weather surveillance radar are complementary datasets, each best suited for answering different types of research questions.

6.2 Implications

On a global and continental scale, the loss of migratory birds will have cascading effects throughout the ecosystems in which they exist. Migratory birds provide many valuable ecosystem services, ranging from predation and scavenging to seed dispersal and pest consumption (Whelan et al. 2008). In addition, migrating birds link spatially and temporally distant processes and fluxes, and are important economically and socially to humans (Sekercioglu 2002, Whelan et al. 2008). The population declines seen on continental scales, and to a lesser extent within urban systems in Indiana and during autumn migration, will impact many of these ecosystem services.

Identification of stopover sites within the Midwestern United States is important for continued conservation of declining populations of migrating birds, particularly within urban systems. A network of sites along migration pathways, including sites not typically considered for breeding or wintering habitat, must be conserved for effective management throughout the full annual cycle (Mehlman et al. 2005). My work suggests that urban neighborhoods and small habitat patches within the Midwestern United States may be disproportionately important for migrating birds and effective management of these species during migration should target private landowners and city managers.

eBird and weather surveillance radar, rather than being interchangeable tools for counting birds, are complementary sources for understanding different aspects of migration ecology. The successful integration of these two sources has been accomplished on a continental scale (Horton et al. 2018, 2019). However, my work on a local scale suggests eBird and weather surveillance radar may only be correlated in terms of their ability to identify stopover sites, and not necessarily their ability to count densities of migrating birds. One primary strength of eBird citizen science is the ability to map occurrences of specific species across space and time, while a primary strength of weather surveillance radar is the ability to track densities of migrating birds across space and time. Currently, ornithologists are able to integrate the two on a continental scale, which will continue to provide important insights into migration ecology of both individual species and migrating birds as a whole.

6.3 Future research possibilities

Future research should continue to explore methods to integrate weather surveillance radar and eBird citizen science, particularly on a local scale in addition to continental scales (Horton et al. 2018). Weather surveillance radar has been able to provide numerous important insights about

migration, such as how bird populations are changing within distinct habitat types across time. eBird, if integration with radar on a local scale were possible, could identify specific communities of birds and how populations are changing over time and space on a species-specific level. Given that eBird and weather surveillance radar data are both freely accessible and remotely sensed, the scientific community could benefit greatly from the wealth of inexpensive information they provide.

The use of socioeconomics and social science within ecology is a novel and increasingly important field of study. My work using data derived from the U. S. Census was limited by the relatively large size of many census blocks and inability to track individual species, so future research could continue to explore how bird abundances or biodiversity are related to socioeconomic factors such as household income, human population density, or housing structures and value on a fine scale. In addition, I found that migrating birds used areas within wealthier and often newer neighborhoods in higher densities but was unable to ascertain whether these stopover sites provided adequate refueling potential for migrating birds. Future studies could explore patterns of fuel deposition and food availability within urban areas to ensure that migrating birds are able to refuel efficiently during stopovers in an increasingly urbanized landscape.

6.4 Conservation recommendations

I believe that migratory bird conservation in the United States depends on two things: a top-down approach to conservation via policy-making and legislation based on democratic action and a bottom-up conservation approach through individual motivations and actions. In the remainder of this chapter, I will discuss each of these approaches briefly. I will also provide several practical tools for citizens, landowners, and land managers to effectively conserve migrating birds within this mindset of a bottom-up approach to conservation.

If policies to protect migrating birds often are put in place legislatively in the United States, the true responsibility of policy-making often rests in the hands of the electorate. While scientific evidence about the dangers of habitat loss and climate change continues to mount, conservation is largely achieved through policy actions (Berger 2019). A conservation ethic, whereby the electorate can become motivated to protect and preserve migratory birds, can be jumpstarted in part through seeing and hearing the fascinating stories of migration (Hutto 2000). While the scientific process should remain unbiased in its methodology, perhaps scientific studies can and should focus on “attractiveness” of research to the general public, such as the incredible ability of

birds as small as hummingbirds to fly thousands of miles annually (Hutto 2000). Furthermore, focus should be placed on making this phenomenon accessible and visible to all citizens, not just those with financial resources to travel and go birdwatching. Migration happens in urban backyards as well as exotic locations, and all individuals regardless of income should be able to see and appreciate migratory birds. Urban ecosystems are vitally important to conservation, even if those ecosystems are dominated by relatively common species such as American Robins (*Turdus migratorius*) and Rock Pigeons (*Columba livia*; Dunn et al. 2006).

In addition, actions by individuals on a small scale can have compounding effects to mitigate future avian population declines. Migrating birds, especially in the eastern United States where most land is privately owned, depend on effective land management at the scales of both complex landscapes and individual yards for efficient stopovers. Positive experiences with wildlife and the natural world make people more likely to conserve nature (Dunn et al. 2006). Creation of new habits that support conservation is notoriously difficult; however, providing practical solutions and specific strategies may help catalyze habit formation, leading to long-term conservation action from people who show interest and intention to conserve nature (Hughes 2013). Practical, implementable strategies that make a tangible difference may be difficult to find, but in the remainder of this chapter I aim to provide such strategies for individuals.

Domestic cats are not native to North America and have caused extremely high levels of mortality for avian species including migrating birds (Loss et al. 2013). Across the United States, free-ranging domestic cats have been shown to kill between 1.4-4.0 billion birds and 6.3-22.3 billion mammals annually, making cats likely the greatest source of human-related mortality for these species (Loss et al. 2013). While trap-neuter-return programs are promoted by some as non-lethal methods of feline population control, a combination of approaches is necessary for control, particularly of unowned cats (Slater 2004). Warning systems such as bells or electronic sonic devices have also been shown to reduce but not eliminate predation (Nelson et al. 2005). Individual cat owners can help solve or mitigate this problem, however, by keeping owned cats as indoor pets and choosing to adopt pets carefully and thoughtfully, so that pets are not abandoned or released.

Collisions with built structures have also been a large cause of mortality for migrating birds, and actions to lessen these collisions can help protect populations of birds. While domestic cats depredate between 1.4-4.0 billion birds annually, collisions with buildings and windows kill between 365 and 988 million birds annually; over half of these collisions are at low-rise buildings, and around 44% occur at residences (Loss et al. 2014). While targeting low-rise buildings that kill

proportionately more birds per building can have a large impact on reducing overall mortality, mitigating mortality at individual residences can be beneficial as well (Loss et al. 2014). UV light-reflective stickers or materials on windows, careful placement of feeders, or reduction of vegetation near windows can reduce mortality from window collisions and mitigate risks for birds.

One potential cause of collisions with built structures is attraction to and disorientation from bright lights at night (ALAN). While often these light sources are from entire cities, single light installations have been shown to disorient and subsequently attract birds, increasing their risk of collisions with buildings (Van Doren et al. 2017). Several programs such as BirdCast seek to reduce collisions by turning unnecessary lights off, particularly during periods of high migration intensity (Van Doren and Horton 2018). Reducing light at nighttime, especially during migration seasons in cities within migration passage areas, can mitigate the risk of building collisions (Cabrera-Cruz et al. 2018, Van Doren and Horton 2018).

Particularly in agricultural areas, pesticide use can negatively affect a bird's ability to migrate efficiently. Neonicotinoids, widely used in agriculture, have negative effects on pollinators and migrating birds, reducing their ability to refuel and delays migration (Eng et al. 2019). While many pesticides are used primarily in agriculture, pesticides used in private settings have been shown to have negative impacts on non-target insects such as butterflies and bees (Muratet and Fontaine 2015), which could have cascading effects for insectivorous birds. Using bird friendly insect, pest, or weed control methods, such as avoiding those made with acetamiprid, clothianidin, dinotefuran, imidacloprid, thiacloprid, thiamethoxam, or glyphosate (American Bird Conservancy 2020), can help reduce the negative effects on migrating birds and other susceptible species.

Planting native species can provide nutrient-rich food sources in the form of berries and seeds as well as habitat for other food sources such as arthropods. Nonnative plant species have lower arthropod abundances, which has negative impacts on fecundity of breeding birds (Narango et al. 2018). Fruits of native plant species also provide higher energy resources and are consumed by migrating birds at higher rates than invasive plant species (Smith et al. 2013). Choosing to plant native species in landscaping will thus have noticeable beneficial effects for migrating birds and other wildlife.

Finally, "bird friendly" agriculture is a growing field, pioneered by the coffee industry and continued recently in cattle ranching. While most coffee, especially in Central America, is grown in intensive monocultural systems in full sun, it was traditionally grown under a canopy of shade trees, which can preserve high levels of biodiversity (Perfecto et al. 1996). Consumers purchasing

shade-grown coffee, such as that certified by the Bird Friendly® program from the Smithsonian Institution Migratory Bird Center, can support this biodiversity and habitat protection. In addition, other bird friendly programs have become more popular, such as the National Audubon Society's Conservation Ranching Initiative, which seeks to use regenerative grazing practices on cattle ranches, allowing native grasslands to grow and provide habitat for declining grassland birds (National Audubon Society 2020). Similarly to bird friendly coffee, consumers can purchase beef raised on Audubon-certified bird friendly land. Other bird friendly agriculture techniques in the Midwestern United States include intercropping to cultivate two or more crops in the same field, planting cover crops to promote biodiversity and lessen soil erosion, or enrolling land in the Conservation Reserve Program (USDA) to restore wildlife habitat. Simple actions by consumers can incentivize these “greener” forms of agriculture, shifting the culture to become more bird friendly.

In conclusion, conservation of migrating birds in Indiana is necessary and possible through the actions of individuals. My work has demonstrated the importance of monitoring birds across time and space, using both novel and well-tested methodologies to address issues of migratory bird conservation in the Midwestern United States. Despite the steep declines in populations of migratory birds due to global climate change and habitat loss, individuals can help mitigate these declines and provide beneficial habitat for migrating birds through further education and experiences with nature.

“This quest may be attempted by the weak with as much hope as the strong. Yet such is oft the course of deeds that move the wheels of the world: small hands do them because they must, while the eyes of the great are elsewhere” (Tolkien 1954).

APPENDIX A. RADAR PROCESSING METHODOLOGY

We selected NEXRAD reflectivity data primarily from the 0.5° (i.e., lowest) tilt-angle elevation for final analysis, as our goal was to observe birds immediately after take-off when they are close to the ground. We geo-referenced these data using a fixed basegrid centered on each radar's spatial location with pixels corresponding to super-resolution sample volumes (250 m x 0.5° with a radius of 100 km). For each sample volume, we calculated the amount of water using the National Land Cover Dataset (NLCD 2011; Homer et al. 2015) and mean ground elevation using digital elevation models from the National Map (<http://viewer.nationalmap.gov/basic>), and filtered out sample volumes containing greater than 75% water. Areas with consistent clutter, such as reflectivity from anthropogenic features like large buildings or wind energy farms, were removed by selecting a series of radar scans (>1500 scans) in summers 2006 and 2016, determining the sample volumes with mean reflectivity >30dBZ, and eliminating those areas from further analysis (Buler and Diehl 2009). Radial beams partially blocked by structures close to the radar were also removed from further analysis.

In addition to clutter, other sources of contamination include precipitation, insects, or anomalous propagation (radar beam refraction occurring under certain atmospheric conditions; Buler and Dawson 2014). These factors can confound and obscure bird densities aloft, so we visually screened imagery to remove such contaminated nights from further analysis. Additionally, most insects have significantly slower air speeds than most birds (Larkin 1991), so we were able to distinguish insect-dominated nights from bird-dominated nights by calculating the mean animal air speed during the peak of migration each night, approximately three hours after sunset. We obtained wind speed data from the North American Regional Reanalysis (NARR) project managed by NOAA (Mesinger 2006). Nights dominated by bird activity were separated from nights dominated by insect activity by measuring the horizontal velocity of radar-detected targets, accomplished by measuring the difference between wind velocity and target velocity vectors. Nights with mean animal airspeeds of >5 m/s were considered bird-dominated nights.

To find the instant of peak exodus for each sampling night, we fit a cubic spline to mean reflectivity close to the radar over time, and interpolated reflectivity to the time of maximum increase following McLaren et al. (2018). We performed interpolation using the `w2birddensity` function from the Warning Decision Support System – Integrated Information (WDSS-II), a software program developed jointly by the Aeroecology Program at the University of Delaware,

the National Severe Storms Laboratory (NOAA), and the University of Oklahoma. Using algorithms developed by Buler and Diehl (2009) and Buler et al. (2012) to adjust for range and sun-angle biases, this program outputs a measure of vertically integrated reflectivity (VIR) of aggregate bird density aloft at the time of peak exodus each night.

We summarized data across each season by year and radar using a regression on order statistics (ROS) for multiply censored data (Buler and Dawson 2014) using R software package NADA version 1.6-1 (Lee 2017). Minimum observed reflectivity values among sampling volumes at a given range were used to determine range-specific censoring limit values in the ROS algorithm for each sampling day (Buler and Dawson 2014). The ROS algorithm outputs estimates of arithmetic mean and coefficient of variation (CV) of VIR in units of cm^2/ha (Buler and Dawson 2014) for each sample volume. For final analyses, we removed all sample volumes with consistent clutter, extensive beam blockage, greater than 75% water cover, and >25% of within-season censored sample volumes (or non-detects as classified by the ROS algorithm; Buler and Dawson 2014).

APPENDIX B. LIST OF AVIAN SPECIES OCCURRING IN INDIANA AND SUPPLEMENTAL RESULTS

Table A.1 List of 408 species regularly occurring in Indiana (Brock 2006), breeding category, and classification as migratory or non-migratory. Italicized species (62) were excluded from eBird datasets. In addition, species listed in eBird as “domestic” variations (i.e., domestic ducks and geese) were excluded from analysis.

Common name	Scientific name	Breeding category (Brock 2006)	Migratory? ¹	Reason excluded
Black-bellied Whistling-Duck	<i>Dendrocygna autumnalis</i>	Occasional		
Fulvous Whistling-Duck	<i>Dendrocygna bicolor</i>	Accidental		
Greater White-fronted Goose	<i>Anser albifrons</i>	Winter	*	
Snow Goose	<i>Chen caerulescens</i>	Winter	*	
Ross’s Goose	<i>Chen rossii</i>	Winter	*	
Canada Goose	<i>Branta canadensis</i>	Resident	*	
Cackling Goose	<i>Branta hutchinsii</i>	Winter	*	
Brant	<i>Branta bernicla</i>	Accidental		
Mute Swan	<i>Cygnus olor</i>	Resident		Non-migratory resident
Trumpeter Swan	<i>Cygnus buccinator</i>	Winter	*	
Tundra Swan	<i>Cygnus columbianus</i>	Winter	*	
Wood Duck	<i>Aix sponsa</i>	Summer	*	
Gadwall	<i>Mareca strepera</i>	Winter	*	
Eurasian Wigeon	<i>Mareca penelope</i>	Accidental		
American Wigeon	<i>Anas americana</i>	Migrant	*	
American Black Duck	<i>Anas rubripes</i>	Winter	*	
Mallard	<i>Anas platyrhynchos</i>	Resident	*	
Blue-winged Teal	<i>Anas discors</i>	Migrant	*	
Cinnamon Teal	<i>Anas cyanoptera</i>	Occasional		
Northern Shoveler	<i>Anas clypeata</i>	Migrant	*	
Northern Pintail	<i>Anas acuta</i>	Migrant	*	
Green-winged Teal	<i>Anas carolinensis</i>	Winter	*	
Canvasback	<i>Aythya valisineria</i>	Winter	*	
Redhead	<i>Aythya americana</i>	Migrant	*	
Ring-necked Duck	<i>Aythya collaris</i>	Winter	*	
Greater Scaup	<i>Aythya marila</i>	Migrant	*	
Lesser Scaup	<i>Aythya affinis</i>	Migrant	*	
King Eider	<i>Somateria spectabilis</i>	Accidental		
Harlequin Duck	<i>Histrionicus histrionicus</i>	Occasional		
Surf Scoter	<i>Melanitta perspicillata</i>	Migrant	*	
White-winged Scoter	<i>Melanitta deglandi</i>	Migrant	*	
Black Scoter	<i>Melanitta americana</i>	Migrant	*	
Long-tailed Duck	<i>Clangula hyemalis</i>	Winter	*	
Bufflehead	<i>Bucephala albeola</i>	Winter	*	
Barrow’s Goldeneye	<i>Bucephala islandica</i>	Accidental		
Common Goldeneye	<i>Bucephala clangula</i>	Winter	*	
Hooded Merganser	<i>Lophodytes cucullatus</i>	Summer	*	
Common Merganser	<i>Mergus merganser</i>	Winter	*	
Red-breasted Merganser	<i>Mergus serrator</i>	Migrant	*	

Ruddy Duck	<i>Oxyura jamaicensis</i>	Migrant	*	
Gray Partridge	<i>Perdix perdix</i>	Extirpated		
Ring-necked Pheasant	<i>Phasianus colchicus</i>	Resident		Non-migratory resident
Ruffed Grouse	<i>Bonasa umbellus</i>	Resident		Non-migratory resident
Greater Prairie-Chicken	<i>Tympanuchus cupido</i>	Extirpated		
Wild Turkey	<i>Meleagris gallopavo</i>	Resident		Non-migratory resident
Northern Bobwhite	<i>Colinus virginianus</i>	Resident		Non-migratory resident
Red-throated Loon	<i>Gavia stellate</i>	Migrant	*	
Pacific Loon	<i>Gavia pacifica</i>	Occasional		
Common Loon	<i>Gavia immer</i>	Migrant	*	
Yellow-billed Loon	<i>Gavia adamsii</i>	Accidental		
Pied-billed Grebe	<i>Podilymbus podiceps</i>	Summer	*	
Horned Grebe	<i>Podiceps auritus</i>	Migrant	*	
Red-necked Grebe	<i>Podiceps grisegena</i>	Migrant	*	
Eared Grebe	<i>Podiceps nigricollis</i>	Migrant	*	
Western Grebe	<i>Aechmophorus occidentalis</i>	Migrant	*	
Band-rumped Storm-Petrel	<i>Oceanodroma castro</i>	Accidental		
Northern Gannet	<i>Morus bassanus</i>	Accidental		
American White Pelican	<i>Pelecanus erythrorhynchos</i>	Migrant	*	Diurnal migrant
Brown Pelican	<i>Pelecanus occidentalis</i>	Accidental		
Double-crested Cormorant	<i>Phalacrocorax auritus</i>	Summer	*	
Magnificent Frigatebird	<i>Fregata magnificens</i>	Accidental		
American Bittern	<i>Botaurus lentiginosus</i>	Summer	*	
Least Bittern	<i>Ixobrychus exilis</i>	Migrant	*	
Great Blue Heron	<i>Ardea herodias</i>	Summer	*	
Great Egret	<i>Ardea alba</i>	Summer	*	
Snowy Egret	<i>Egretta thula</i>	Migrant	*	
Tricolored Heron	<i>Egretta tricolor</i>	Occasional		
Little Blue Heron	<i>Egretta caerulea</i>	Summer	*	
Reddish Egret	<i>Egretta rufescens</i>	Accidental		
Cattle Egret	<i>Bubulcus ibis</i>	Migrant	*	
Green Heron	<i>Butorides virescens</i>	Summer	*	
Black-crowned Night-Heron	<i>Nycticorax nycticorax</i>	Summer	*	
Yellow-crowned Night-Heron	<i>Nyctanassa violacea</i>	Summer	*	
White Ibis	<i>Eudocimus albus</i>	Accidental		
Glossy Ibis	<i>Plegadis falcinellus</i>	Accidental		
White-faced Ibis	<i>Plegadis chihi</i>	Occasional		
Wood Stork	<i>Mycteria americana</i>	Occasional		Diurnal migrant
Black Vulture	<i>Coragyps atratus</i>	Resident	*	Diurnal migrant
Turkey Vulture	<i>Cathartes aura</i>	Summer	*	Diurnal migrant
Osprey	<i>Pandion haliaetus</i>	Summer	*	Diurnal migrant
Swallow-tailed Kite	<i>Elanoides forficatus</i>	Occasional		Diurnal migrant
White-tailed Kite	<i>Elanus leucurus</i>	Accidental		Diurnal migrant
Mississippi Kite	<i>Ictinia mississippiensis</i>	Occasional		Diurnal migrant
Bald Eagle	<i>Haliaeetus leucocephalus</i>	Resident	*	Diurnal migrant
Northern Harrier	<i>Circus hudsonius</i>	Winter	*	Diurnal migrant
Sharp-shinned Hawk	<i>Accipiter striatus</i>	Migrant	*	Diurnal migrant
Cooper's Hawk	<i>Accipiter cooperii</i>	Resident	*	Diurnal migrant
Northern Goshawk	<i>Accipiter gentilis</i>	Migrant	*	Diurnal migrant

<i>Red-shouldered Hawk</i>	<i>Buteo lineatus</i>	<i>Resident</i>	*	<i>Diurnal migrant</i>
<i>Broad-winged Hawk</i>	<i>Buteo platypterus</i>	<i>Migrant</i>	*	<i>Diurnal migrant</i>
<i>Swainson's Hawk</i>	<i>Buteo swainsoni</i>	<i>Migrant</i>	*	<i>Diurnal migrant</i>
<i>Red-tailed Hawk</i>	<i>Buteo jamaicensis</i>	<i>Resident</i>	*	<i>Diurnal migrant</i>
<i>Ferruginous Hawk</i>	<i>Buteo regalis</i>	<i>Accidental</i>		<i>Diurnal migrant</i>
<i>Rough-legged Hawk</i>	<i>Buteo lagopus</i>	<i>Winter</i>	*	<i>Diurnal migrant</i>
<i>Golden Eagle</i>	<i>Aquila chrysaetos</i>	<i>Winter</i>	*	<i>Diurnal migrant</i>
<i>Yellow Rail</i>	<i>Coternicops</i>	<i>Migrant</i>	*	
	<i>noveboracensis</i>			
<i>Black Rail</i>	<i>Laterallus jamaicensis</i>	<i>Occasional</i>		
<i>King Rail</i>	<i>Rallus elegans</i>	<i>Summer</i>	*	
<i>Virginia Rail</i>	<i>Rallus limicola</i>	<i>Migrant</i>	*	
<i>Sora</i>	<i>Porzana Carolina</i>	<i>Summer</i>	*	
<i>Purple Gallinule</i>	<i>Porphyrio martinicus</i>	<i>Occasional</i>		
<i>Common Moorhen</i>	<i>Gallinula chloropus</i>	<i>Summer</i>	*	
<i>American Coot</i>	<i>Fulica americana</i>	<i>Migrant</i>	*	
<i>Sandhill Crane</i>	<i>Grus canadensis</i>	<i>Migrant</i>	*	
<i>Common Crane</i>	<i>Grus grus</i>	<i>Accidental</i>		
<i>Whooping Crane</i>	<i>Grus americana</i>	<i>Occasional</i>		
<i>Black-bellied Plover</i>	<i>Pluvialis squatarola</i>	<i>Migrant</i>	*	
<i>American Golden-Plover</i>	<i>Pluvialis dominica</i>	<i>Migrant</i>	*	
<i>Snowy Plover</i>	<i>Charadrius nivosus</i>	<i>Accidental</i>		
<i>Wilson's Plover</i>	<i>Charadrius wilsonia</i>	<i>Accidental</i>		
<i>Semipalmated Plover</i>	<i>Charadrius</i>	<i>Migrant</i>	*	
	<i>semipalmatus</i>			
<i>Piping Plover</i>	<i>Charadrius melodus</i>	<i>Migrant</i>	*	
<i>Killdeer</i>	<i>Charadrius vociferous</i>	<i>Summer</i>	*	
<i>Mountain Plover</i>	<i>Charadrius montanus</i>	<i>Accidental</i>		
<i>Black-necked Stilt</i>	<i>Himantopus</i>	<i>Summer</i>	*	
	<i>mexicanus</i>			
<i>American Avocet</i>	<i>Recurvirostra</i>	<i>Migrant</i>	*	
	<i>americana</i>			
<i>Greater Yellowlegs</i>	<i>Tringa melanoleuca</i>	<i>Migrant</i>	*	
<i>Lesser Yellowlegs</i>	<i>Tringa flavipes</i>	<i>Migrant</i>	*	
<i>Solitary Sandpiper</i>	<i>Tringa solitaria</i>	<i>Migrant</i>	*	
<i>Willet</i>	<i>Tringa semipalmata</i>	<i>Migrant</i>	*	
<i>Spotted Sandpiper</i>	<i>Actitis macularius</i>	<i>Summer</i>	*	
<i>Upland Sandpiper</i>	<i>Bartramia longicauda</i>	<i>Summer</i>	*	
<i>Eskimo Curlew</i>	<i>Numenius borealis</i>	<i>Extirpated</i>		
<i>Whimbrel</i>	<i>Numenius phaeopus</i>	<i>Migrant</i>	*	
<i>Long-billed Curlew</i>	<i>Numenius americanus</i>	<i>Accidental</i>		
<i>Hudsonian Godwit</i>	<i>Limosa haemastica</i>	<i>Occasional</i>		
<i>Marbled Godwit</i>	<i>Limosa fedoa</i>	<i>Migrant</i>	*	
<i>Ruddy Turnstone</i>	<i>Arenaria interpres</i>	<i>Migrant</i>	*	
<i>Red Knot</i>	<i>Calidris canutus</i>	<i>Migrant</i>	*	
<i>Sanderling</i>	<i>Calidris alba</i>	<i>Migrant</i>	*	
<i>Semipalmated Sandpiper</i>	<i>Calidris pusilla</i>	<i>Migrant</i>	*	
<i>Western Sandpiper</i>	<i>Calidris mauri</i>	<i>Migrant</i>	*	
<i>Least Sandpiper</i>	<i>Calidris minutilla</i>	<i>Migrant</i>	*	
<i>White-rumped Sandpiper</i>	<i>Calidris fuscicollis</i>	<i>Migrant</i>	*	
<i>Baird's Sandpiper</i>	<i>Calidris bairdii</i>	<i>Migrant</i>	*	
<i>Pectoral Sandpiper</i>	<i>Calidris melanotos</i>	<i>Migrant</i>	*	
<i>Sharp-tailed Sandpiper</i>	<i>Calidris acuminata</i>	<i>Accidental</i>		
<i>Purple Sandpiper</i>	<i>Calidris maritima</i>	<i>Occasional</i>		
<i>Dunlin</i>	<i>Calidris alpina</i>	<i>Migrant</i>	*	
<i>Curlew Sandpiper</i>	<i>Calidris ferruginea</i>	<i>Accidental</i>		

Stilt Sandpiper	<i>Calidris himantopus</i>	Migrant	*
Buff-breasted Sandpiper	<i>Tryngites subruficollis</i>	Migrant	*
Ruff	<i>Philomachus pugnax</i>	Occasional	
Short-billed Dowitcher	<i>Limnodromus griseus</i>	Migrant	*
Long-billed Dowitcher	<i>Limnodromus scolopaceus</i>	Migrant	*
Wilson's Snipe	<i>Gallinago delicata</i>	Migrant	*
American Woodcock	<i>Scolopax minor</i>	Summer	*
Wilson's Phalarope	<i>Phalaropus tricolor</i>	Migrant	*
Red-necked Phalarope	<i>Phalaropus lobatus</i>	Migrant	*
Red Phalarope	<i>Phalaropus fulicarius</i>	Occasional	
Pomarine Jaeger	<i>Stercorarius pomarinus</i>	Migrant	*
Parasitic Jaeger	<i>Stercorarius parasiticus</i>	Migrant	*
Long-tailed Jaeger	<i>Stercorarius longicaudus</i>	Migrant	*
Laughing Gull	<i>Leucophaeus atricilla</i>	Summer	*
Franklin's Gull	<i>Leucophaeus pipixcan</i>	Migrant	*
Little Gull	<i>Hydrocoloeus minutus</i>	Occasional	
Black-headed Gull	<i>Chroicocephalus ridibundus</i>	Occasional	
Bonaparte's Gull	<i>Chroicocephalus philadelphia</i>	Migrant	*
Black-tailed Gull	<i>Larus crassirostris</i>	Accidental	
Mew Gull	<i>Larus canus</i>	Occasional	
Ring-billed Gull	<i>Larus delawarensis</i>	Winter	
California Gull	<i>Larus californicus</i>	Occasional	
Herring Gull	<i>Larus argentatus</i>	Resident	*
Iceland Gull	<i>Larus glaucoides</i>	Winter	*
Lesser Black-backed Gull	<i>Larus fuscus</i>	Winter	*
Slaty-backed Gull	<i>Larus schistisagus</i>	Accidental	
Glaucous Gull	<i>Larus hyperboreus</i>	Occasional	
Great Black-backed Gull	<i>Larus marinus</i>	Winter	*
Kelp Gull	<i>Larus dominicanus</i>	Accidental	
Sabine's Gull	<i>Xema sabini</i>	Occasional	
Black-legged Kittiwake	<i>Rissa tridactyla</i>	Migrant	*
Ross's Gull	<i>Rhodostethia rosea</i>	Accidental	
Gull-billed Tern	<i>Gelochelidon nilotica</i>	Accidental	
Caspian Tern	<i>Hydroprogne caspia</i>	Summer	*
Royal Tern	<i>Thalasseus maximus</i>	Accidental	
Roseate Tern	<i>Sterna dougallii</i>	Accidental	
Common Tern	<i>Sterna hirundo</i>	Migrant	*
Arctic Tern	<i>Sterna paradisaea</i>	Accidental	
Forster's Tern	<i>Sterna forsteri</i>	Migrant	*
Least Tern	<i>Sternula antillarum</i>	Summer	*
Sooty Tern	<i>Onychoprion fuscatus</i>	Accidental	
White-winged Tern	<i>Chlidonias leucopterus</i>	Accidental	
Black Tern	<i>Chlidonias niger</i>	Migrant	*
Black Skimmer	<i>Rynchops niger</i>	Accidental	
Thick-billed Murre	<i>Uria lomvia</i>	Accidental	
Long-billed Murrelet	<i>Brachyramphus perdix</i>	Accidental	
Ancient Murrelet	<i>Synthliboramphus antiquus</i>	Accidental	
Rock Pigeon	<i>Columba livia</i>	Resident	

Non-migratory
resident

Band-tailed Pigeon <i>Eurasian Collared-Dove</i>	<i>Patagioenas fasciata</i> <i>Streptopelia decaocto</i>	Accidental Resident		Non-migratory resident
White-winged Dove <i>Mourning Dove</i>	<i>Zenaida asiatica</i> <i>Zenaida macroura</i>	Occasional Resident		Non-migratory resident
Passenger Pigeon Common Ground Dove Black-billed Cuckoo	<i>Ectopistes migratorius</i> <i>Columbina passerina</i> <i>Coccyzus erythrophthalmus</i>	Extirpated Accidental Summer	*	
Yellow-billed Cuckoo Groove-billed Ani	<i>Coccyzus americanus</i> <i>Crotophaga sulcirostris</i>	Summer Accidental	*	
<i>Barn Owl</i>	<i>Tyto alba</i>	Resident		Non-migratory resident
<i>Eastern Screech-Owl</i>	<i>Megascops asio</i>	Resident		Non-migratory resident
<i>Great Horned Owl</i>	<i>Bubo virginianus</i>	Resident		Non-migratory resident
Snowy Owl Burrowing Owl <i>Barred Owl</i>	<i>Bubo scandiacus</i> <i>Athene cunicularia</i> <i>Strix varia</i>	Winter Accidental Resident		Non-migratory resident
Long-eared Owl Short-eared Owl	<i>Asio otus</i> <i>Asio flammeus</i>	Winter Winter	*	
Northern Saw-whet Owl Common Nighthawk Chuck-will's-widow	<i>Aegolius acadicus</i> <i>Chordeiles minor</i> <i>Antrostomus carolinensis</i>	Winter Summer Summer	* * *	
Whip-poor-will	<i>Caprimulgus vociferous</i>	Summer	*	
<i>Chimney Swift</i> <i>Ruby-throated Hummingbird</i> Rufous Hummingbird Belted Kingfisher Red-headed Woodpecker	<i>Chaetura pelagica</i> <i>Archilochus colubris</i> <i>Selasphorus rufus</i> <i>Megaceryle alcyon</i> <i>Melanerpes erythrocephalus</i>	Summer Summer Occasional Resident Summer	* * *	Diurnal migrant Diurnal migrant Diurnal migrant
<i>Red-bellied Woodpecker</i>	<i>Melanerpes carolinus</i>	Resident		Non-migratory resident
Yellow-bellied Sapsucker <i>Downy Woodpecker</i>	<i>Sphyrapicus varius</i> <i>Picoides pubescens</i>	Migrant Resident	*	Non-migratory resident
<i>Hairy Woodpecker</i>	<i>Leuconotopicus villosus</i>	Resident		Non-migratory resident
Black-backed Woodpecker Northern Flicker <i>Pileated Woodpecker</i>	<i>Picoides arcticus</i> <i>Colaptes auratus</i> <i>Dryocopus pileatus</i>	Accidental Summer Resident	*	Non-migratory resident
<i>American Kestrel</i> <i>Merlin</i> <i>Gyr Falcon</i> <i>Peregrine Falcon</i> <i>Prairie Falcon</i> Monk Parakeet Carolina Parakeet	<i>Falco sparverius</i> <i>Falco columbarius</i> <i>Falco rusticolus</i> <i>Falco peregrinus</i> <i>Falco mexicanus</i> <i>Myiopsitta monachus</i> <i>Conuropsis carolinensis</i>	Migrant Winter Accidental Resident Occasional Extirpated	* * *	Diurnal migrant Diurnal migrant Diurnal migrant Diurnal migrant
Olive-sided Flycatcher	<i>Contopus cooperi</i>	Migrant	*	

Western Wood-Pewee	<i>Contopus sordidulus</i>	Accidental		
Eastern Wood-Pewee	<i>Contopus virens</i>	Summer	*	
Yellow-bellied Flycatcher	<i>Empidonax flaviventris</i>	Migrant	*	
Acadian Flycatcher	<i>Empidonax virescens</i>	Summer	*	
Alder Flycatcher	<i>Empidonax alnorum</i>	Summer	*	
Willow Flycatcher	<i>Empidonax traillii</i>	Summer	*	
Least Flycatcher	<i>Empidonax minimus</i>	Summer	*	
Eastern Phoebe	<i>Sayornis phoebe</i>	Summer	*	
Say's Phoebe	<i>Sayornis saya</i>	Accidental		
Vermillion Flycatcher	<i>Pyrocephalus rubinus</i>	Accidental		
Great Crested Flycatcher	<i>Myiarchus crinitus</i>	Summer	*	
Western Kingbird	<i>Tyrannus verticalis</i>	Occasional		
Eastern Kingbird	<i>Tyrannus tyrannus</i>	Summer	*	
Gray Kingbird	<i>Tyrannus dominicensis</i>	Accidental		
Scissor-tailed Flycatcher	<i>Tyrannus forficatus</i>	Accidental		
Loggerhead Shrike	<i>Lanius ludovicianus</i>	Summer	*	
Northern Shrike	<i>Lanius excubitor</i>	Winter	*	
White-eyed Vireo	<i>Vireo griseus</i>	Summer	*	
Bell's Vireo	<i>Vireo bellii</i>	Summer	*	
Yellow-throated Vireo	<i>Vireo flavifrons</i>	Summer	*	
Blue-headed Vireo	<i>Vireo solitarius</i>	Migrant	*	
Warbling Vireo	<i>Vireo gilvus</i>	Summer	*	
Philadelphia Vireo	<i>Vireo philadelphicus</i>	Migrant	*	
Red-eyed Vireo	<i>Vireo olivaceus</i>	Summer	*	
Blue Jay	<i>Cyanocitta cristata</i>	Migrant	*	
Western Scrub-Jay	<i>Aphelocoma californica</i>	Accidental		
Black-billed Magpie	<i>Pica hudsonia</i>	Accidental		
American Crow	<i>Corvus brachyrhynchos</i>	Migrant		
Fish Crow	<i>Corvus ossifragus</i>	Occasional		
Common Raven	<i>Corvus corax</i>	Accidental		
Horned Lark	<i>Eremophila alpestris</i>	Resident		Non-migratory resident
Purple Martin	<i>Progne subis</i>	Summer	*	Diurnal migrant
Tree Swallow	<i>Tachycineta bicolor</i>	Migrant	*	Diurnal migrant
Northern Rough-winged Swallow	<i>Stelgidopteryx serripennis</i>	Migrant	*	Diurnal migrant
Bank Swallow	<i>Riparia riparia</i>	Summer	*	Diurnal migrant
Cliff Swallow	<i>Petrochelidon pyrrhonata</i>	Summer	*	Diurnal migrant
Cave Swallow	<i>Petrochelidon fulva</i>	Accidental		Diurnal migrant
Barn Swallow	<i>Hirundo rustica</i>	Summer	*	Diurnal migrant
Carolina Chickadee	<i>Poecile carolinensis</i>	Resident		Non-migratory resident
Black-capped Chickadee	<i>Poecile atricapillus</i>	Resident		Non-migratory resident
Boreal Chickadee	<i>Poecile hudsonicus</i>	Accidental		
Tufted Titmouse	<i>Baeolophus bicolor</i>	Resident		Non-migratory resident
Red-breasted Nuthatch	<i>Sitta canadensis</i>	Migrant	*	
White-breasted Nuthatch	<i>Sitta carolinensis</i>	Resident		Non-migratory resident
Brown-headed Nuthatch	<i>Sitta pusilla</i>	Accidental		
Brown Creeper	<i>Certhia americana</i>	Winter	*	
Rock Wren	<i>Salpinctes obsoletus</i>	Accidental		

<i>Carolina Wren</i>	<i>Thryothorus ludovicianus</i>	<i>Resident</i>		<i>Non-migratory resident</i>
Bewick's Wren	<i>Thryomanes bewickii</i>	Accidental		
House Wren	<i>Troglodytes aedon</i>	Summer	*	
Winter Wren	<i>Troglodytes hiemalis</i>	Winter	*	
Sedge Wren	<i>Cistothorus platensis</i>	Summer	*	
Marsh Wren	<i>Cistothorus palustris</i>	Summer	*	
Golden-crowned Kinglet	<i>Regulus satrapa</i>	Winter	*	
Ruby-crowned Kinglet	<i>Regulus calendula</i>	Winter	*	
Blue-gray Gnatcatcher	<i>Polioptila caerulea</i>	Summer	*	
Northern Wheatear	<i>Oenanthe oenanthe</i>	Accidental		
Eastern Bluebird	<i>Sialia sialis</i>	Resident	*	
Mountain Bluebird	<i>Sialia currucoides</i>	Accidental		
Townsend's Solitaire	<i>Myadestes townsendi</i>	Occasional		
Veery	<i>Catharus fuscescens</i>	Summer	*	
Gray-cheeked Thrush	<i>Catharus minimus</i>	Migrant	*	
Swainson's Thrush	<i>Catharus ustulatus</i>	Migrant	*	
Hermit Thrush	<i>Catharus guttatus</i>	Winter	*	
Wood Thrush	<i>Hylocichla mustelina</i>	Summer	*	
American Robin	<i>Turdus migratorius</i>	Resident	*	
Varied Thrush	<i>Ixoreus naevius</i>	Occasional		
Gray Catbird	<i>Dumetella carolinensis</i>	Summer	*	
<i>Northern Mockingbird</i>	<i>Mimus polygottos</i>	<i>Resident</i>		<i>Non-migratory resident</i>
Sage Thrasher	<i>Oreoscoptes montanus</i>	Accidental		
Brown Thrasher	<i>Toxostoma rufum</i>	Summer	*	
<i>European Starling</i>	<i>Sturnus vulgaris</i>	<i>Resident</i>		<i>Non-migratory resident</i>
American Pipit	<i>Anthus rubescens</i>	Winter	*	
Bohemian Waxwing	<i>Bombycilla garrulus</i>	Occasional		
Cedar Waxwing	<i>Bombycilla cedrorum</i>	Resident	*	
McCown's Longspur	<i>Rhynchophanes mccownii</i>	Accidental		
Lapland Longspur	<i>Calcarius lapponicus</i>	Winter	*	
Smith's Longspur	<i>Calcarius pictus</i>	Migrant	*	
Snow Bunting	<i>Plectrophenax nivalis</i>	Winter	*	
Blue-winged Warbler	<i>Vermivora cyanoptera</i>	Summer	*	
Golden-winged Warbler	<i>Vermivora chrysoptera</i>	Migrant	*	
Tennessee Warbler	<i>Leiothlypis peregrine</i>	Migrant	*	
Orange-crowned Warbler	<i>Vermivora celata</i>	Migrant	*	
Nashville Warbler	<i>Leiothlypis ruficapilla</i>	Migrant	*	
Northern Parula	<i>Setophaga americana</i>	Summer	*	
Yellow Warbler	<i>Setophaga petechia</i>	Summer	*	
Chestnut-sided Warbler	<i>Setophaga pensylvanica</i>	Summer	*	
Magnolia Warbler	<i>Setophaga magnolia</i>	Migrant	*	
Cape May Warbler	<i>Setophaga tigrine</i>	Migrant	*	
Black-throated Blue Warbler	<i>Setophaga caerulescens</i>	Migrant	*	
Yellow-rumped Warbler	<i>Setophaga coronate</i>	Migrant	*	
Black-throated Gray Warbler	<i>Setophaga nigrescens</i>	Accidental		
Black-throated Green Warbler	<i>Setophaga virens</i>	Summer	*	
Townsend's Warbler	<i>Setophaga townsendi</i>	Accidental		
Blackburnian Warbler	<i>Setophaga fusca</i>	Migrant	*	

Yellow-throated Warbler	<i>Setophaga dominica</i>	Summer	*
Pine Warbler	<i>Setophaga pinus</i>	Summer	*
Kirtland's Warbler	<i>Setophaga kirtlandii</i>	Accidental	
Prairie Warbler	<i>Setophaga discolor</i>	Summer	*
Palm Warbler	<i>Setophaga palmarum</i>	Migrant	*
Bay-breasted Warbler	<i>Setophaga castanea</i>	Migrant	*
Blackpoll Warbler	<i>Setophaga striata</i>	Migrant	*
Cerulean Warbler	<i>Setophaga cerulean</i>	Summer	*
Black-and-white Warbler	<i>Mniotilta varia</i>	Summer	*
American Redstart	<i>Setophaga ruticilla</i>	Summer	*
Prothonotary Warbler	<i>Protonotaria citrea</i>	Summer	*
Worm-eating Warbler	<i>Helmitheros vermivorum</i>	Summer	*
Swainson's Warbler	<i>Limnithlypis swainsonii</i>	Accidental	
Ovenbird	<i>Seiurus aurocapilla</i>	Summer	*
Northern Waterthrush	<i>Parkesia noveboracensis</i>	Migrant	*
Louisiana Waterthrush	<i>Parkesia motacilla</i>	Summer	*
Kentucky Warbler	<i>Geothlypis formosa</i>	Summer	*
Connecticut Warbler	<i>Oporornis agilis</i>	Migrant	*
Mourning Warbler	<i>Geothlypis philadelphia</i>	Migrant	*
Common Yellowthroat	<i>Geothlypis trichas</i>	Summer	*
Hooded Warbler	<i>Setophaga citrina</i>	Summer	*
Wilson's Warbler	<i>Cardellina pusilla</i>	Migrant	*
Canada Warbler	<i>Cardellina canadensis</i>	Migrant	*
Yellow-breasted Chat	<i>Icteria virens</i>	Summer	*
Summer Tanager	<i>Piranga rubra</i>	Summer	*
Scarlet Tanager	<i>Piranga olivacea</i>	Summer	*
Western Tanager	<i>Piranga ludoviciana</i>	Accidental	
Green-tailed Towhee	<i>Pipilo chlorurus</i>	Accidental	
Spotted Towhee	<i>Pipilo maculatus</i>	Occasional	
Eastern Towhee	<i>Pipilo erythrophthalmus</i>	Summer	*
Cassin's Sparrow	<i>Peucaea cassinii</i>	Accidental	
Bachman's Sparrow	<i>Peucaea aestivalis</i>	Extirpated	
American Tree Sparrow	<i>Spizella arborea</i>	Winter	*
Chipping Sparrow	<i>Spizella passerina</i>	Summer	*
Clay-colored Sparrow	<i>Spizella pallida</i>	Migrant	*
Field Sparrow	<i>Spizella pusilla</i>	Summer	*
Vesper Sparrow	<i>Pooecetes gramineus</i>	Summer	*
Lark Sparrow	<i>Chondestes grammacus</i>	Summer	*
Lark Bunting	<i>Calamospiza melanocorys</i>	Accidental	
Savannah Sparrow	<i>Passerculus sandwichensis</i>	Summer	*
Grasshopper Sparrow	<i>Ammodramus savannarum</i>	Summer	*
Henslow's Sparrow	<i>Ammodramus henslowii</i>	Summer	*
LeConte's Sparrow	<i>Ammodramus leconteii</i>	Migrant	*
Nelson's Sparrow	<i>Ammodramus nelson</i>	Migrant	*
Fox Sparrow	<i>Passerella iliaca</i>	Winter	*
Song Sparrow	<i>Melospiza melodia</i>	Resident	*
Lincoln's Sparrow	<i>Melospiza lincolnii</i>	Migrant	*

Swamp Sparrow	<i>Melospiza georgiana</i>	Winter	*	Non-migratory resident
White-throated Sparrow	<i>Zonotrichia albicollis</i>	Winter	*	
Harris's Sparrow	<i>Zonotrichia querula</i>	Occasional		
White-crowned Sparrow	<i>Zonotrichia leucophrys</i>	Winter	*	
Dark-eyed Junco	<i>Junco hyemalis</i>	Winter	*	
Northern Cardinal	<i>Cardinalis cardinalis</i>	Resident		
Rose-breasted Grosbeak	<i>Pheucticus ludovicianus</i>	Summer	*	
Black-headed Grosbeak	<i>Pheucticus melanocephalus</i>	Accidental		
Blue Grosbeak	<i>Passerina caerulea</i>	Summer	*	
Indigo Bunting	<i>Passerina cyanea</i>	Summer	*	
Painted Bunting	<i>Passerina ciris</i>	Accidental		Non-migratory resident
Dickcissel	<i>Spiza americana</i>	Summer	*	
Bobolink	<i>Dolichonyx oryzivorus</i>	Summer	*	
Red-winged Blackbird	<i>Agelaius phoeniceus</i>	Summer	*	
Eastern Meadowlark	<i>Sturnella magna</i>	Summer	*	
Western Meadowlark	<i>Sturnella neglecta</i>	Migrant	*	
Yellow-headed Blackbird	<i>Xanthocephalus xanthocephalus</i>	Summer	*	
Rusty Blackbird	<i>Euphagus carolinus</i>	Winter	*	
Brewer's Blackbird	<i>Euphagus cyanocephalus</i>	Summer	*	
Common Grackle	<i>Quiscalus quiscula</i>	Summer		Non-migratory resident
Great-tailed Grackle	<i>Quiscalus mexicanus</i>	Accidental		
Brown-headed Cowbird	<i>Molothrus ater</i>	Summer		
Orchard Oriole	<i>Icterus spurius</i>	Summer	*	
Baltimore Oriole	<i>Icterus galbula</i>	Summer	*	
Brambling	<i>Fringilla montifringilla</i>	Accidental		
Pine Grosbeak	<i>Pinicola enucleator</i>	Accidental		
Purple Finch	<i>Haemorhous purpureus</i>	Winter	*	
House Finch	<i>Haemorhous mexicanus</i>	Resident		
Red Crossbill	<i>Loxia curvirostra</i>	Winter	*	Non-migratory resident
White-winged Crossbill	<i>Loxia leucoptera</i>	Winter	*	
Common Redpoll	<i>Acanthis flammea</i>	Winter	*	
Hoary Redpoll	<i>Acanthis hornemanni</i>	Occasional		
Pine Siskin	<i>Spinus pinus</i>	Winter	*	
American Goldfinch	<i>Spinus tristis</i>	Resident	*	
Evening Grosbeak	<i>Coccothraustes vespertinus</i>	Winter	*	
House Sparrow	<i>Passer domesticus</i>	Resident		
Eurasian Tree Sparrow	<i>Passer montanus</i>	Accidental		

¹ Species considered accidental or occasional were not classified as migratory or non-migratory.

Table A.2. Correlations between number of birds of given species counted by citizen science (eBird, birds per minute) and densities of migrating birds measured by weather surveillance radar (mean reflectivity, $\text{cm}^2 \text{ha}^{-1}$) around two radar stations in Indiana, USA, during spring and autumn migration in three time periods (early, 2005-2007; middle, 2010-2012; and late, 2015-2017). The following species have been removed from this analysis, as they have both resident and migratory populations in Indiana: Canada Goose and hybrids (*Branta canadensis*), Mallard and hybrids (*Anas platyrhynchos*), Herring Gull and hybrids (*Larus argentatus*), Belted Kingfisher (*Megasceryle alcyon*), Blue Jay (*Cyanocitta cristata*), American Crow (*Corvus brachyrhynchos*), Eastern Bluebird (*Sialia sialis*), American Robin (*Turdus migratorius*), American Goldfinch (*Spinus tristis*), and Song Sparrow (*Melospiza melodia*).

Period	Season	Pearson's r	95% confidence interval	T statistic	df	Bootstrap p value
Early	Autumn	-0.0585	[-0.360, 0.254]	-0.366	39	0.369
	Spring	-0.116	[-0.316, 0.093]	-1.096	88	0.132
Mid	Autumn	-0.0548	[-0.249, 0.143]	-0.543	98	0.301
	Spring	-0.0192	[-0.163, 0.125]	-0.260	183	0.399
Late	Autumn	-0.0805	[-0.201, 0.043]	-1.284	253	0.101
	Spring	-0.176	[-0.259, 0.091]	-4.061	513	0

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VITA

EDUCATION

Taylor University, Bachelor of Science in Biology, 2016

Purdue University, Doctor of Philosophy in Wildlife Ecology, 2020

PUBLICATIONS

Outcalt, J.M. No room at the inn: Suburban backyards and migratory birds. *Purdue University Extension. FNR-593-W.*

Outcalt, J.M. and J.B. Dunning, interview with Rebecca Thiele. “Your backyard could help migrating birds survive.” Indiana Public Broadcasting, <https://www.wbaa.org/post/your-backyard-could-help-migrating-birds-survive>, November 2019.

Outcalt, J.M., interview with Chad Campbell. “Cloudy with a chance of songbirds.” Purdue University College of Agriculture, <https://ag.purdue.edu/stories/cloudy-with-a-chance-of-songbirds/>, November 2018

Tinklenberg, J.M., invited guest blog. “On the importance of habitat.” A Rocha USA, <https://arocha.us/on-the-importance-of-habitat>, November 2017.

SUBMITTED MANUSCRIPTS

Mahan, D.C., J.T. Betts, E. Nord, **J.M. Outcalt**, A.N. Goetz, F. Van Dyke. Response of benthic macroinvertebrates to dam removal in the restoration of the Boardman River, northern Michigan, USA. *Restoration Ecology*. *In review*.

PRESENTATIONS

Outcalt, J.M., J.J. Buler, J.A. Smolinsky, and J.B. Dunning. Under the radar: trends in migratory bird use of stopover sites in Midwestern forests and urban habitats. American Ornithology. Anchorage, AK, June 2019. *Oral presentation*.

Outcalt, J.M., J.J. Buler, J.A. Smolinsky, and J.B. Dunning. Under the radar: trends in migratory bird use of stopover sites in Midwestern forests and urban habitats. Diversity in Faces, Spaces, and Places of Natural Resources Sciences REEU. West Lafayette, IN, June 2019. *Oral presentation*.

Tinklenberg, J.M. Mapping stopover in Indiana. Annual meeting of the Midwest Migration Network. Port Washington, WI, November 2017. *Oral presentation*.

Tinklenberg, J.M., J.J. Buler, J.A. Smolinsky, and J.B. Dunning. Radar-determined population decline of migratory landbirds at stopover sites in Indiana over a ten-year period. American Ornithology. East Lansing, MI, July 2017. *Poster*.

INVITED PRESENTATIONS

Outcalt, J.M. 2019. Under the Radar: Bird Migration through Celery Bog and Indiana. Wednesdays in the Wild. West Lafayette, IN. *Invited presentation.*

Outcalt, J.M. 2019. Migration Destinations: Stopover Habitats of Migratory Birds in Indiana. Sycamore Audubon Society. West Lafayette, IN. *Invited presentation.*

TEACHING

FNR 44700 Vertebrate Population Dynamics; Fall 2019; Teaching Assistant

FNR 12500 Environmental Science and Conservation; Summers 2019 and 2020; Co-instructor

FNR 25250 Ecology and Systematics of Birds (lab); Spring 2019; Teaching Assistant

FNR 25150 Ecology and Systematics of Birds; Springs 2018, 2019; Guest Lecturer

FNR 49800 Statistical Methods for Natural Resources; Spring 2018; Teaching Assistant

AWARDS

Travel Award, \$500, Research and Extension Experience for Undergraduates (REEU) Internship; Summer 2019

Travel Award, \$580, Annual meeting of the American Ornithological Society in Anchorage AK; June 2019

FUNDING

Frederick N. Andrews Doctoral Assistantship, Purdue University Graduate School, 2016-2017

WORKSHOPS

Graduate student mentor; Diversity in Faces, Spaces, and Places of Natural Resources Sciences, Research and Extension Experience for Undergraduates (REEU) Internship; Purdue University; West Lafayette, IN; Summer 2019

Leader; Bird walk and career talk; Engage Nature Camp; Lafayette, IN; October 2019

Leader; Bird banding demonstration and 4H workshop; Purdue University Extension; West Lafayette, IN; June 2017, June 2018, and June 2019

Co-leader; Bird working group banding day; The Wildlife Society; West Lafayette, IN; February 2020

Co-leader; Birds station, summer field day; Purdue Athletics Life Success (PALS) program; West Lafayette, IN; July 2018 and July 2019

Co-leader; Bird banding demonstration and birding workshop; Natural Resources Teacher's Institute; West Lafayette, IN; July 2019

Co-leader; Field day about birding and bird banding; Tippecanoe County chapter of Indiana Master Naturalists; West Lafayette, IN; September 2017

Participant; Conservation Leaders of Tomorrow; Max McGraw Wildlife Foundation; Dundee, IL; January 10-14, 2020

Participant; Practice of College Teaching Certificate Program; Purdue University Center for Instructional Excellence; West Lafayette, IN; Fall 2019

Participant; Mentoring and Diversity; Mentoring at Purdue (M@P); West Lafayette, IN; June 2019

Participant; Introduction to Extension; Dr. Rod Williams; West Lafayette, IN; June 2019

Participant; Get Spatial with R; American Ornithological Society; Anchorage, AK; June 2019

Participant; Summer Instructor Symposium; Purdue University Center for Instructional Excellence; West Lafayette, IN; April 2019

Participant; Foundations of College Teaching Certificate Program; Purdue University Center for Instructional Excellence; West Lafayette, IN; October 2018

Participant; Radar Aeroecology Training School; University of Oklahoma; Norman, OK; August 2018

Participant; Visiting scholar; Radar aeroecology lab at the University of Delaware; Newark, DE; May 2017

Participant; Responsible Conduct of Research; Purdue University Graduate School; West Lafayette, IN; Fall 2016

Participant; Teaching Assistant Orientation; Purdue University Center for Instructional Excellence; West Lafayette, IN; August 2016

SERVICE

Member of the American Ornithological Society

Member of the Midwest Migration Network

Member of the Au Sable Graduate Fellows program

OTHER

Consulting, radar analysis in Arkansas and Tennessee for Harding University (Dr. Patrick Ruhl), June 2019

Secretary of Sycamore Audubon Society Board of Directors, May 2018 to present

Treasurer of FNR Graduate Student Council, academic year 2017-2018

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