HUMAN-RAPTOR INTERACTIONS ACROSS SPATIAL SCALES

by

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ABSTRACT

HANNAH C. PARTRIDGE. Human-Raptor Interactions Across Spatial Scales. (Under the direction of DR. SARA A. GAGNÉ)

Human-wildlife interactions and conflicts are becoming increasingly common over time, as humans and wildlife are sharing more space and resources than previously. These interactions and conflicts negatively affect humans in direct and indirect ways, but also have important consequences for wildlife populations, with conflict species being more prone to extinction. In this era of rapid global change, we should strive to coexist with wildlife populations, for our own benefit and theirs. Long-term human-wildlife coexistence requires (1) an understanding of species life history, threats, and interactions, (2) proper management of negative interactions and conflicts that is suitable for both human and wildlife populations, and (3) the use of conservation measures to protect species and the resources they need. The interaction of these three dimensions will allow us to evaluate human-wildlife interactions in more depth that highlights both the social and environmental contributing factors, and by ensuring that all three dimensions are incorporated into interactions, we can work towards promoting long-term coexistence between humans and wildlife.

This dissertation includes four different research chapters, all working to promote long-term coexistence between human and raptor populations by building our knowledge of species spatial ecology, evaluating management actions for conflicts, and assessing potential conservation needs. In Chapter Two, I discuss plastic ingestion by black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) populations, providing information on threats as well as opportunities for future conservation actions. In Chapter

Three, I introduce RaPTR, an online GIS spatial decision support system that helps raptor rehabilitators select suitable release sites for raptors that maximize the chances of post-release survival while minimizing the chances of human-wildlife conflict and the time and effort required by rehabilitators. In Chapter Four, I present research on human-black vulture conflicts, providing a deeper understanding of the contributing factors to conflicts and the best long-term management strategies. Finally, in Chapter Five, I discuss the current black vulture range change and future projected expansions and contractions in the range across the United States, aiming to provide knowledge that can promote better conflict management and conservation actions as needed. Combined, these research chapters fill some knowledge gaps, expose others, and highlight opportunities for raptor conflict management and conservation that will promote long-term human-raptor coexistence going forward.

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LIST OF ABBREVIATIONS

APHIS	Animal & Plant Health Inspection Service
AUC	Area under the curve
BCR	Bird Conservation Region
bio6	Mean daily minimum air temperature of the coldest month
bio13	Precipitation amount of the wettest month
bio15	Precipitation seasonality
Cathartid vultures	Vultures in the Cathartidae family
CMA	Charlotte Metropolitan Area, USA
FTIR	Fourier transform infrared spectroscopy
GIS	Geographic information system
HPAI	Highly pathogenic avian influenza
IRB	Institutional Review Board
IUCN	International Union for Conservation of Nature
LUH2	Land-Use Harmonization project
MaxEnt	Maximum entropy
Max TPR+TNR	Maximum True Positive Rate and True Negative Rate
NLCD	National Land Cover Database
RaPTR	Raptor Placement Tool for Release
RCP7.0	Representative Concentration Pathway 7.0
scd	Snow cover days
SDSS	Spatial decision support system
SSP3	Shared Socioeconomic Pathway #3
USDA	United States Department of Agriculture
VIF	Variance inflation factor

CHAPTER 1: INTRODUCTION

1.1 Human-wildlife interactions

Throughout much of human history, humans have dominated anything that we have come into contact with. We have drastically altered landscapes, we have domesticated wildlife, and we have driven species to extinction. These interactions continue to this day with discussions regarding human-wildlife interactions driving international conservation, economic, social, and political decisions (Nyhus, 2016). Human-wildlife interactions include any interaction between human and wildlife populations, whether positive or negative (Nyhus, 2016; Woodroffe et al., 2005) with human-wildlife conflicts receiving the most attention. These are defined by the World Conservation Union as "occurring when wildlife's requirements overlap with those of human populations" (Distefano, 2005). Human-wildlife conflict is a broad term encompassing many possible types of conflict, including any actions that negatively impact the other group (Conover, 2001), direct or indirect threats posed by wildlife to humans (Treves & Karanth, 2003), or the perception of threats to humans (Peterson et al., 2010). This includes all interactions from deer eating garden flowers across urban landscapes to mosquitoes spreading malaria in Africa to jaguars predating upon children in South America.

Threats of wildlife to health and human safety, including wildlife attacks, disease transmissions, and collisions with vehicles and airplanes, are perhaps the most well studied and highly valued of human-wildlife conflicts. While extreme, relatively few human-wildlife conflicts in the United States threaten human lives directly. Between 2008-2015, a total of 1,610 humans were killed as a direct result of conflicts in the United States (~200 people/year), of which 57% were caused by dogs and other mammalian species (Forrester et al., 2018). Far more deadly are those interactions caused by insects, arthropods, and parasites that can transmit deadly diseases such as dengue, yellow fever, or malaria, with malaria alone causing over 400,000 deaths annually worldwide (World Health Organization, 2020). Lastly, bird collisions pose a serious threat to airlines worldwide that risk the lives of humans and are estimated to cost $1.2 billion per year in damages and delays (Allan, 2000).

In addition to threatening health and human safety, many wildlife species threaten agricultural areas through crop raiding, contamination, and livestock depredation. Threats to property are of similar importance in the United States, as many wildlife species will readily damage or infiltrate yards and/or homes. Finally, threats to natural resources include those that damage parks, lakes, forests, wildlife, and wetlands, including damage from invasive species and the protection of threatened or endangered species. Among these threat types, threats to property are the most commonly reported in the United States (37%), followed by threats to agriculture (33%), threats to health and human safety (23%), and finally, threats to natural resources (7%) (USDA, 2022). Within the agricultural group, the most common threats in 2022 were those to cattle and calves, with 9,000 events, generally involving depredation by predators such as grizzly bears (*Ursus arctos horribilis*), bobcats (*Lynx rufus*), coyotes (*Canis latrans*), mountain lions (*Puma concolor*), black vultures (*Coragyps atratus*), and gray wolves (*Canis lupus*) (USDA, 2022).

While humans can be greatly affected by wildlife interactions, wildlife also face significant threats from interactions; species that are more exposed to conflict have been found to be more prone to extinction (Ogada et al., 2003). This is especially true for large carnivores, who require large territories and large prey. They are widely admired globally, yet imperiled due to persecution and habitat loss (Ripple et al., 2014; Woodroffe, 2000). Population impacts to these species can lead to broader environmental impacts contributing to changes in ecosystem functioning and equilibrium (Distefano, 2005), especially considering the significant ecosystem services provided by large carnivore species that human actions cannot fully replace (Ripple et al., 2014).

1.2 Factors contributing to human-wildlife conflicts

Human-wildlife interactions and conflicts are becoming more frequent over time, influenced by many social and environmental factors broadly grouped into the categories of global development trends, wildlife behavior and local ecology, and human behavior (Distefano, 2005; Nyhus, 2016). First, the human population is continuing to grow and expand. As we continue growing, we are also altering landscapes globally, changing natural landscapes to agricultural or urban areas as our demand for food, energy, and space grows with our population size (Abrahms, 2021; Distefano, 2005; Madden, 2008; Nyhus, 2016). This growth and land transformation contributes to habitat loss, degradation, and fragmentation. Further, this growth contributes to the increasing population of livestock that dominates many landscapes globally and excludes wild herbivores, forcing predators to find alternative food sources (Distefano, 2005). The relationship between conflict and density of development is not linear, with conflicts occurring at all levels of development. For example, higher human population densities have been found to be correlated with conflict and population declines in large carnivores (Woodroffe, 2000), although the opposite may also be true due to favorable local policies and management strategies in urban areas (Chapron et al., 2014; Linnell et al., 2001;

Nyhus, 2016). In some cases, smaller, rural communities may actually experience more conflict as these communities may be situated in areas with more prey and habitat and fewer humans (Ohrens et al., 2016). Other land use patterns such as agricultural and livestock production, transportation corridors, and energy production also influence human-wildlife conflict rates, although in complex and situation-specific ways as well (Conover & Conover, 2022; Naugle, 2011; Woodroffe et al., 2005).

Second, several behavioral and ecological factors also influence the occurrence of conflict. It has been hypothesized that older, sick, or injured animals may be more likely to engage in risky behaviors that lead to conflict (such as livestock depredation, crop raiding, etc.) as they have been displaced through competition or can no longer catch wild prey (Chiyo et al., 2012; Nyhus, 2016). However, the same may be true for younger individuals that are less risk averse (Lambert et al., 2006). There are similar factors related to sex – males often maintain larger territories that contribute to an increased frequency of conflicts, while females may be more likely to engage in conflicts while they have young nearby. The spatial distribution of food, water, and habitat have also been hypothesized to influence the occurrence of conflict globally (Hoare, 2012; Naughton-Treves, 1998; Nyhus, 2016) – although again with unclear and situation-specific patterns. For example, large predators may attack livestock and humans in areas with low prey abundance as they struggle to find other food, or in areas with high prey abundance as these are generally more attractive landscapes that draw large predators in (Distefano, 2005; Nyhus, 2016). Decreasing distance to natural habitats and protected land, however, is often seen to increase the occurrence of conflicts, with more conflicts occurring near the boundaries of large natural areas and protected lands and in urban landscapes with more access to parks and greenspaces (Distefano, 2005; Nyhus, 2016). A final environmental driver may be climatic factors, such as seasonal changes in rainfall that control the intensity of carnivore activity and livestock depredation, or random events such as wildfires that force wildlife to flee their natural environment in search of safety (Distefano, 2005).

Finally, human behavior is a major contributor of conflict, influenced by factors including an individual's culture, upbringing, and worldviews, and the economics and politics of the area (Dickman, 2010; Nyhus, 2016; Teixeira et al., 2021). Within this, the perception of risk from wildlife is an important social factor contributing to conflict. While small animals such as mice may cause more damage, there may be more conflict with large animals (e.g., tigers) or "scary" animals (e.g., snakes) due to an increased perception of risk (Dickman, 2010). Education programs and media may help reduce these perceptions of risk and shape public opinion, especially for those species associated with high rates of perceived conflict but low levels of actual conflict. While some human-wildlife conflicts can be minimized in these ways, many conflicts are fueled or hindered by deeper human-human conflicts regarding distrust or inequities between communities, different values and morals, or political and economic issues (Dickman, 2010; Madden, 2008; Nyhus, 2016; Viollaz et al., 2021). These make mitigation of conflict much more difficult, with the true solutions rooted in individual and social change rather than the wildlife population. A good example of this comes from Pennsylvania in the late 1900's, where a small rural community held an annual pigeon shoot to help manage problematic pigeon populations (Dickman, 2010). Upon further investigation, the pigeons were not found to cause significant local damage and rather, the conflict was fueled by the pigeons association with urban areas and the urban threats to the rural community.

1.3 Human-raptor interactions

Humans and raptors have been interacting for centuries, with interactions likely predating modern humanity (Bildstein & Therrien, 2018). Ancient human-raptor interactions likely included humans following vultures to carcasses (a practice still seen today in parts of Tanzania), which then may have changed to vultures and other raptors relying on human settlements as humans began keeping large groups of livestock and other organic waste material – transitioning humans from the role of carcass consumer to carcass provider (Bildstein & Therrien, 2018; Moleón et al., 2014; Morelli et al., 2015). In a practice dating back 4,000+ years that is still regularly seen today, humans began capturing raptors and training them to hunt for humans, providing benefits to all involved (Bildstein & Therrien, 2018; Epstein, 1943).

Today, raptors are still associated with humans and urban areas although they experience different situations than they would in their natural environment (Bildstein & Therrien, 2018; Tryjanowski et al., 2020). Many species have adapted to survive in heavily urbanized landscapes and are common sights across cities worldwide (Bildstein & Therrien, 2018). Raptors provide a variety of ecosystem services such as maintaining prey population sizes, consuming carcasses across landscapes, and holding cultural significance for many people, and as such, they are important aspects of urban areas (Donázar et al., 2016). Yet, due to the close encounters with humans that are inevitable for species living in cities, raptors often face a great deal of criticism and are not always welcomed in urban areas, ending up in frequent conflicts with humans despite their cultural and ecological significance (Boal & Dykstra, 2018; Donázar et al., 2016). For example, owls nesting in urban landscapes have been known to attack humans as they defend their nests, eagles and hawks will regularly prey upon livestock and domestic animals such as chickens and small domestic animals, and many raptor species use humanmade structures for roosting and nesting, occasionally damaging the infrastructure (Boal & Dykstra, 2018).

Vultures are one group of raptors unlike many others. Most vultures are obligate scavengers, keeping the environment free of carcasses and managing infectious diseases across the landscape. Vultures are one of the most threatened avian groups globally and have experienced the most rapid declines in conservation status out of all bird groups since approximately 2000 (Buechley & Şekercioğlu, 2016), with nearly 70% of vulture species worldwide threatened or near threatened (IUCN, 2022). There are many causes for these rapid declines including toxins within food sources, persecution by humans, habitat loss, and decreasing food availability. Some of the most dramatic recent declines in vulture populations have occurred across India. A veterinary drug called diclofenac was widely used across India to treat livestock and has been found to be toxic to vultures within the Gyps family at even low doses (Swan et al., 2006). In India, the vultures consumed deceased livestock that were treated with diclofenac and quickly died due to the toxicity. The declines of long-billed vulture (*Gyps indicus*) and oriental white-backed vulture (*Gyps bengalensis*) populations between 1992-2007 are estimated to be 96.8% and 99.9% respectively (Markandya et al., 2008). Declines of this amount can have significant impacts on ecosystems as nutrient cycling and disease dynamics can be altered and cultural practices can be lost (Markandya et al., 2008).

Unlike the vultures across Europe, Asia, and Africa that are experiencing drastic declines, many vulture species in North and South America are thriving, such as black vultures (*Coragyps atratus*) and turkey vultures (*Cathartes aura*). These species have adapted well to urban environments and use humanmade structures for daily activities such as roosting, nesting, and foraging. Both species regularly roost in urban areas overnight, with black vultures often choosing to roost on humanmade structures such as transmission and cellular towers (Avery et al., 2002; Buckley et al., 2022). Black vultures and turkey vultures are secretive in their nesting habits, although they have been found more regularly to nest in humanmade structures in forested habitat, such as barns and outhouses (Buckley et al., 2022; McHargue, 1981; Stewart, 1974). When it comes to foraging, both species will regularly use food sources within urban areas including roadkill, landfills, and other sources of organic waste material such as dumpsters or roadside pollution (Buckley et al., 2022). Turkey vultures are almost exclusively scavengers while black vultures are known to occasionally prey upon live animals (often those that are weak, injured, or otherwise vulnerable), although the extent to which these predation events occur requires additional research (Buckley et al., 2022). Yet, many conflicts have arisen in recent years regarding livestock depredation by black vultures, as farmers fear for the safety of their livestock. To further complicate this, black vulture populations are growing, and their range has continually expanded over recent decades, spreading across large portions of North and South America (Buckley et al., 2022; Kluever et al., 2020). As with human-wildlife conflicts more broadly, human-vulture conflicts are complex and have a variety of aspects that make understanding and finding solutions difficult.

1.4 Working towards long-term coexistence

Species do not exist in isolation but rather are part of an everchanging ecosystem, dependent upon the social and environmental conditions. As such, human-wildlife conflicts do not exist in isolation but are dependent on various factors at various levels within the social and environmental realms. The prevention and management of conflicts must take a macro-ecological approach, considering all potential influences rather than the individual species in conflict (Liu et al., 2024). For this, we must understand the patterns and drivers behind conflict scenarios. For example, the rate and type of bear-human conflicts differs between agricultural and mixed landscapes due to environmental and social features that extend past the individual bears, and as such, the management for these conflicts must differ as well (Liu et al., 2024). Much human-wildlife conflict research has approached the issue by evaluating social and environmental components separately (Teixeira et al., 2021), although the amount of interdisciplinary and social research is still greatly lacking when compared to that of environmental research (Canney et al., 2021). To truly make progress, the environmental and the social factors must be evaluated together as a coupled human and natural system, defined by Liu et al. (2021) as science that "uses a holistic perspective to integrate patterns and processes that connect human and natural systems, as well as within-scale and cross-scale interactions and feedbacks between human and natural components of such systems" (p. 1778).

Several authors have proposed frameworks for the evaluation and mitigation of human-wildlife interactions. Morzillo et al. (2014) created a framework showing human-wildlife interactions and feedbacks within a coupled human and natural system. This framework includes many factors that contribute to interactions, including human reactions and characteristics, habitat and landscape characteristics, and implemented policies. Soulsbury and White (2019) created a framework showing the connections between the socio-environment, outcomes and impacts of conflict, and the interventions used. Marchini et al. (2021) proposed a framework that places coexistence at the intersection of conservation problems and social problems. Finally, Lischka et al. (2018) created a model showing human-wildlife interactions from a broad scale, as the combination of social and ecological factors, where separate systems meet: ecosystems and society, natural communities and social institutions, and individuals of both human and wildlife populations. Each of these frameworks adds value to the field, focusing on both specific and general drivers and systems.

Yet, researchers are calling for frameworks that better address incidents both in the moment and long-term. Specifically, this includes new frameworks that include policies and procedures to investigate conflicts in the field and strategies to solve conflicts as much as possible (Rush et al., 2023). Based on my review of existing frameworks, I have created a framework (Figure 1.1) that places long-term coexistence between human and wildlife populations at the center of three dimensions, each of which are reliant on the view that we exist in the coupled human-natural system – (1) *Understand*: an understanding of species life history, threats, and interactions, (2) *Manage*: proper management of negative interactions and conflicts that is suitable for both the humans and the wildlife, and (3) *Conserve*: the use of conservation measures to protect species and the resources they need. By relying on the view of a coupled human and natural system and including both ecological dimensions and social dimensions, this framework can be used to move towards coexistence from both dimensions. This framework combines elements of existing frameworks, including the view of coupled human and natural systems seen in Liu et al. (2021) and many of the features from the four human-wildlife interaction framework discussed previously. This framework combines the specific features and drivers shown in other frameworks into the three dimensions. While this framework is still general and applicable to any species, it can be specified and expanded with additional depth in each dimension depending on the situation. With the interaction of these three dimensions, viewed within a coupled human and natural system mindset, we can work towards the goal of long-term coexistence between humans and wildlife.

The first dimension is *Understand*, within which I include an understanding of the species life history and spatial ecology, including needs, threats, opportunities, and interactions. Without this species-specific knowledge, any management or conservation may be relying on inaccurate information and thus, may not truly promote long-term coexistence. For example, without the knowledge that some sea turtle species ingest plastic bags in open ocean waters because they resemble their typical jellyfish prey (Schuyler et al., 2012), conservation and management efforts may focus on surface or benthic pollution of all types that would not truly address the issue.

The second dimension is *Manage*, which includes the proper management of negative interactions and conflicts between humans and wildlife. Importantly, this management should be suitable for both human and wildlife populations. For example, the eradication of foxes in areas with many farms may be considered management, but this is only suitable for the human population present. This management would disadvantage the fox population, of which some individuals would likely return to the area over time to take advantage of the habitat and resources where no other foxes were maintaining territory. As such, this would promote only short-term, rather than long-term, coexistence. The use of proper management strategies that are supported by research, and that target habitat and resource availability are necessary to work towards long-term coexistence. Returning to the fox example, rather than eradication, we could work with farmers to provide more predator-proof confinement for livestock and reduce suitable habitat directly adjacent to farms (which requires species-specific knowledge). With these management strategies, we would reduce the food availability and reduce the quality of habitat in problematic areas, likely reducing the rate of depredation incidents.

The final dimension is *Conserve*, which includes the use of appropriate conservation measures to protect species and the resources they rely on. Returning to the sea turtle example, appropriate conservation measures should be used that address the specific issue (free-floating plastic bags) rather than broad conservation measures such as pollution cleanup. This again requires species-specific knowledge in order to be successful. Each of the three dimensions relies on the other two dimensions to be truly successful. When combined, these three dimensions then promote long-term coexistence. This is coexistence that incorporates needs and threats now and in the future, as well as the social and ecological factors, to promote lasting and durable solutions. This framework is not designed to recommend specific actions but rather to provide an approach by which to improve socio-ecological relationships of various types.

Nearly all case studies on human-wildlife coexistence concentrate on large carnivores such as lions and jaguars or other large mammals such as elephants. Birds remain a group lacking in research attention regarding conflict and coexistence (Canney et al., 2021). As such, let's consider a case study focusing on Chacma baboons (*Papio ursinus*) to highlight the opportunities provided by this framework. The baboons in Zimbabwe would cause significant damage to plantations and were seen as vermin, regularly hunted (FAO, 2023). While hunting showed immediate success in conflict management, the baboons would return to the area within two years and continue damaging resources. After years of this cycle, managers began observing the baboon behavior for more information. They found that the baboons were not consuming the actual farmed resource but rather stripping bark from the trees, causing damage, and interestingly, it was only some of the baboons engaging in this behavior (*Understand*). They hypothesized that the increase of non-native plantations had disrupted the natural landscapes and reduced other food resources, encouraging the baboons to seek the resources available on plantations. With fewer available resources, more baboons began congregating in plantations and fighting for territory, stripping bark due to frustration and aggression. With this knowledge, the managers could then target only the problematic baboons that exhibited this behavior (rather than lethal control of all baboons; *Manage*) and protect natural habitat and food resources outside of plantations (*Manage & Conserve*). As the bark stripping is a learned behavior, with lethal control of problematic individuals, the goal is to remove the behavior (rather than all baboons) from the population and thus, reduce the conflict. While there is still progress to be made, the situation is at a point of long-term coexistence between humans and baboons, made possible by the combination of species-specific knowledge, proper management of conflicts, and conservation of the species and necessary habitat and resources.

1.5 Dissertation overview

By relying on the view that we exist in a coupled human and natural system, this framework and this dissertation incorporate several different fields that add value to this work. As a field, geography is interdisciplinary, and the research produced should be as well, incorporating the biophysical and social factors whenever possible. The many approaches to geography offer unique methodologies and philosophies that can benefit research. This dissertation incorporates insights from the fields of biogeography, landscape ecology, GIScience, human and more-than-human geography, and translational ecology.

First, this work relies heavily on the fields of biogeography and landscape ecology. A core focus in the field of biogeography is an understanding of why, how, and where organisms are situated in space and time – essentially 'ecological geography' (Kent, 2007). This is often equated with landscape ecology, although landscape ecology is seen more as a subdiscipline of ecology rather than geography, focusing on "how landscape structure affects the abundance and distribution of organisms" (Fahrig, 2005) or "the effect of pattern on process" (Turner, 1989). In this way, landscape ecology and physical geography are very similar, showcasing the interdisciplinary nature of the field of geography. However, landscape ecology often focuses on the more broad, landscape scale and may lack clear hypotheses with experimental design that allow for replication (Kent, 2007) – something that physical geography and biogeography are more likely to offer. On the other hand, landscape ecology incorporates a strong focus on the effects of scale, grain, and connectivity on organisms, a focus that views landscapes from the organisms point of view rather than that of humans and thus, may uncover patterns that would otherwise remain unseen. Both fields offer different perspectives and methods that, combined, provide strength to this work. All four research chapters rely on a strong foundation of principles from landscape ecology and biogeography – working to evaluate why organisms exist where they do, with further focus on the effects of different scales that may be important to the study species.

As landscape ecology focuses on the spatial-temporal patterns of landscapes, spatial questions and analyses are inherently tied to the field of landscape ecology in which the spatial patterns of living and nonliving things are evaluated across space (Fortin, 1999). Many statistical methods assume that data points are independent observations with a normal distribution, but this is often not the case with landscape ecology, where data is riddled with issues of spatial dependence, stationarity, and isotropy that makes analyses difficult (Chun & Griffith, 2013). Landscape ecological research requires different methodologies that address these issues – GIScience and spatial statistics thus come into play (Wagner & Fortin, 2005). The term "geographic information systems" was coined in the 1960s and grew into a software application over the next two decades (Goodchild, 2004, 2010). Geographic information systems developed into geographic information science (or GIScience), defined as "the discipline that uses geographic information systems as tools to understand the world" (Clarke, 1997, as quoted in Goodchild, 2004). Spatial statistics and geostatistics are important subfields of statistics that provide techniques for GIScience (Zhang & Goodchild, 2002). Spatial statistics, geostatistics, and GIScience provide the methods and frameworks upon which much of this research was created – allowing for powerful and robust spatial analyses and problem-solving that has the potential to answer questions across space and time.

Finally, much of this research relies on two growing fields that don't often interact despite the value they can provide to each other – more-than-human geography and translational ecology. More than human geographies focus on the 'more-than-human' – on the living, nonhuman aspects of society and their spatial patterns. The relations and impacts of humans on nature have long been left out of human geography despite the widespread acceptance and scientific evidence of human-environment interactions across all aspects of human geography (Braun, 2005). More than-human geographies thus work to incorporate the environmental features into the existing field of human geography and place the actors in nature at the center of the discussion rather than humans. Translational ecologies on the other hand, work to find the best ways to bring humans into the study of the natural world and communicate scientific findings to a broad audience (Schlesinger, 2010). Translational ecology teams combine standard ecological research with social science researchers and practitioners to impact decision-making on a variety of complex environmental issues (Enquist et al., 2017). The field of translational ecology stems from the same idea as that of translational medicine, that the "basic research findings were not moving effectively into the development of drugs and treatments", or in the case of ecology, the development of laws, regulations, and environmental practices (Schlesinger, 2010). Each field offers valuable insight into this dissertation and the opportunity to create more engaged, honest research that strives to understand the human and non-human aspects of this topic.

This dissertation includes four different research chapters, all working to promote long-term coexistence between human and raptor populations by filling knowledge gaps and contributing to our understanding of species spatial ecology, evaluating and implementing management actions, or assessing conservation needs and actions (Figure 1.2).

In Chapter Two, I present research evaluating the plastic ingestion of black vulture and turkey vulture populations in the southeastern United States, providing an understanding of the amounts and types of plastic ingested by these important species and thus, opportunities for future conservation actions geared towards plastic pollution and ingestion.

Next, in Chapter Three, I introduce the RaPTR tool – an online GIS spatial decision support system that selects release locations for rehabilitated raptors, promoting long-term coexistence by maximizing the chances of post-rehabilitation survival while minimizing the chances of conflict and the time and effort required by rehabilitators.

In Chapter Four, I discuss conflicts between humans and black vulture populations, providing a deeper understanding of the factors contributing to conflicts and the best long-term management strategies that address the root issue.

Finally, in Chapter Five, I showcase research evaluating the current and future distribution of black vultures within the midwestern United States in an effort to better understand landscape associations and thus, manage and prevent conflicts across the region.

Each of these chapters relies on building knowledge, contributing to the *Understand* dimension of my framework, and has opportunities for species conservation and conflict management provided by the knowledge gained (Figure 1.2). Our understanding of vulture plastic ingestion will allow us to better conserve vulture populations from this threat going forward. Our understanding of rehabilitated raptor release suitability will allow us to better protect threatened species and better manage or prevent human-raptor conflicts. Our understanding of the drivers and solutions for human-black vulture conflicts will allow us to better manage existing conflicts and prevent future conflicts worldwide. Finally, our understanding of the black vulture range change will allow us to protect populations at risk of future decline and manage conflicts in areas with projected growth.

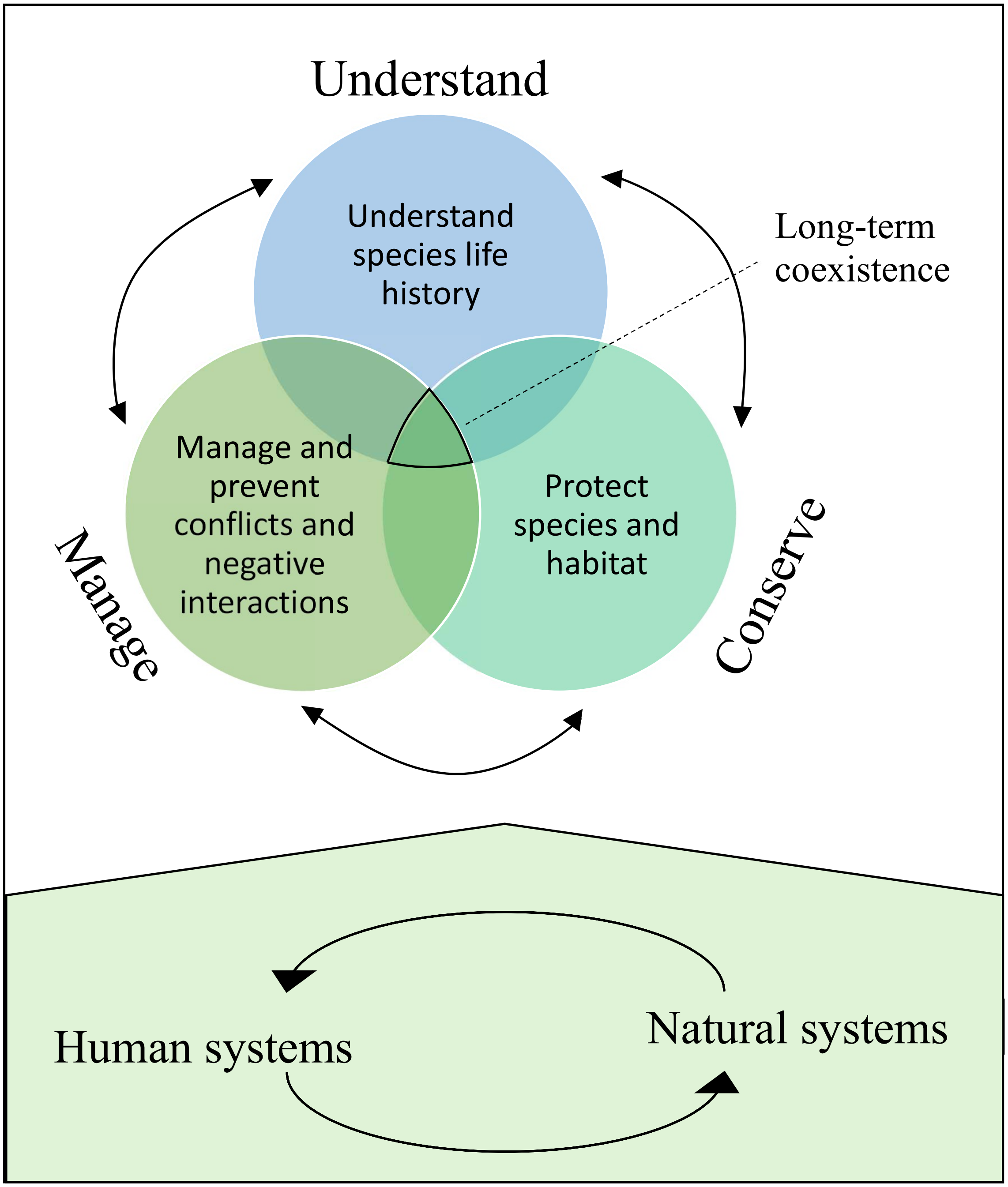

Figure 1.1 Framework for long-term human-wildlife coexistence that relies on the view that we exist within a coupled human-natural system and incorporates three unique dimensions – (1) *Understand*: an understanding of species life history, threats, and interactions, (2) *Manage*: proper management of negative interactions and conflicts that is suitable for both the human and the wildlife populations, and (3) *Conserve*: the use of conservation measures to protect species and the resources they need. With each of these interacting dimensions combined, we can promote long-term coexistence between human and wildlife populations.

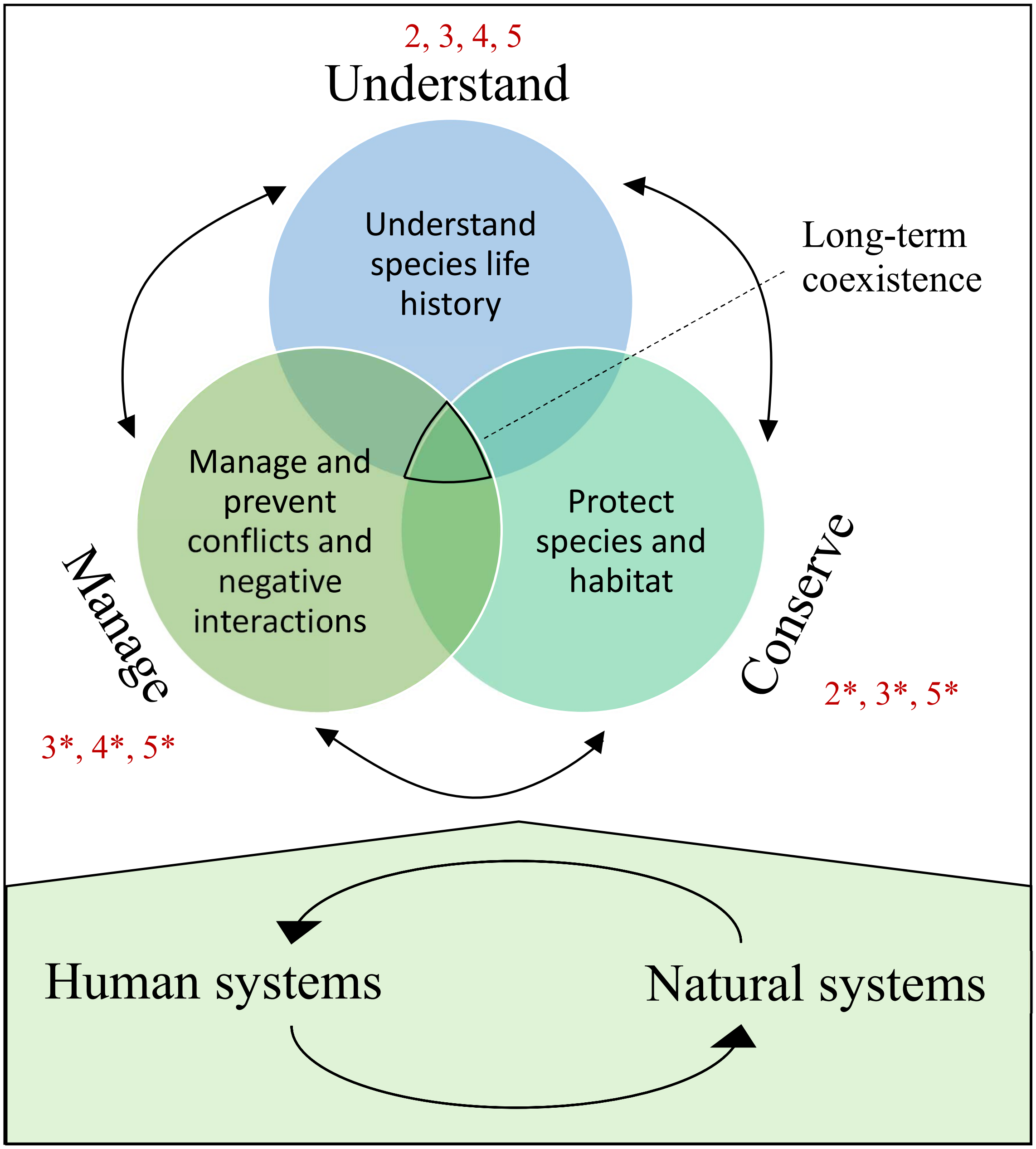

Figure 1.2 Framework for long-term human-wildlife coexistence that relies on the view that we exist within a coupled human-natural system and incorporates three unique dimensions – (1) *Understand*: an understanding of species life history, threats, and interactions, (2) *Manage*: proper management of negative interactions and conflicts that is suitable for both the human and the wildlife populations, and (3) *Conserve*: the use of conservation measures to protect species and the resources they need. With each of these interacting dimensions combined, we can promote long-term coexistence between human and wildlife populations. The chapters that directly contribute to each dimension are indicated by numbers, and chapters with indirect contributions are indicated by numbers with asterisks.

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CHAPTER 2: VULTURES IN THE SOUTHEASTERN UNITED STATES INGEST MORE PLASTIC IN LANDSCAPES WITH MORE DEVELOPED LANDCOVER

This article was originally published in *Frontiers in Ecology and Evolution* as Partridge HC, Barnett S, Amodeo J, Snyder J and Gagné SA (2023) Vultures in the southeastern United States ingest more plastic in landscapes with more developed landcover. Front. Ecol. Evol. 11:1158453. doi: 10.3389/fevo.2023.1158453.

Abstract

Introduction: Plastics are found in ecosystems worldwide and can have widespread impacts on organisms and the environment. Cathartid vultures, including the black vulture (*Coragyps atratus*) and the turkey vulture (*Cathartes aura*), have adapted to urbanized environments, making frequent use of human-made structures and anthropogenic resources. Thus, urban vultures are likely exposed to more plastic materials than rural vultures, which they intentionally or unintentionally ingest when foraging or loafing.

Methods: My objective was to determine the extent and type of plastic ingested by black and turkey vultures in an urban environment by (1) measuring the plastic content of regurgitated pellets collected along an urban-to-rural gradient, and (2) identifying the plastics within pellets. I dissected 1,087 pellets collected at eight vulture congregation sites in the Charlotte Metropolitan Area, United States between January 2021 and July 2022.

Results and Discussion: Sixty percent of pellets contained plastic materials, with an average plastic composition by weight of 2.66 ± 8.76%. Repeated measures linear mixed models of the proportion of pellets that were plastic suggested that black and turkey vultures are ingesting more plastic materials when congregation sites are surrounded by more developed landcover and a greater density of commercial food

providers, such as food stores and restaurants, within 20km. Fourier transform infrared (FTIR) spectroscopy of a subset of pellets indicated that the most common types of plastic ingested by vultures were silicone rubber (used in tires and automobile/boat seals) and polyethylene (used in plastic bags and food packages). Future research should investigate the relative importance of plastic sources in vulture diets, vulture behavioral changes associated with plastic ingestion, and the consequences of plastic pollution on species health and urban ecosystem functioning.

Keywords: black vulture, turkey vulture, plastic ingestion, urbanization, landscape, spectroscopy

2.1 Introduction

Plastics are widely used by humans and are found in ecosystems worldwide (Barnes et al., 2009). Common sources of environmental plastics include personal care products, plastic mulch, tires, and synthetic paints (Duis & Coors, 2016). In addition to urban areas, plastics have been found in remote locations such as the summit of Mount Everest (Napper et al., 2020) and the Mariana Trench (Jamieson et al., 2019). There is evidence of the cycling of plastics in each of Earth's major subsystems (de Souza Machado et al., 2018; Dris et al., 2016; Dris et al., 2015; Wilcox et al., 2015) but the impact of pervasive plastic pollution on natural systems is not well understood.

Cathartid vultures (i.e., vultures from the Cathartidae family) have adapted to urbanized environments and are commonly considered pests in cities (Blackwell et al., 2007). Black vultures (*Coragyps atratus*) are a vulture species that use human-made structures and resources frequently. They regularly roost on transmission and cellular towers (Avery et al., 2002; Buckley, 1998; Seamans, 2004), nest in abandoned buildings

(Crowley et al., 2022; C. S. Houston et al., 2007; Stewart, 1974), and forage regularly at street markets, dumpsters, and landfills in large numbers (Cunha et al., 2022; Elías, 1987; Hill et al., 2022; Novaes & Cintra, 2015). Turkey vultures (*Cathartes aura*), with a range that overlaps that of black vultures, may also use human-subsidized resources in urbanized environments, such as transmission towers in suburban and exurban areas for roosting, but they prefer rural and forested landscapes (Novaes & Cintra, 2015).

Plastic materials have been found in regurgitated black vulture pellets since at least the 1980s (Elías, 1987), showing evidence of plastic ingestion dating back decades. More recently, 30% of black or turkey vulture pellets in South Carolina (Hill et al., 2022) and 82% in the Falkland Islands contained plastics (Augé, 2017). In Patagonia, black and turkey vultures roosting near dumpsters and landfills had a high probability of ingesting plastic (Ballejo et al., 2021) and in Florida, the black vulture was the only raptor species found to ingest plastics (Carlin et al., 2020). This literature shows significant and widespread ingestion of plastic materials by black and turkey vultures across North and South America.

Vultures may be intentionally or unintentionally ingesting plastic materials by building up bulk to expel pellets (D. C. Houston et al., 2007), mistaking plastic materials as bone fragments, or ingesting plastics from carcasses and other food sources. Additionally, vultures may be ingesting plastic materials while loafing as they are known to regularly pick at materials such as boat seats, rubber seals, or roofing materials. Regardless of the cause, the impacts of plastic ingestion on vulture adults and juveniles are not well understood. Plastic ingestion could lead to gut blockages, internal injuries, and mortality (D. C. Houston et al., 2007) and plastics could contain pollutants and heavy metals (Borges-Ramírez et al., 2021) – black vultures that ingest more plastic materials have worse health than those that ingest less plastic (Cunha et al., 2022).

Although there is evidence of black and turkey vulture pellets containing plastics, to my knowledge, only a single study has investigated the ingestion of plastics by these species and their sources in an urban environment (Carlin et al., 2020). Given the potential impacts to vulture health, environmental plastic pollution, and ecosystem functioning, my objective was to determine the extent and type of plastic ingested by black and turkey vultures in an urban environment by (1) measuring the plastic content of regurgitated pellets collected along an urban-to-rural gradient, and (2) identifying the plastics within pellets. I predicted that the plastic content of pellets would increase with developed landcover, density of commercial food providers and density of livestock and game producers in landscapes surrounding pellet collection sites, and decreasing distance to the nearest landfill.

2.2 Materials and methods

2.2.1 Study area

The Charlotte Metropolitan Area (CMA) is an urban area in North Carolina and South Carolina composed of 12 counties surrounding the City of Charlotte. The CMA human population is estimated at 2.8 million with rapid growth rates over the last two decades (United States Census Bureau, 2019). The population of Mecklenburg County, in which Charlotte is located, is expected to grow by over 570,000 people between 2010 and 2040, an annual rate of 2.3% (Charlotte Future, 2019). Charlotte largely consists of developed landcover types, but development within the CMA is sprawling and dominated by developed open space and single-family housing.

Objective 1: Plastic content of regurgitated pellets along an urban-to-rural gradient

2.2.2 Pellet collections

In 2019 and 2020, for a related study, I identified 29 black and turkey vulture roosts within the CMA using eBird hotspots, expert reports, and personal observations of vulture movements (Partridge & Gagné, 2023). These 29 sites were active, overnight vulture roosts that usually hosted 20–500 individuals. As many roosts are inaccessible by foot, a total of eight vulture congregation sites were selected for this study (Figure 2.1). These eight sites were regularly occupied by vultures, accessible on foot, and occurred along an urban-to-rural gradient. In the study area, black and turkey vultures occasionally roost together in roughly equal numbers, but study sites were ~ 95–100% composed of black vultures. This research is likely more indicative of black vulture patterns than those of turkey vultures.

I collected structurally intact vulture pellets from the ground at each site, aiming for 10–15 pellets collected/visit/site. Each site was visited 15 times between January 2021 and July 2022, with visits occurring approximately every 2 weeks throughout each season.

2.2.3 Pellet dissections

Collected pellets were stored in a freezer at -21°C before dissection. I air-dried frozen pellets for 48 h to reduce moisture content (Yahner et al., 1986). Dried pellets were then weighed using a Mettler Toledo PL303 balance and dissected using a Nikon SMZ1000 stereomicroscope and a Parco compound microscope with magnifications of 4-100x. During dissection, I visually identified the natural materials (vegetation, dirt, rocks, and animal remains), plastic materials, and other anthropogenic materials (metal, fabric, paper, wood, and glass) in each pellet and weighed each material type for the proportion of each pellet composed of natural, plastic, or other anthropogenic material.

2.2.4 Explanatory variables

I measured four explanatory variables that could be important predictors of plastic ingestion by vultures (Campbell, 2014; Novaes & Cintra, 2015): commercial food provider density, livestock and game producer density, amount of developed landcover, and distance to the nearest landfill. Commercial food provider density, livestock and game producer density, and the amount of developed landcover were measured in circular landscapes centered on collection sites with 0.4, 0.5, 1, 2, 3, 4, 5, 10, 15, and 20 km radii, capturing variations in space use by black and turkey vultures (Holland et al., 2019; Houston et al., 2011).

I used Data Axle Reference Solutions databases to identify commercial food providers, livestock and game producers, and landfills (Data Axle, 2022). Database records were current as of June 6, 2022, when I accessed records. Commercial food providers included 9,105 “Retail Trade” records with the descriptors “Food Stores” and “Eating Places.” Livestock and game producers included 129 “Agriculture, Forestry, and Fishing” records with the descriptors “Agricultural Production - Livestock” or “Fishing, Hunting, and Trapping” and landfills included 29 “Public Administration” records with the descriptors “Air, Water, and Solid Waste Management.” I calculated the density of commercial food providers or livestock and game producers in landscapes as the number of businesses of each type divided by landscape area and measured the distance from each congregation site to the nearest landfill. Finally, I measured the amount of developed landcover in landscapes as the proportion composed of the National Land

Cover Database developed classes (i.e., Developed Open Space, Developed Low Intensity, Developed Medium Intensity, and Developed High Intensity) (Dewitz & United States Geological Survey, 2021). I used ArcGIS Pro 2.9.2 (Esri Inc., 2021) and Google Earth Pro 7.3.4.8642 (Google Inc., 2022) to calculate explanatory variables.

2.2.5 Analysis

I used repeated measures linear mixed models to test for the effects of commercial food provider density, livestock and game producer density, amount of developed landcover, and distance to the nearest landfill on the proportion of pellets composed of plastic materials, with a log transformation to address heteroscedasticity in the data. All models included a random site effect to account for non-independence of observations from the same collection site. I modeled each landscape scale separately to minimize collinearity among explanatory variables. For some scales, commercial food provider density, livestock and game producer density, and/or distance to the nearest landfill were nil because no businesses were located in landscapes. These variables were absent from models when this occurred.

Variance inflation factors (VIF) and pairwise correlation matrices were calculated to test for collinearity in explanatory variables, which I defined as VIF ≥ 5 or $r \geq 0.7$ (Dormann et al., 2013). Due to high levels of collinearity between developed landcover, commercial food provider density, and livestock and game producer density (Tables A2.1–A2.11), I created a total of 23 models (Tables 2.1, A2.12–A2.37). With variables separated into these models, all VIF and pairwise correlation values were below specified thresholds.

I tested for spatial autocorrelation in the residuals of each model using Moran's I. Significant spatial autocorrelation did not occur in the residuals of any model (Figures A2.1–A2.23). I inferred the effects of explanatory variables on pellet plastic composition using the model with the largest log-likelihood value. I used RStudio v2021.09.2 + 382 (R Core Team, 2022) and the ncf v1.3–2 (Bjornstad, 2020), regclass v1.6 (Petrie, 2020), spdep v1.2–4 (Bivand, 2022), stats v4.3.0 (R Core Team, 2022), and lme4 v1.1–30 (Bates et al., 2015) packages to carry out analyzes.

Objective 2: Identification of plastics in regurgitated pellets

Eighty-three pellets were randomly selected for plastic analysis with some stratification by site and date. Given time constraints, I sampled three out of four study seasons and eight out of eight study sites, resulting in 6.2 pellets/site analyzed in fall 2021, 6.5 pellets/site analyzed in spring 2022, and one pellet/site analyzed in summer 2022. For the selected pellets, I cleaned each plastic material and performed Fourier transform infrared (FTIR) spectroscopy using a PerkinElmer FT-IR Spectrometer Spectrum Two to produce infrared spectra of each material. The transmittance of plastics was analyzed by wavenumbers 450 cm−1 to 4,000 cm−1 with four scans and a resolution of 8 cm−1. I used Open Specy to match the infrared spectrum of each material to spectra within the Open Specy database, with intensity adjusted for transmittance, baseline correction, and using the full processed plot (Cowger et al., 2021). Database spectra correlated with sample spectra at Pearson's r values of ≥0.75 were accepted as matches.

2.3 Results

Objective 1: Plastic content of regurgitated pellets along an urban-to-rural gradient

I dissected 1,087 pellets, 648 (60%) of which contained plastic material, with an average plastic composition by weight of 2.66 ± 8.76% (Figure A2.24). Eleven pellets (1%) were more than 50% plastic material, and five pellets (0.5%) were more than 75% plastic material.

The best model describing the plastic content of vulture pellets included site, date [0.03 ± 0.03 (SE), $p = 0.35$], distance to the nearest landfill [0.02 ± 0.06 (SE), $p > 0.05$], and the amount of developed landcover [0.16 ± 0.06 (SE), $p = 0.01$] in 20 km landscapes. Another model that included site, date, distance to the nearest landfill and commercial food provider density in 20 km landscapes had a very similar log-likelihood value and variable estimates (Table 2.1; Figure 2.2). Overall, vulture pellets contained more plastic materials when congregation sites were located closer to landfills or were surrounded by more developed landcover within 20 km. There was minimal variation in pellet plastic composition across sites or dates with no noticeable trends in plastic ingestion over time.

Objective 2: Identification of plastics in regurgitated pellets

I performed FTIR spectroscopy on 187 pieces of plastic, resulting in 171 matches with spectra in the Open Specy database. I report only the matches for each sample with the highest Pearson's r value (Table A2.38). Some samples were identified as different materials with the same Pearson's r value and thus a total of 234 identifications are presented. Of all matched samples, 54.7% were matched with plastic materials–the remaining 45.3% were matched with various natural or non-plastic materials (Figure 2.3A,B). The six most common plastic materials identified in pellets were silicone rubber (n = 14), high density polyethylene (n = 13), polyethylene (n = 12), silicate bio polyethylene (n = 10), polyethylene with silicate inorganic (n = 9), and low density polyethylene (n = 7; Figure 2.3C). There was no apparent variation in plastic identification across sites or dates.

2.4 Discussion

As I predicted, my results indicate that black and turkey vultures are ingesting more plastic materials when congregating in landscapes with more developed landcover and a greater density of commercial food providers. Developed landcover and commercial food provider density had the largest effects on pellet plastic proportion when I measured these variables in the largest landscapes I considered, those with radii of 20 km. Distance to the nearest landfill was also included in the most supported models, although it did not have a significant effect.

The positive effects of developed landcover and commercial food provider density that I report, and the presence of distance to the nearest landfill in the best models of pellet plastic content, are supported by evidence from the literature and my ongoing research in the study area. Black vultures are regularly observed foraging at dumpsters and landfills (Kluever et al., 2020; Lowney, 1999) where they would be more likely to ingest various plastic materials with food items. While loafing, black vultures are known to destroy property such as roofing, insulation, and vehicle/boat seats and seals in urban and rural landscapes (Evans, 2013; Kluever et al., 2020; Tillman et al., 2002). These patterns are also supported by ongoing research featuring interviews of researchers and practitioners working with nuisance black vulture populations worldwide. When not foraging, black vultures will loaf in various landscapes and pick at anthropogenic materials, often near a consistent food source.

The positive effect of developed landcover in my results suggests that plastic materials ingested by vultures in urban landscapes originate from a wide variety of sources, including commercial dumpsters and smaller waste containers, institutional and industrial waste, household waste, roadside waste and roadkill, and built structures themselves. The positive effect of commercial food provider density that I report suggests that, of these potential sources, food stores and restaurants may be particularly important, and that foraging is a primary means by which plastic materials are ingested. However, future research is needed to test this hypothesis and to investigate in more detail the roles that other sources and vulture behaviors play in plastic ingestion.

A cosmopolitan nature to plastic ingestion by vultures in urban landscapes is supported by my plastic identification results. The most common plastics in my sample were silicone rubber and polyethylene, each commonly found in the environment due to human pollution and the breakdown of anthropogenic objects. Silicone rubber is used to make automobile tires, seals, baking pans, and food molds (Shit & Shah, 2013) and polyethylene (low-density and high-density) is used to make plastic bags, food containers, and liners for landfills and pools (Kumar et al., 2011).

Nearly half of the samples I analyzed using FTIR were matched with non-plastic materials such as plant material, fur, or fabric. It is likely that these were materials coating or embedded within the plastic samples and thus, may provide insight into what the vulture was eating when the plastic was ingested. Interestingly, the second most commonly matched non-plastic material was red deer (*Cervus elaphus*) fur, which is a frequently farmed deer species in the United States. While this finding requires additional investigation, it does provide some evidence that vultures are ingesting plastic in areas of livestock and game production where they may be preying on domestic animals. The other common non-plastic materials were silk slubbing fiber, which is used in clothing and bicycle tires (Madhu et al., 2022) and jute fiber, which is used in twines, clothing, and reusable bags (Aly-Hassan, 2015).

I observed the largest effects of developed landcover and commercial food provider density when I measured these variables in landscapes of 20 km radii, the largest I considered. This scale corresponds to the large home ranges of my study species – 30-60 km^2 in the southeastern US, or possibly larger, as indicated by a 900 km^2 estimate for turkey vultures near the northern limit of their range. The fact that the effect sizes of developed landcover and commercial food provider density were largest at the largest landscape scale I considered suggests that the scale of effect of these explanatory variables is likely to occur at even broader spatial scales, which future studies of vulture plastic ingestion should consider (Jackson & Fahrig, 2015).

2.5 Conclusion

I found widespread ingestion of plastic by vultures, with 60% of dissected pellets containing plastic materials. Vultures that congregated in landscapes with more developed land cover and a higher density of commercial food providers at broad spatial scales ingested more plastic, particularly silicone rubber and polyethylene. Vultures in urban landscapes may also be ingesting plastic at landfills and in areas of livestock and game production. Future research should seek to estimate the relative importance of sources of plastic in vulture diets, the vulture behaviors associated with plastic ingestion from different sources and of different types, and the physiological consequences of plastic pollution on species health and urban ecosystem functioning.

Table 2.1 Variable estimates (± SE) of models describing the plastic composition of black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets in the Charlotte Metropolitan Area, United States. Commercial food provider density ("Restaurant"), livestock and game producer density ("LivestockDensity"), and developed landcover ("Developed") were measured in landscapes of varying radii surrounding pellet collection sites (landscape size in km noted in parentheses with the model number). Distance to the nearest landfill ("LandfillDist") was measured as the distance to the nearest landfill (km). Significant ($p < 0.05$) effects are labeled with an asterisk.

Model	Date	Commercial food provider density	Livestock and game producer density	Developed landcover	Distance to the nearest landfill	Log-likelihood	AICc	ΔAICc
1 (0.4 km)	0.03 ± 0.03			−0.02 ± 0.07	−0.08 ± 0.07	−1539.63	3091.27	4.68
2 (0.5 km)	0.03 ± 0.03			−0.02 ± 0.07	−0.08 ± 0.07	−1539.61	3091.22	4.63
3 (1 km)	0.03 ± 0.03			−0.02 ± 0.08	−0.08 ± 0.07	−1539.57	3091.14	4.55
4 (2 km)	0.03 ± 0.03			0.00 ± 0.09	−0.07 ± 0.07	−1539.48	3090.96	4.37
5 (3 km)	0.03 ± 0.03		0.09 ± 0.12	−0.05 ± 0.13	−0.14 ± 0.13	−1540.30	3094.60	8.01
6 (4 km)	0.03 ± 0.03		0.06 ± 0.12	0.00 ± 0.13	−0.10 ± 0.13	−1540.39	3094.78	8.19
7 (5 km)	0.03 ± 0.03		0.00 ± 0.08	0.07 ± 0.13	−0.04 ± 0.13	−1540.37	3094.73	8.14
8 (0.4 km)	0.03 ± 0.03	0.00 ± 0.08			−0.07 ± 0.07	−1539.60	3091.19	4.60
9 (0.5 km)	0.03 ± 0.03	−0.03 ± 0.08			−0.09 ± 0.07	−1539.45	3090.91	4.32
10 (1 km)	0.03 ± 0.03	−0.05 ± 0.08			−0.09 ± 0.07	−1539.35	3090.69	4.10
11 (2 km)	0.03 ± 0.03	−0.03 ± 0.08			−0.08 ± 0.07	−1539.48	3090.96	4.37
12 (3 km)	0.03 ± 0.03	−0.11 ± 0.12	0.14 ± 0.11		−0.17 ± 0.10	−1540.04	3094.07	7.48
13 (4 km)	0.03 ± 0.03	−0.06 ± 0.11	0.09 ± 0.10		−0.13 ± 0.09	−1540.44	3094.88	8.29
14 (5 km)	0.03 ± 0.03	−0.07 ± 0.12	0.09 ± 0.12		−0.13 ± 0.10	−1540.41	3094.82	8.23
15 (10 km)	0.03 ± 0.03		0.11 ± 0.08		−0.02 ± 0.07	−1538.61	3089.23	2.64
16 (15 km)	0.03 ± 0.03		0.06 ± 0.08		−0.05 ± 0.07	−1539.27	3090.53	3.94
17 (20 km)	0.03 ± 0.03		0.12 ± 0.07		−0.02 ± 0.06	−1538.32	3088.64	2.05
18 (10 km)	0.03 ± 0.03	0.10 ± 0.09			−0.01 ± 0.08	−1538.74	3089.48	2.89
19 (15 km)	0.03 ± 0.03	0.12 ± 0.09			0.00 ± 0.08	−1538.54	3089.08	2.49
20 (20 km)	0.03 ± 0.03	0.18 ± 0.07*			0.05 ± 0.07	−1537.30	3086.59	0.00
21 (10 km)	0.03 ± 0.03			0.15 ± 0.07*	0.01 ± 0.07	−1537.96	3087.92	1.33
22 (15 km)	0.03 ± 0.03			0.15 ± 0.07*	0.01 ± 0.06	−1537.91	3087.83	1.24
23 (20 km)	0.03 ± 0.03			0.16 ± 0.06*	0.02 ± 0.06	−1537.29	3086.59	0.00

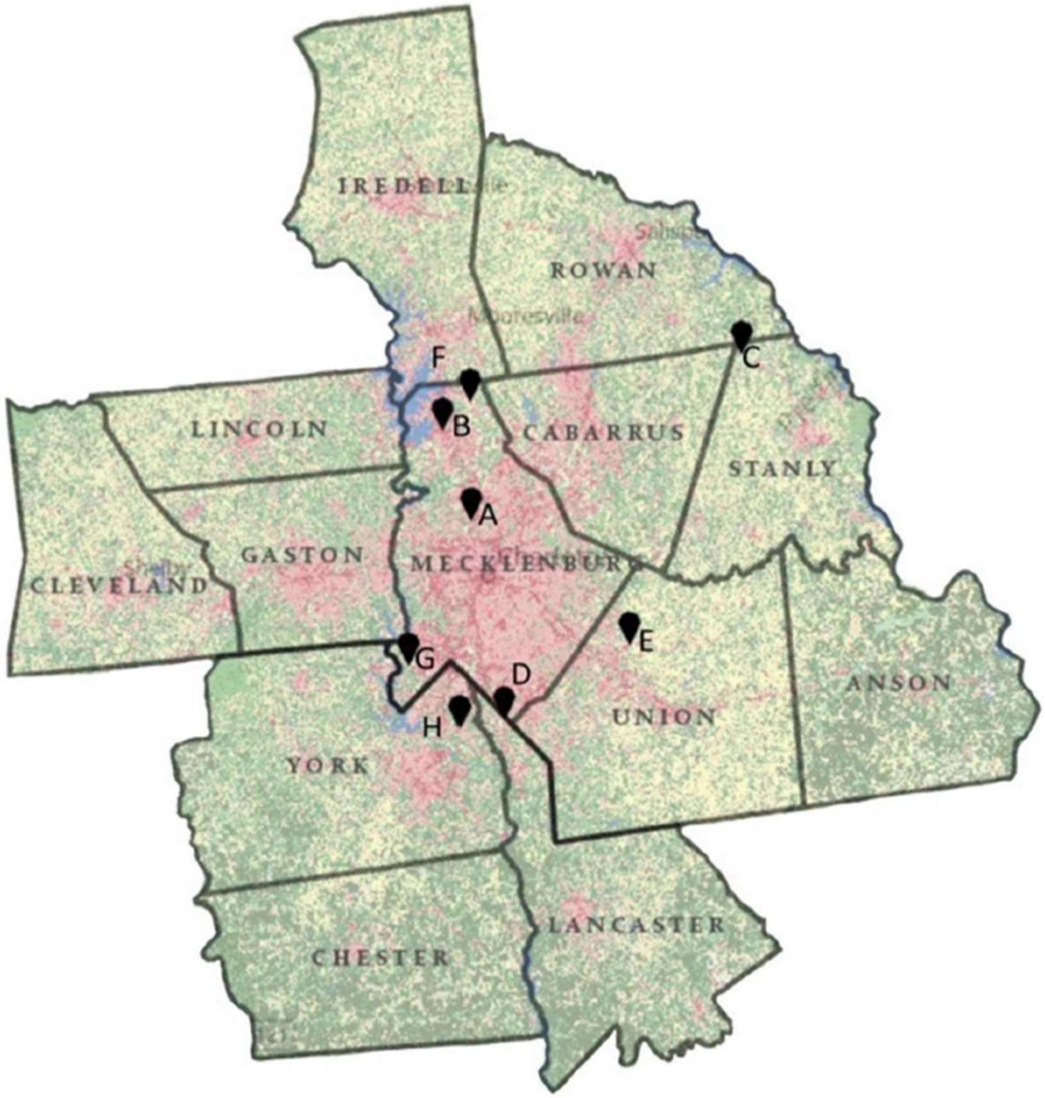

Figure 2.1 The Charlotte Metropolitan Area, USA with black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellet collection sites identified by lettered markers and counties indicated by name. Developed land is shown in shades of red, open water is blue, forest types are in shades of green, and pasture, grassland, and cultivated crops are in shades of yellow (Dewitz and United States Geological Survey, 2021).

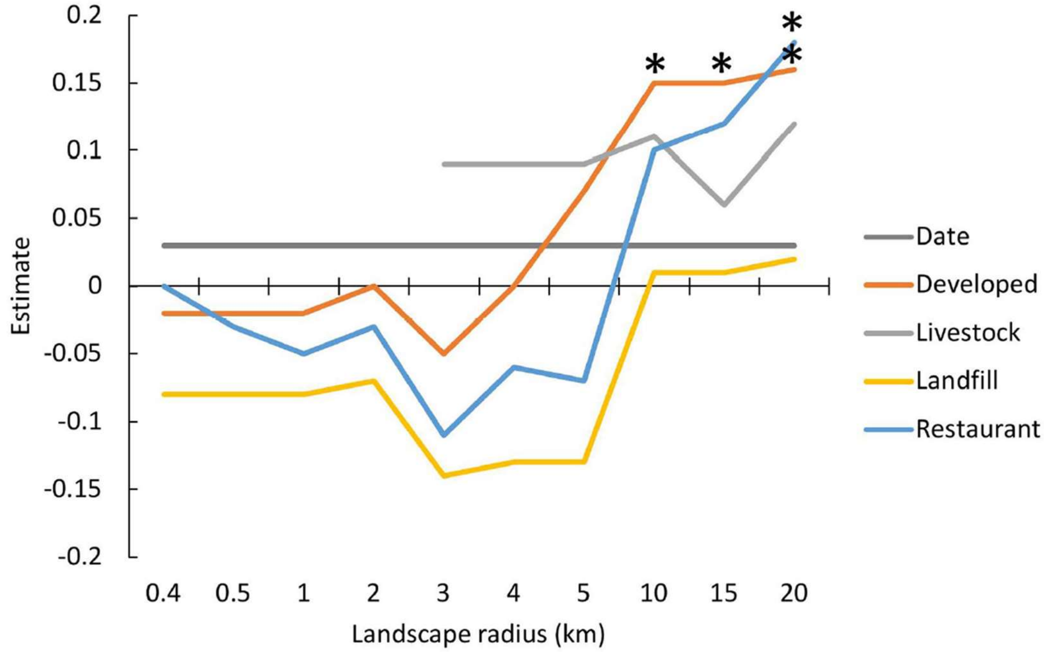

Figure 2.2 Effect sizes and significance of explanatory variables in models of the plastic content of black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets in the Charlotte Metropolitan Area, USA. Significant ($p < 0.05$) effects are labeled with an asterisk. Commercial food provider density ("Restaurant"), livestock and game producer density ("Livestock"), and amount of developed landcover ("Developed") were measured in landscapes of varying radii surrounding pellet collection sites. Distance from pellet collection sites to the nearest landfill is labeled as "Landfill." For variables that were included in more than one model at the same scale, the estimate from the best performing model was used. All models also included a site variable to account for the non-independence of pellets collected at the same site.

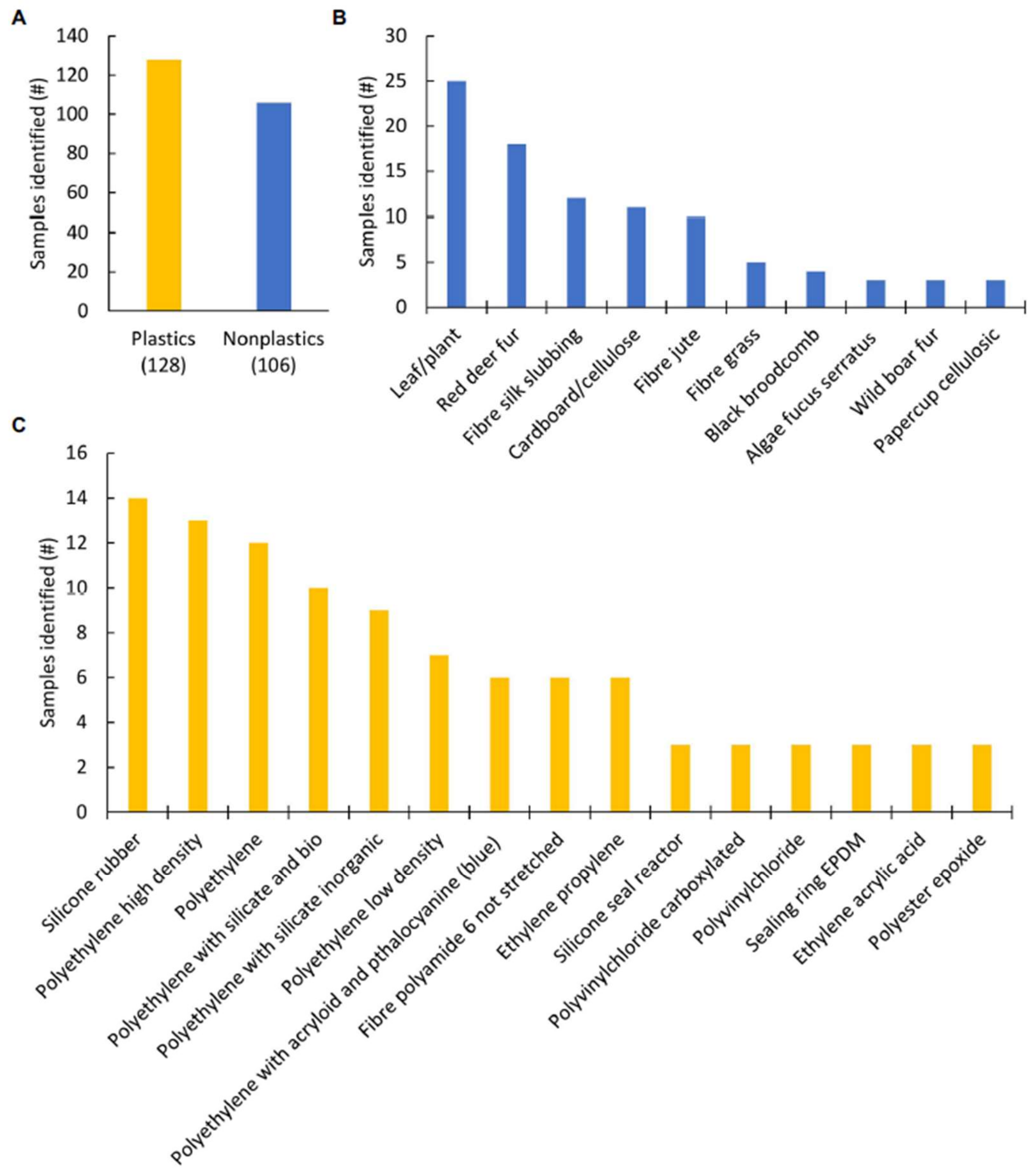

Figure 2.3 (A) Fourier transform infrared spectroscopy results for 187 pieces of plastic material from 83 black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. The samples identified as different types of plastics or natural or other non-plastic anthropogenic materials coating or embedded in samples with the number of samples in parentheses There are a total of 234 sample identifications as some samples were identified as different materials with the same Pearson's r value. (B) The number of samples identified as natural or nonplastic materials, identifications with less than three samples are omitted from this figure. (C) The number of samples identified as plastic materials, identifications with less than three samples are omitted from this figure.

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2.7 Appendix

Table A2.1 Correlation matrix for all variables. Livestock and game producer density, commercial food provider density, and developed landcover were landscape variables measured within 0.4km of all collection sites. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models. NA values indicate that the variable was not present in the landscape.

	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density	Developed landcover
Date	1				
Livestock and game producer density	NA	1			
Distance to a landfill	0.00	NA	1		
Commercial food provider density	-0.10	NA	-0.44	1	
Developed landcover	0.00	NA	-0.31	0.79	1

Table A2.2 Correlation matrix for all variables. Livestock and game producer density, commercial food provider density, and developed landcover were landscape variables measured within 0.5km of all collection sites. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models. NA values indicate that the variable was not present in the landscape.

	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density	Developed landcover
Date	1				
Livestock and game producer density	NA	1			
Distance to a landfill	0.00	NA	1		
Commercial food provider density	-0.10	NA	-0.48	1	
Developed landcover	-0.01	NA	-0.35	0.91	1

Table A2.3 Correlation matrix for all variables. Livestock and game producer density, commercial food provider density, and developed landcover were landscape variables measured within 1km of all collection sites. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models. NA values indicate that the variable was not present in the landscape.

	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density	Developed landcover
Date	1				
Livestock and game producer density	NA	1			
Distance to a landfill	0.00	NA	1		
Commercial food provider density	-0.13	NA	-0.30	1	
Developed landcover	-0.02	NA	-0.33	0.92	1

Table A2.4 Correlation matrix for all variables. Livestock and game producer density, commercial food provider density, and developed landcover were landscape variables measured within 2km of all collection sites. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models. NA values indicate that the variable was not present in the landscape.

	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density	Developed landcover
Date	1				
Livestock and game producer density	NA	1			
Distance to a landfill	0.00	NA	1		
Commercial food provider density	-0.14	NA	-0.17	1	
Developed landcover	-0.05	NA	-0.44	0.91	1

Table A2.5 Correlation matrix for all variables. Livestock and game producer density, commercial food provider density, and developed landcover were landscape variables measured within 3km of all collection sites. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models.

	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density	Developed landcover
Date	1				
Livestock and game producer density	-0.06	1			
Distance to a landfill	0.00	0.51	1		
Commercial food provider density	-0.11	0.50	-0.29	1	
Developed landcover	-0.05	0.31	-0.53	0.85	1

Table A2.6 Correlation matrix for all variables. Livestock and game producer density, commercial food provider density, and developed landcover were landscape variables measured within 4km of all collection sites. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models.

	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density	Developed landcover
Date	1				
Livestock and game producer density	-0.06	1			
Distance to a landfill	0.00	0.51	1		
Commercial food provider density	-0.06	0.46	-0.27	1	
Developed landcover	-0.04	0.28	-0.56	0.82	1

Table A2.7 Correlation matrix for all variables. Livestock and game producer density, commercial food provider density, and developed landcover were landscape variables measured within 5km of all collection sites. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models.

	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density	Developed landcover
Date	1				
Livestock and game producer density	-0.09	1			
Distance to a landfill	0.00	0.53	1		
Commercial food provider density	-0.11	0.48	-0.29	1	
Developed landcover	-0.01	0.24	-0.56	0.84	1

Table A2.8 Correlation matrix for all variables. Livestock and game producer density, commercial food provider density, and developed landcover were landscape variables measured within 10km of all collection sites. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models.

	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density	Developed landcover
Date	1				
Livestock and game producer density	0.08	1			
Distance to a landfill	0.00	-0.62	1		
Commercial food provider density	0.07	0.97	-0.72	1	
Developed landcover	0.11	0.98	-0.68	0.98	1

Table A2.9 Correlation matrix for all variables. Livestock and game producer density, commercial food provider density, and developed landcover were landscape variables measured within 15km of all collection sites. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models.

	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density	Developed landcover
Date	1				
Livestock and game producer density	0.05	1			
Distance to a landfill	0.00	-0.47	1		
Commercial food provider density	0.09	0.90	-0.73	1	
Developed landcover	0.13	0.92	-0.66	0.96	1

Table A2.10 Correlation matrix for all variables. Livestock and game producer density, commercial food provider density, and developed landcover were landscape variables measured within 20km of all collection sites. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models.

	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density	Developed landcover
Date	1				
Livestock and game producer density	0.13	1			
Distance to a landfill	0.00	-0.50	1		
Commercial food provider density	0.10	0.92	-0.73	1	
Developed landcover	0.12	0.97	-0.65	0.99	1

Table A2.11 Variance inflation factors for all variables at each landscape scale for the models. Landscape features were measured at each scale including livestock and game producer density, commercial food provider density, and developed landcover. Distance to a landfill was measured as the distance to the nearest landfill, regardless of landscape scale. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models. NA values indicate that the variable was not present in the landscape.

Landscape scale	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density	Developed landcover
0.4 km	1.03	NA	1.24	3.10	2.75
0.5 km	1.06	NA	1.42	7.88	6.78
1 km	1.08	NA	1.12	6.92	6.97
2 km	1.08	NA	1.99	9.64	11.38
3 km	1.02	4.06	4.71	4.69	6.60
4 km	1.01	3.69	4.93	3.81	6.76
5 km	1.04	3.97	4.78	4.83	6.29
10 km	1.07	39.72	2.92	33.95	38.25
15 km	1.10	11.30	3.67	19.90	18.62
20 km	1.05	51.56	3.63	150.13	304.53

Table A2.12 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and developed landcover were landscape variables measured within 0.4km of all collection sites. NA values indicate that the variable was not present in the landscape.

	Date	Developed landcover	Livestock and game producer density	Distance to a landfill
Date	1			
Developed landcover	0.00	1		
Livestock and game producer density	NA	NA	1	
Distance to a landfill	0.00	-0.31	NA	1

Table A2.13 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and developed landcover were landscape variables measured within 0.5km of all collection sites. NA values indicate that the variable was not present in the landscape.

	Date	Developed landcover	Livestock and game producer density	Distance to a landfill
Date	1			
Developed landcover	-0.01	1		
Livestock and game producer density	NA	NA	1	
Distance to a landfill	0.00	-0.35	NA	1

Table A2.14 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and developed landcover were landscape variables measured within 1km of all collection sites. NA values indicate that the variable was not present in the landscape.

	Date	Developed landcover	Livestock and game producer density	Distance to a landfill
Date	1			
Developed landcover	-0.02	1		
Livestock and game producer density	NA	NA	1	
Distance to a landfill	0.00	-0.33	NA	1

Table A2.15 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and developed landcover were landscape variables measured within 2km of all collection sites. NA values indicate that the variable was not present in the landscape.

	Date	Developed landcover	Livestock and game producer density	Distance to a landfill
Date	1			
Developed landcover	-0.05	1		
Livestock and game producer density	NA	NA	1	
Distance to a landfill	0.00	-0.44	NA	1

Table A2.16 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and developed landcover were landscape variables measured within 3km of all collection sites.

	Date	Developed landcover	Livestock and game producer density	Distance to a landfill
Date	1			
Developed landcover	-0.05	1		
Livestock and game producer density	-0.06	0.31	1	
Distance to a landfill	0.00	-0.53	0.51	1

Table A2.17 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and developed landcover were landscape variables measured within 4km of all collection sites.

	Date	Developed landcover	Livestock and game producer density	Distance to a landfill
Date	1			
Developed landcover	-0.04	1		
Livestock and game producer density	-0.06	0.28	1	
Distance to a landfill	0.00	-0.56	0.51	1

Table A2.18 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and developed landcover were landscape variables measured within 5km of all collection sites.

	Date	Developed landcover	Livestock and game producer density	Distance to a landfill
Date	1			
Developed landcover	-0.01	1		
Livestock and game producer density	-0.09	0.24	1	
Distance to a landfill	0.00	-0.56	0.53	1

Table A2.19 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and developed landcover were landscape variables measured within 10km of all collection sites. Due to high levels of correlation, developed landcover was removed from this model.

	Date	Livestock and game producer density	Distance to a landfill
Date	1		
Livestock and game producer density	0.08	1	
Distance to a landfill	0.00	-0.62	1

Table A2.20 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and developed landcover were landscape variables measured within 15km of all collection sites. Due to high levels of correlation, developed landcover was removed from this model.

	Date	Livestock and game producer density	Distance to a landfill
Date	1		
Livestock and game producer density	0.06	1	
Distance to a landfill	0.00	-0.47	1

Table A2.21 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and developed landcover were landscape variables measured within 20km of all collection sites. Due to high levels of correlation, developed landcover was removed from this model.

	Date	Livestock and game producer density	Distance to a landfill
Date	1		
Livestock and game producer density	0.13	1	
Distance to a landfill	0.00	-0.50	1

Table A2.22 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and commercial food provider density were landscape variables measured within 0.4km of all collection sites. NA values indicate that the variable was not present in the landscape.

	Date	Commercial food provider density	Livestock and game producer density	Distance to a landfill
Date	1			
Commercial food provider density	-0.10	1		
Livestock and game producer density	NA	NA	1	
Distance to a landfill	0.00	-0.44	NA	1

Table A2.23 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and commercial food provider density were landscape variables measured within 0.5km of all collection sites. NA values indicate that the variable was not present in the landscape.

	Date	Commercial food provider density	Livestock and game producer density	Distance to a landfill
Date	1			
Commercial food provider density	-0.10	1		
Livestock and game producer density	NA	NA	1	
Distance to a landfill	0.00	-0.48	NA	1

Table A2.24 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and commercial food provider density were landscape variables measured within 1km of all collection sites. NA values indicate that the variable was not present in the landscape.

	Date	Commercial food provider density	Livestock and game producer density	Distance to a landfill
Date	1			
Commercial food provider density	-0.13	1		
Livestock and game producer density	NA	NA	1	
Distance to a landfill	0.00	-0.30	NA	1

Table A2.25 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and commercial food provider density were landscape variables measured within 2km of all collection sites. NA values indicate that the variable was not present in the landscape.

	Date	Commercial food provider density	Livestock and game producer density	Distance to a landfill
Date	1			
Commercial food provider density	-0.14	1		
Livestock and game producer density	NA	NA	1	
Distance to a landfill	0.00	-0.17	NA	1

Table A2.26 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and commercial food provider density were landscape variables measured within 3km of all collection sites.

	Date	Commercial food provider density	Livestock and game producer density	Distance to a landfill
Date	1			
Commercial food provider density	-0.11	1		
Livestock and game producer density	-0.06	0.50	1	
Distance to a landfill	0.00	-0.29	0.51	1

Table A2.27 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and commercial food provider density were landscape variables measured within 4km of all collection sites.

	Date	Commercial food provider density	Livestock and game producer density	Distance to a landfill
Date	1			
Commercial food provider density	-0.06	1		
Livestock and game producer density	-0.06	0.46	1	
Distance to a landfill	0.00	-0.27	0.51	1

Table A2.28 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Livestock and game producer density and commercial food provider density were landscape variables measured within 5km of all collection sites.

	Date	Commercial food provider density	Livestock and game producer density	Distance to a landfill
Date	1			
Commercial food provider density	-0.11	1		
Livestock and game producer density	-0.09	0.48	1	
Distance to a landfill	0.00	-0.29	0.53	1

Table A2.29 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Developed landcover was a landscape variables measured within 10km of all collection sites. Due to high levels of correlation, livestock and game producer density was removed from this model.

	Date	Developed landcover	Distance to a landfill
Date	1		
Developed landcover	-0.09	1	
Distance to a landfill	-0.07	0.66	1

Table A2.30 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Developed landcover was a landscape variable measured within 15km of all collection sites. Due to high levels of correlation, livestock and game producer density was removed from this model.

	Date	Developed landcover	Distance to a landfill
Date	1		
Developed landcover	-0.11	1	
Distance to a landfill	-0.08	0.65	1

Table A2.31 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Developed landcover was a landscape variable measured within 20km of all collection sites. Due to high levels of correlation, livestock and game producer density was removed from this model.

	Date	Developed landcover	Distance to a landfill
Date	1		
Developed landcover	-0.11	1	
Distance to a landfill	-0.08	0.65	1

Table A2.32 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Commercial food provider density was a landscape variables measured within 10km of all collection sites. Due to high levels of correlation, livestock and game producer density was removed from this model.

	Date	Commercial food provider density	Distance to a landfill
Date	1		
Commercial food provider density	-0.05	1	
Distance to a landfill	-0.04	0.68	1

Table A2.33 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Commercial food provider density was a landscape variables measured within 15km of all collection sites. Due to high levels of correlation, livestock and game producer density was removed from this model.

	Date	Commercial food provider density	Distance to a landfill
Date	1		
Commercial food provider density	-0.07	1	
Distance to a landfill	-0.06	0.69	1

Table A2.34 Correlation matrix for all variables after splitting commercial food provider density and developed landcover. Commercial food provider density was a landscape variables measured within 20km of all collection sites. Due to high levels of correlation, livestock and game producer density was removed from this model.

	Date	Commercial food provider density	Distance to a landfill
Date	1		
Commercial food provider density	-0.10	1	
Distance to a landfill	-0.08	0.73	1

Table A2.35 Variance inflation factors for all variables at each landscape scale for the models after removing developed landcover from 10-20km landscape scales. Landscape features were measured at each scale including livestock and game producer density, commercial food provider density, and developed landcover. Distance to a landfill was measured as the distance to the nearest landfill, regardless of landscape scale. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models. NA values indicate that the variable was not present in the landscape.

Landscape scale	Date	Livestock and game producer density	Distance to a landfill	Developed landcover
0.4 km	1.00	NA	1.11	1.11
0.5 km	1.00	NA	1.14	1.14
1 km	1.00	NA	1.12	1.12
2 km	1.00	NA	1.24	1.24
3 km	1.01	3.74	4.71	3.88
4 km	1.01	3.61	4.85	3.91
5 km	1.02	3.50	4.77	3.62
10 km	1.07	29.93	2.06	34.27
15 km	1.10	9.33	2.52	13.43
20 km	1.03	24.69	2.81	31.77

Table A2.36 Variance inflation factors for all variables at each landscape scale for the models with neither developed landcover nor commercial food provider density at 10-20km landscape scales. Landscape features were measured at each scale including livestock and game producer density, commercial food provider density, and developed landcover. Distance to a landfill was measured as the distance to the nearest landfill, regardless of landscape scale. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models. NA values indicate that the variable was not present in the landscape.

Landscape scale	Date	Livestock and game producer density	Distance to a landfill	Developed landcover
0.4 km	1.00	NA	1.11	1.11
0.5 km	1.00	NA	1.14	1.14
1 km	1.00	NA	1.12	1.12
2 km	1.00	NA	1.24	1.24
3 km	1.01	3.74	4.71	3.88
4 km	1.01	3.61	4.85	3.91
5 km	1.02	3.50	4.77	3.62
10 km	1.01	1.65	1.64	NA
15 km	1.00	1.28	1.28	NA
20 km	1.02	1.37	1.35	NA

Table A2.37 Variance inflation factors for all variables at each landscape scale for the models with developed landcover removed from 10-20km landscape scales. Landscape features were measured at each scale including livestock and game producer density, commercial food provider density, and developed landcover. Distance to a landfill was measured as the distance to the nearest landfill, regardless of landscape scale. Due to high levels of correlation, commercial food provider density and developed landcover were separated into different models. NA values indicate that the variable was not present in the landscape.

Landscape scale	Date	Livestock and game producer density	Distance to a landfill	Commercial food provider density
0.4 km	1.01	NA	1.24	1.25
0.5 km	1.01	NA	1.31	1.33
1 km	1.02	NA	1.10	1.12
2 km	1.02	NA	1.03	1.05
3 km	1.01	3.37	2.78	2.75
4 km	1.01	2.76	2.34	2.20
5 km	1.01	3.54	2.99	2.78
10 km	1.01	23.53	2.82	30.42
15 km	1.05	8.53	3.52	14.35
20 km	1.02	9.76	3.41	15.66

Table A2.38 Fourier transform infrared spectroscopy results for pieces of plastic material from black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. Only matches for each sample with the highest Pearson's r value are listed (some samples have multiple matches).

Sample no.	Top result	Pearson's r	Source
194-1	Silicone seal reactor	0.98	Primpke et al. 2018
199-1	Polypropylene	0.91	Primpke et al. 2018
199-3	Polyethylene low density	0.99	Primpke et al. 2018
205-1	Leaf-plant	0.76	Suja Sukumaran, Thermo Fisher Scientific
205-3	HDPE	0.95	Chabuka et al. 2020
216-1	Polyethylene	0.97	Suja Sukumaran, Thermo Fisher Scientific
221-1	Poly(vinyl chloride) carboxylated/ Polyvinylchloride with plasticizer	0.91	Primpke et al. 2018
221-2	HDPE	0.9	Chabuka et al. 2020
221-3	HDPE	0.79	Chabuka et al. 2020
221-4	HDPE	0.85	Chabuka et al. 2020
227-1	Poly(vinyl chloride) carboxylated/ Polyvinylchloride/ Vinylidene chloride vinyl chloride	0.95	Primpke et al. 2018
234-1	Polyethylene with acryloid and pthalocyanine (blue)/ Ethylene ethyl acrylate/ HDPE	0.94	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018 Chabuka et al. 2020
238-1	Fur red deer/ Fibre polyamide 6 (not)stretched	0.86	Primpke et al. 2018
263-1	Sealing ring EPDM	0.76	Primpke et al. 2018
267-1	Polyvinylchloride/ Polyvinylchloride with plasticizer	0.83	Primpke et al. 2018
269-1	Ethylene acrylic acid	0.93	Primpke et al. 2018
270-1	Ethylene acrylic acid	0.95	Primpke et al. 2018

Table A2.38 (continued) Fourier transform infrared spectroscopy results for pieces of plastic material from black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. Only matches for each sample with the highest Pearson's r value are listed (some samples have multiple matches).

Sample no.	Top result	Pearson's r	Source
274-1	Polyethylene with acryloid and pthalocyanine (blue)	0.96	Suja Sukumaran, Thermo Fisher Scientific
275-1	Leaf-plant/ Ethyl cellulose	0.79	Suja Sukumaran, Thermo Fisher Scientific
284-1	Polyethylene with acryloid and pthalocyanine (blue)	0.83	Suja Sukumaran, Thermo Fisher Scientific
297-1	HDPE	0.92	Chabuka et al. 2020
301-1	Polyethylene	0.95	Suja Sukumaran, Thermo Fisher Scientific
301-2	HDPE	0.93	Chabuka et al. 2020
315-1	PE+Silicate+bio/ PE with silicate inorganic	0.77	Suja Sukumaran, Thermo Fisher Scientific
321-1	Sealing ring EPDM	0.9	Primpke et al. 2018
321-2	Ethylene propylene/polyethylene	0.95	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
321-3	LDPE	0.95	Chabuka et al. 2020
337-1	PE	0.81	Chabuka et al. 2020
345-1	Leaf-plant	0.83	Suja Sukumaran, Thermo Fisher Scientific
345-2	Poly(vinyl chloride) carboxylated	0.85	Primpke et al. 2018
362-1	Fur cat European shorthair/zein purified	0.87	Primpke et al. 2018
366-1	PE+Silicate+bio/PE with silicate inorganic	0.81	Suja Sukumaran, Thermo Fisher Scientific
366-2	Poly(vinyl stearate)	0.9	Primpke et al. 2018
366-3	Fibre jute	0.95	Primpke et al. 2018

Table A2.38 (continued) Fourier transform infrared spectroscopy results for pieces of plastic material from black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. Only matches for each sample with the highest Pearson's r value are listed (some samples have multiple matches).

Sample no.	Top result	Pearson's r	Source
369-1	Fur red deer	0.89	Primpke et al. 2018
371-1	Chitin cancer pagurus	0.93	Primpke et al. 2018
371-5	Polyethylene/Ethylene propylene/Polyethylene with acryloid and pthalocyanine (blue)/Polyethylene low density	0.9	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
372-1	Fibre jute	0.94	Primpke et al. 2018
373-1	Algae fucus serratus	0.86	Primpke et al. 2018
374-1	Fur red deer	0.91	Primpke et al. 2018
374-2	Fur red deer	0.89	Primpke et al. 2018
376-1	Silicone rubber	0.97	Primpke et al. 2018
376-2	Silicone rubber	0.97	Primpke et al. 2018
376-3	Silicone rubber	0.97	Primpke et al. 2018
376-4	Fur red deer	0.86	Primpke et al. 2018
378-1	Fur red deer	0.92	Primpke et al. 2018
378-2	Polystyrene	0.96	Suja Sukumaran, Thermo Fisher Scientific
378-3	Fur red deer/Fibre silk slubbing/Fibre mulberry silk	0.78	Primpke et al. 2018
379-1	Fur red deer	0.81	Primpke et al. 2018
379-2	Fibre tussah silk	0.9	Primpke et al. 2018

Table A2.38 (continued) Fourier transform infrared spectroscopy results for pieces of plastic material from black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. Only matches for each sample with the highest Pearson's r value are listed (some samples have multiple matches).

Sample no.	Top result	Pearson's r	Source
380-2	Polyethylene/polyethylene low density	0.99	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
381-2	Fibre jute	0.94	Primpke et al. 2018
383-1	Zein purified/Fur red deer	0.89	Primpke et al. 2018
383-2	Fibre jute	0.94	Primpke et al. 2018
384-1	PE+Silicate+bio/PE with silicate inorganic/Sealing ring EPDM	0.79	Suja Sukumaran, Thermo Fisher Scientific
386-1	Fibre jute	0.96	Primpke et al. 2018
386-2	Cardboard/cellulose	0.95	Suja Sukumaran, Thermo Fisher Scientific
386-3	Fibre jute	0.95	Primpke et al. 2018
390-1	Silicone rubber	0.98	Primpke et al. 2018
390-2	Fur red deer	0.86	Primpke et al. 2018
391-1	Polyethylene	0.93	Suja Sukumaran, Thermo Fisher Scientific
392-1	Polyamide	0.76	Primpke et al. 2018
395-2	Polyvinylchloride	0.84	Primpke et al. 2018
395-3	Pthalate and propyl alcohol mix	0.68	Suja Sukumaran, Thermo Fisher Scientific
397-1	Silicone rubber	0.99	Primpke et al. 2018
397-2	Vinylidene chloride acrylonitrile	0.75	Primpke et al. 2018
397-3	Silicone rubber	0.99	Primpke et al. 2018
401-1	Black broodcomb	0.75	Primpke et al. 2018

Table A2.38 (continued) Fourier transform infrared spectroscopy results for pieces of plastic material from black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. Only matches for each sample with the highest Pearson's r value are listed (some samples have multiple matches).

Sample no.	Top result	Pearson's r	Source
401-2	Silicone rubber	0.99	Primpke et al. 2018
401-3	Silicone rubber	0.99	Primpke et al. 2018
404-1	Algae fucus serratus	0.83	Primpke et al. 2018
404-2	Fur red deer	0.91	Primpke et al. 2018
406-1	Polyethylene/Polyethylene oxidized/Ethylene propylene/Polyethylene low density	0.97	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
406-3	Chitin from crustacean shells	0.75	Primpke et al. 2018
406-4	Fibre jute	0.95	Primpke et al. 2018
406-5	Leaf-plant	0.95	Suja Sukumaran, Thermo Fisher Scientific
409-1	HDPE	0.96	Chabuka et al. 2020
423-1	HDPE	0.94	Chabuka et al. 2020
424-1	HDPE	0.97	Chabuka et al. 2020
433-1	PE+Silicate+bio/PE with silicate inorganic	0.86	Suja Sukumaran, Thermo Fisher Scientific
434-1	Silicone rubber	0.99	Primpke et al. 2018
435-2	Fur red deer	0.87	Primpke et al. 2018
435-3	Cardboard/cellulose	0.78	Suja Sukumaran, Thermo Fisher Scientific
554-6	Silicone rubber	0.99	Primpke et al. 2018
556-7	Silicone rubber	0.99	Primpke et al. 2018
565-1	PE+Silicate+bio/PE with silicate inorganic/Leaf-plant	0.84	Suja Sukumaran, Thermo Fisher Scientific

Table A2.38 (continued) Fourier transform infrared spectroscopy results for pieces of plastic material from black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. Only matches for each sample with the highest Pearson's r value are listed (some samples have multiple matches).

Sample no.	Top result	Pearson's r	Source
577-2	Fibre silk slubbing	0.86	Primpke et al. 2018
577-5	Black broodcomb	0.82	Primpke et al. 2018
580-1	Fur red deer/Fibre silk slubbing/Fur wild boar	0.84	Primpke et al. 2018
580-4	Fibre silk slubbing	0.85	Primpke et al. 2018
580-5	Fur wild boar	0.81	Primpke et al. 2018
580-7	Fibre silk slubbing	0.83	Primpke et al. 2018
580-10	Fur red deer/Fur wild board	0.84	Primpke et al. 2018
580-11	Leaf-plant/Chitin from crustacean shells	0.8	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
581-1	Polyethylene low density/Ethylene propylene/Polyethylene/Fibre thermoplastic elastomere	0.97	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
581-2	PE+Silicate+bio/PE with silicate inorganic	0.84	Suja Sukumaran, Thermo Fisher Scientific
581-4	Nylon 6 9	0.76	Primpke et al. 2018
581-5	Fibre silk slubbing/Fur red deer	0.88	Primpke et al. 2018
613-3	Polyamide 66	0.79	Primpke et al. 2018
613-6	Leaf-plant	0.92	Suja Sukumaran, Thermo Fisher Scientific
613-11	Black broodcomb	0.89	Primpke et al. 2018
618-2	Leaf-plant	0.94	Suja Sukumaran, Thermo Fisher Scientific

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Table A2.38 (continued) Fourier transform infrared spectroscopy results for pieces of plastic material from black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. Only matches for each sample with the highest Pearson's r value are listed (some samples have multiple matches).

Sample no.	Top result	Pearson's r	Source
620-1	Leaf-plant	0.9	Suja Sukumaran, Thermo Fisher Scientific
626-4	Silicone rubber	0.98	Primpke et al. 2018
636-1	Silicone/PDMS	0.97	Suja Sukumaran, Thermo Fisher Scientific
636-2	Cardboard/cellulose	0.9	Suja Sukumaran, Thermo Fisher Scientific
646-2	PE+Silicate+bio/PE with silicate inorganic	0.75	Suja Sukumaran, Thermo Fisher Scientific
654-1	HDPE	0.91	Chabuka et al. 2020
658-3	Cardboard/cellulose	0.86	Suja Sukumaran, Thermo Fisher Scientific
658-4	Styrene allyl alcohol	0.86	Suja Sukumaran, Thermo Fisher Scientific
672-1	PE+Silicate+bio/PE with silicate inorganic	0.77	Suja Sukumaran, Thermo Fisher Scientific
672-2	Silicone seal reactor	0.97	Primpke et al. 2018
672-3	Polyethylene low density/Ethylene propylene/Polyethylene/Fibre thermoplastic elastomere	0.97	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
672-4	Ethylene propylene	0.94	Primpke et al. 2018
672-8	Fibre jute/Fibre grass/Cardboard/cellulose/Le af-plant	0.93	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
672-13	Fibre jute	0.94	Primpke et al. 2018

Table A2.38 (continued) Fourier transform infrared spectroscopy results for pieces of plastic material from black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. Only matches for each sample with the highest Pearson's r value are listed (some samples have multiple matches).

Sample no.	Top result	Pearson's r	Source
676-2	Polyethylene with acryloid and pthalocyanine (blue)	0.79	Suja Sukumaran, Thermo Fisher Scientific
676-3	Broodcomb once brooded	0.8	Primpke et al. 2018
676-4	Polyethylene/Polyethylene with acryloid and pthalocyanine (blue)	0.9	Suja Sukumaran, Thermo Fisher Scientific
677-1	Fibre tussah silk	0.9	Primpke et al. 2018
677-2	Fibre polyamide 6 (not)stretched/Fibre silk slubbing	0.84	Primpke et al. 2018
677-3	Fur red deer	0.89	Primpke et al. 2018
677-4	Fibre silk slubbing/Fur red deer	0.9	Primpke et al. 2018
678-1	Silicone rubber	1	Primpke et al. 2018
680-3	Leaf-plant	0.77	Suja Sukumaran, Thermo Fisher Scientific
685-1	Algae fucus serratus	0.84	Primpke et al. 2018
685-2	Polypropylene	0.93	Primpke et al. 2018
686-3	Copolyamide	0.78	Primpke et al. 2018
686-4	Fibre silk slubbing	0.9	Primpke et al. 2018
686-5	Fibre silk slubbing	0.9	Primpke et al. 2018
692-3	HDPE	0.76	Chabuka et al. 2020
699-3	Ethylene acrylic acid	0.91	Primpke et al. 2018
700-1	Silicone rubber/Silicone seal reactor	0.98	Primpke et al. 2018
704-2	PE+Silicate+bio/PE with silicate inorganic	0.8	Suja Sukumaran, Thermo Fisher Scientific

Table A2.38 (continued) Fourier transform infrared spectroscopy results for pieces of plastic material from black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. Only matches for each sample with the highest Pearson's r value are listed (some samples have multiple matches).

Sample no.	Top result	Pearson's r	Source
704-7	Black broodcomb/Broodcomb once brooded	0.86	Primpke et al. 2018
704-8	Alkyd varnish	0.84	Primpke et al. 2018
704-11	PE+Silicate+Bio	0.79	Suja Sukumaran, Thermo Fisher Scientific
704-15	Leaf-plant	0.86	Suja Sukumaran, Thermo Fisher Scientific
704-17	Fibre grass/Cardboard/cellulose	0.93	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
704-19	Cardboard/cellulose/Fibre grass/Leaf-plant/Papercup_Cellulosic	0.93	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
704-21	Polyethylene	0.89	Suja Sukumaran, Thermo Fisher Scientific
704-24	HDPE	0.91	Chabuka et al. 2020
704-25	Cardboard/cellulose/Fibre grass/Fibre jute/Papercup_Cellulosic	0.94	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
707-1	Leaf-plant	0.94	Suja Sukumaran, Thermo Fisher Scientific
707-2	Cardboard/cellulose/Fibre grass/Papercup_Cellulosic	0.94	Suja Sukumaran, Thermo Fisher Scientific Primpke et al. 2018
707-6	Leaf-plant/Cardboard/cellulose	0.91	Suja Sukumaran, Thermo Fisher Scientific

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Table A2.38 (continued) Fourier transform infrared spectroscopy results for pieces of plastic material from black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. Only matches for each sample with the highest Pearson's r value are listed (some samples have multiple matches).

Sample no.	Top result	Pearson's r	Source
707-13	Leaf-plant	0.94	Suja Sukumaran, Thermo Fisher Scientific
707-16	Leaf-plant	0.92	Suja Sukumaran, Thermo Fisher Scientific
708-1	Alkyd varnish	0.88	Primpke et al. 2018
708-2	Poly(vinyl stearate)	0.83	Primpke et al. 2018
708-4	Cellulose	0.95	Suja Sukumaran, Thermo Fisher Scientific
708-7	Leaf-plant	0.94	Suja Sukumaran, Thermo Fisher Scientific
722-1	Fibre polyamide 6 (not)stretched	0.76	Primpke et al. 2018
722-2	Fur red deer	0.82	Primpke et al. 2018
722-3	Leaf-plant	0.78	Suja Sukumaran, Thermo Fisher Scientific
722-4	Leaf-plant	0.88	Suja Sukumaran, Thermo Fisher Scientific
724-1	Polyamide 66	0.78	Primpke et al. 2018
724-2	Polyamide/Nylon 6 9	0.79	Primpke et al. 2018
922-22	Polyester epoxide	0.78	Primpke et al. 2018
925-2	Leaf-plant	0.89	Suja Sukumaran, Thermo Fisher Scientific
927-1	Fibre polyamide 6 (not)stretched	0.79	Primpke et al. 2018
927-3	Fibre silk slubbing	0.83	Primpke et al. 2018

Table A2.38 (continued) Fourier transform infrared spectroscopy results for pieces of plastic material from black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) pellets collected in the Charlotte Metropolitan Area, USA. Only matches for each sample with the highest Pearson's r value are listed (some samples have multiple matches).

Sample no.	Top result	Pearson's r	Source
927-4	Epoxide resin	0.85	Primpke et al. 2018
927-6	Epoxide resin/Polyester epoxide	0.82	Primpke et al. 2018
927-9	Leaf-plant	0.82	Suja Sukumaran, Thermo Fisher Scientific
927-11	Leaf-plant	0.82	Suja Sukumaran, Thermo Fisher Scientific
927-12	Fibre polyamide 6 (not)stretched	0.78	Primpke et al. 2018
927-13	Fibre silk slubbing	0.89	Primpke et al. 2018
927-14	Leaf-plant	0.81	Suja Sukumaran, Thermo Fisher Scientific
927-15	Leaf-plant	0.78	Suja Sukumaran, Thermo Fisher Scientific
927-16	Polyester epoxide	0.82	Primpke et al. 2018
927-21	Fibre polyamide 6 (not)stretched	0.81	Primpke et al. 2018

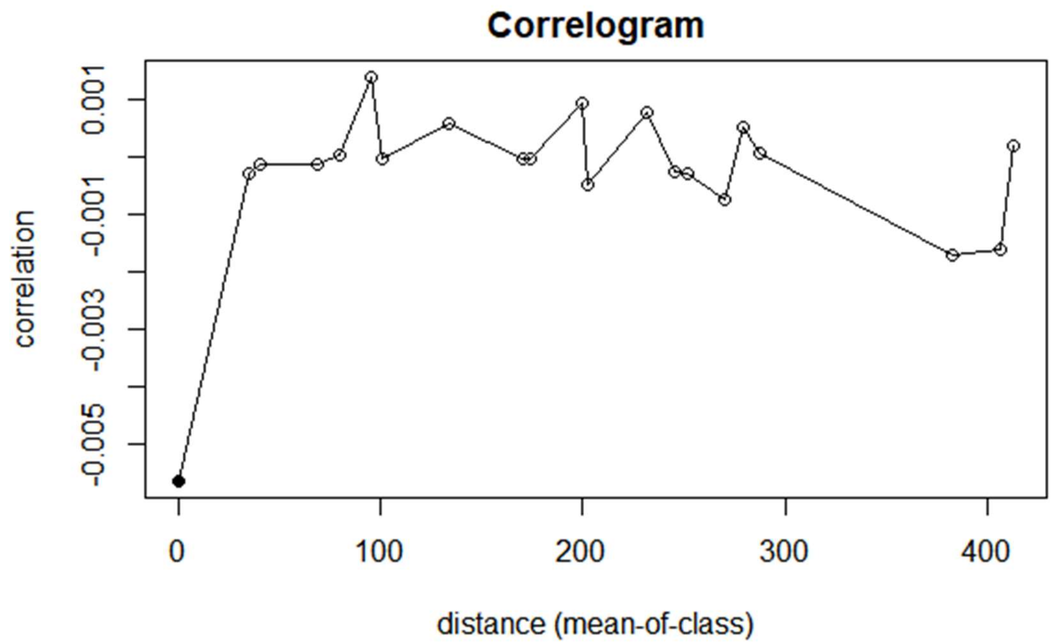

Figure A2.1 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and developed landcover in 0.4km landscapes. Moran I statistic = -4.21e-3, p-value = 0.92.

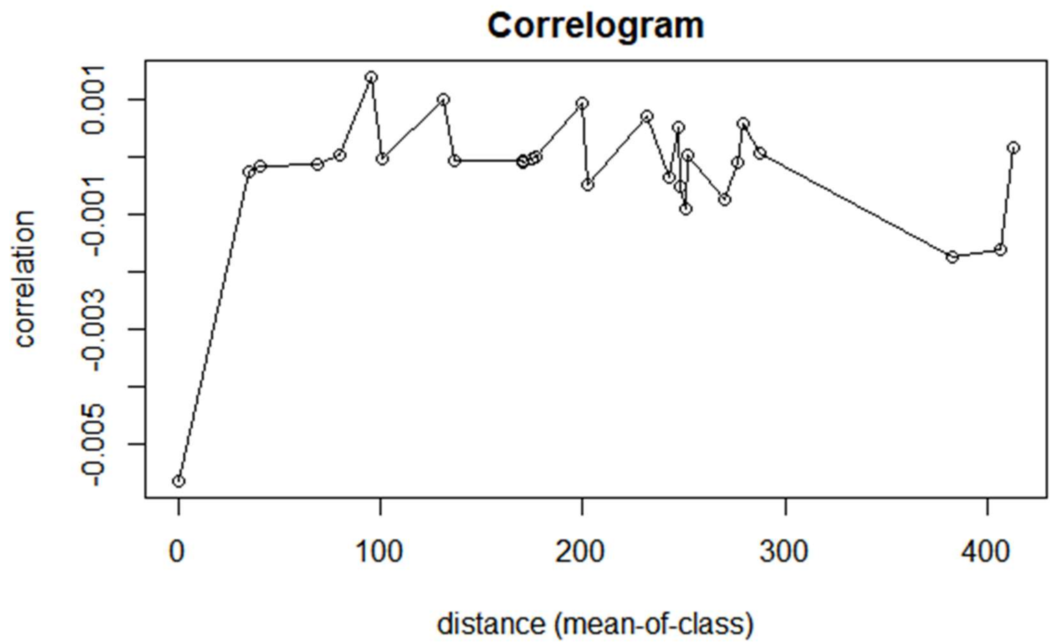

Figure A2.2 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and developed landcover in 0.5km landscapes. Moran I statistic = -4.20e-3, p-value = 0.92.

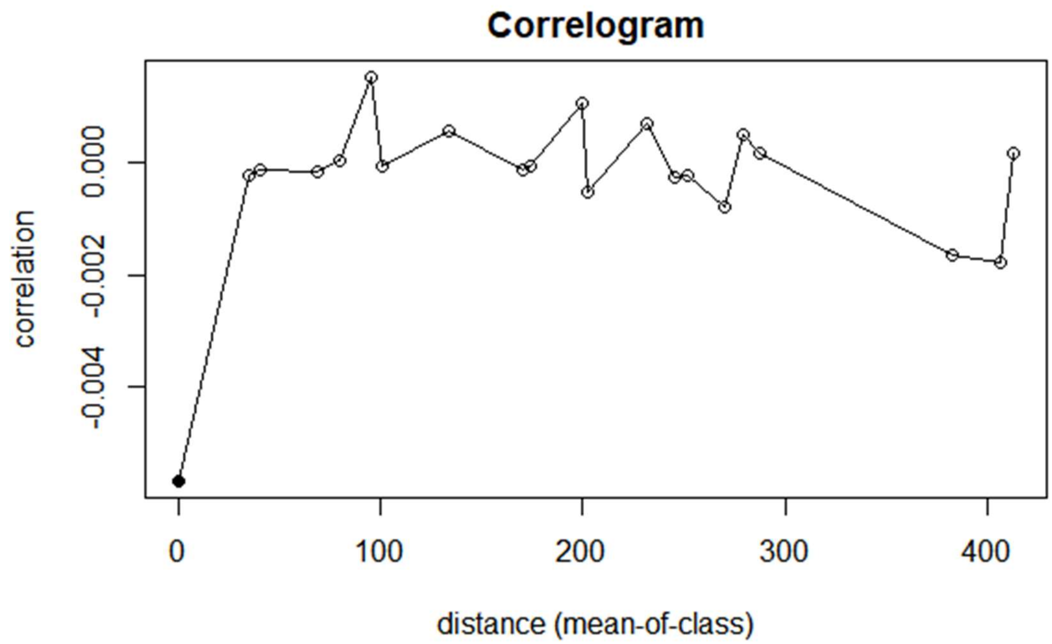

Figure A2.3 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and developed landcover in 1km landscapes. Moran I statistic = -4.21e-3, p-value = 0.92.

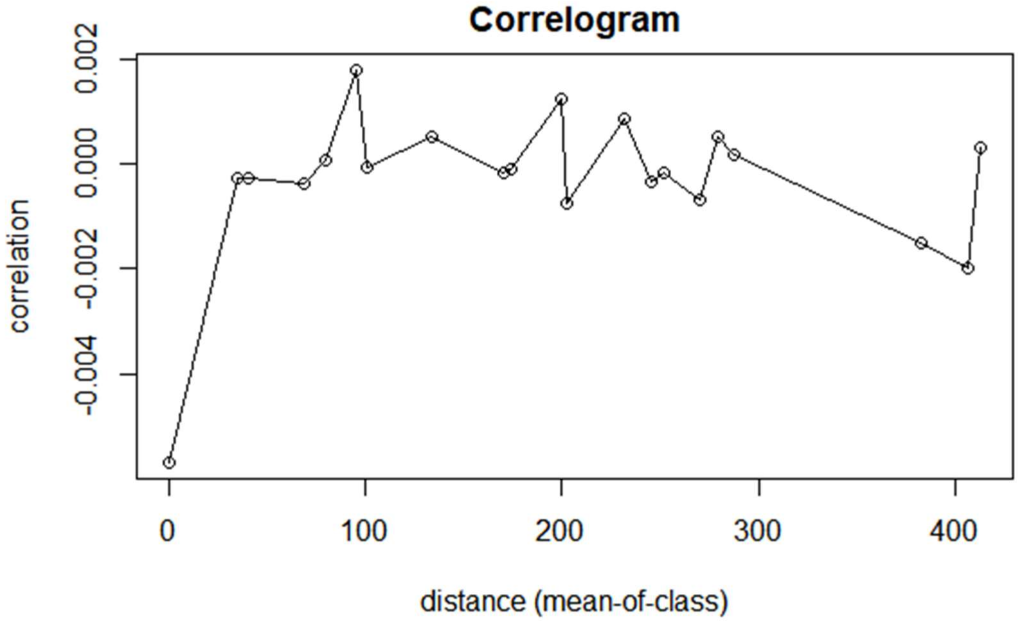

Figure A2.4 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and developed landcover in 2km landscapes. Moran I statistic = -4.26e-3, p-value = 0.93.

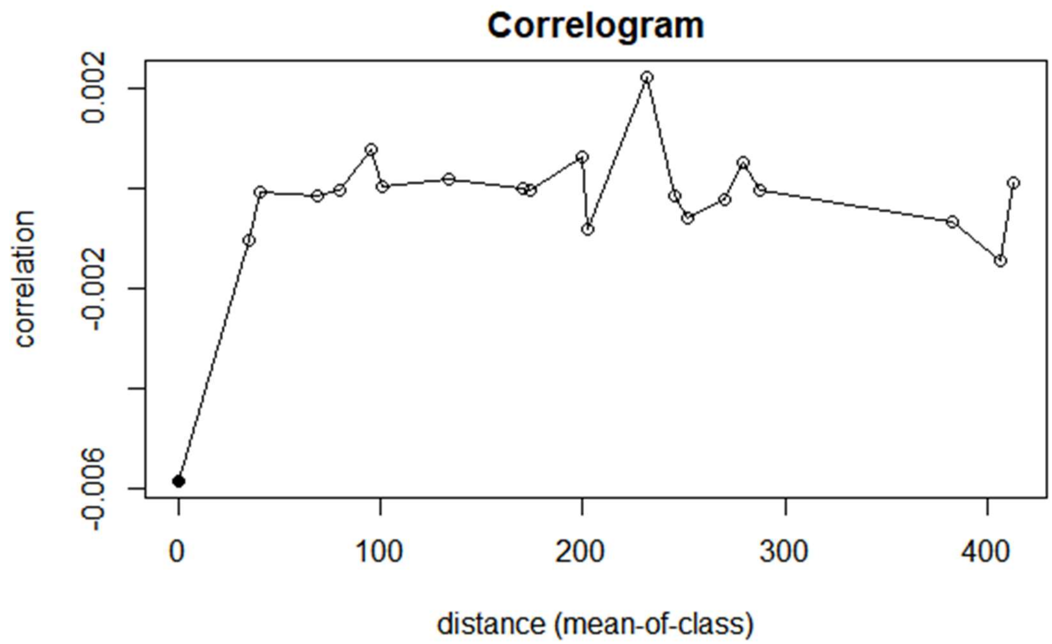

Figure A2.5 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, site, and developed landcover and livestock and game producer density in 3km landscapes. Moran I statistic = -4.47e-3, p-value = 0.94.

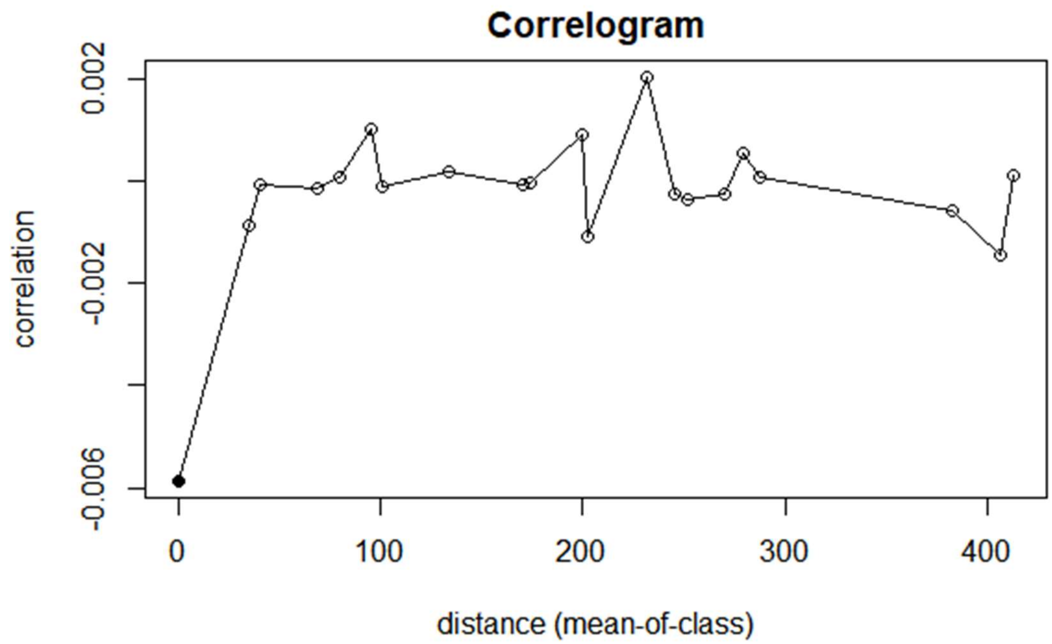

Figure A2.6 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and developed landcover and livestock and game producer density in 4km landscapes. Moran I statistic = -4.47e-3, p-value = 0.94.

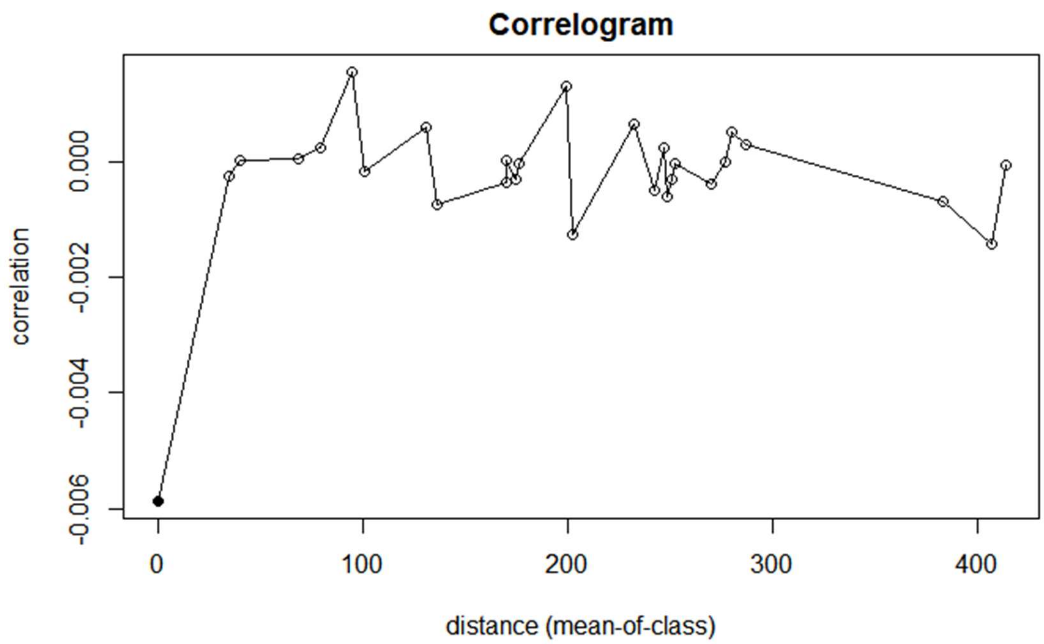

Figure A2.7 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and developed landcover and livestock and game producer density in 5km landscapes. Moran I statistic = -4.35e-3, p-value = 0.93.

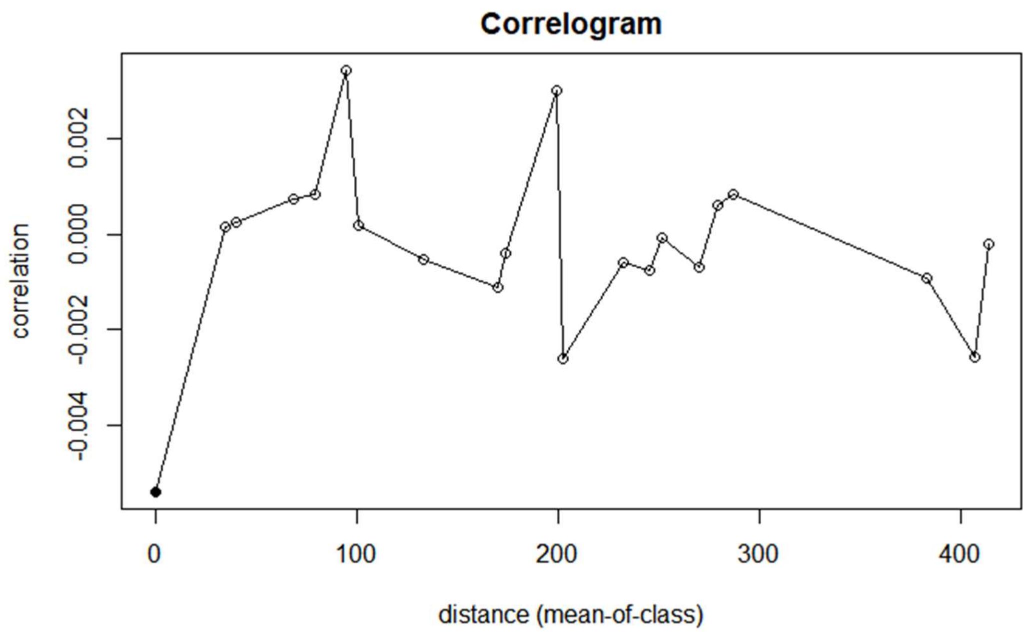

Figure A2.8 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and livestock and game producer density in 10km landscapes. Moran I statistic = -3.83e-3, p-value = 0.90.

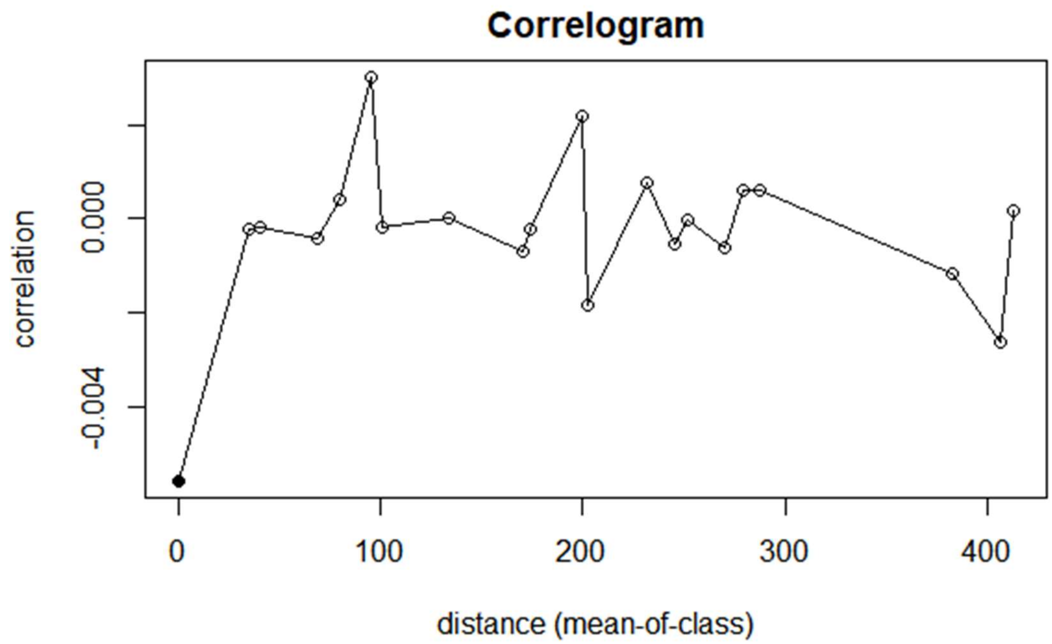

Figure A2.9 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and livestock and game producer density in 15km landscapes. Moran I statistic = -4.14e-3, p-value = 0.92.

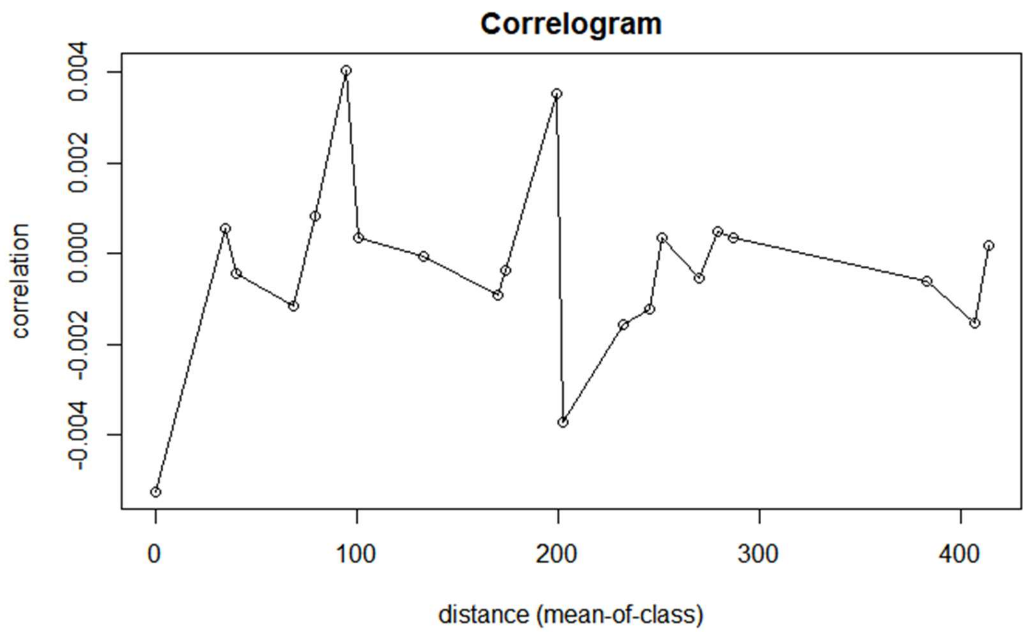

Figure A2.10 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and livestock and game producer density in 20km landscapes. Moran I statistic = -3.94e-3, p-value = 0.90.

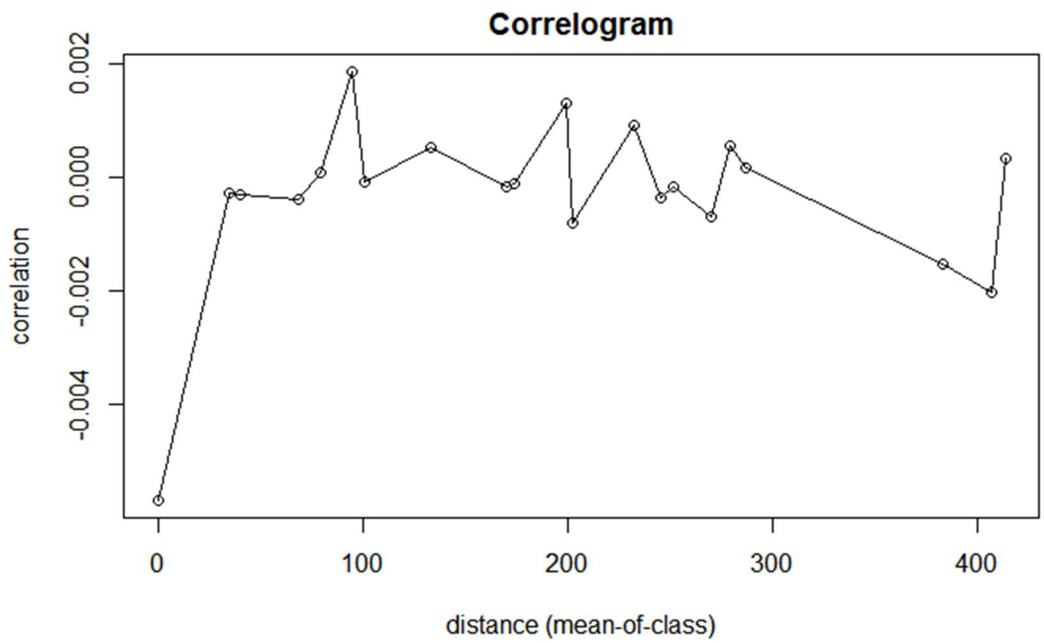

Figure A2.11 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and commercial food provider density in 0.4km landscapes. Moran I statistic = -4.25e-3, p-value = 0.93.

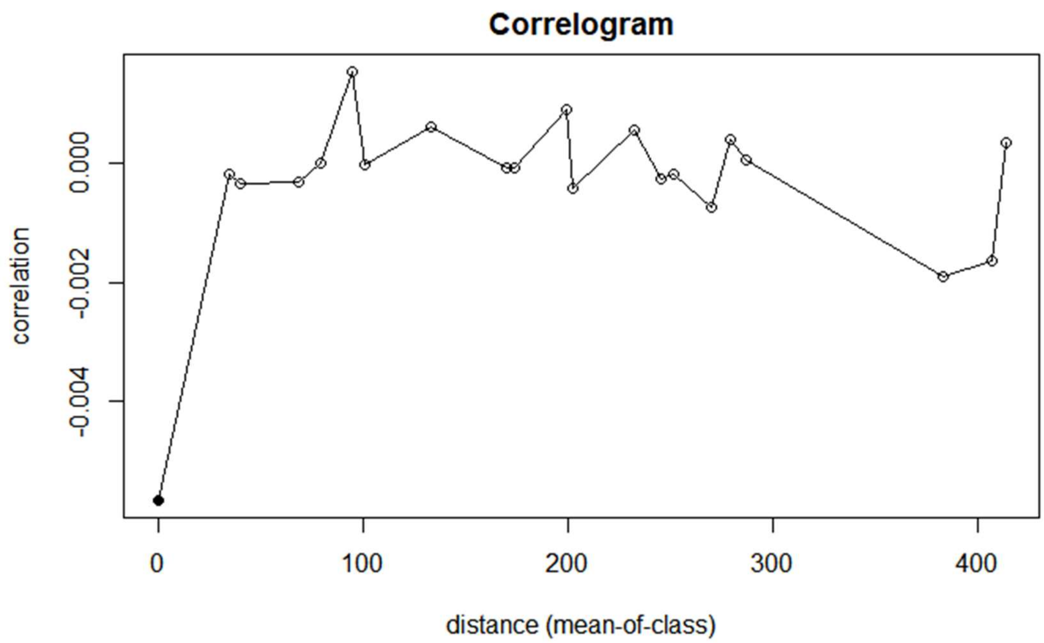

Figure A2.12 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and commercial food provider density in 0.5km landscapes. Moran I statistic = -4.22e-3, p-value = 0.92.

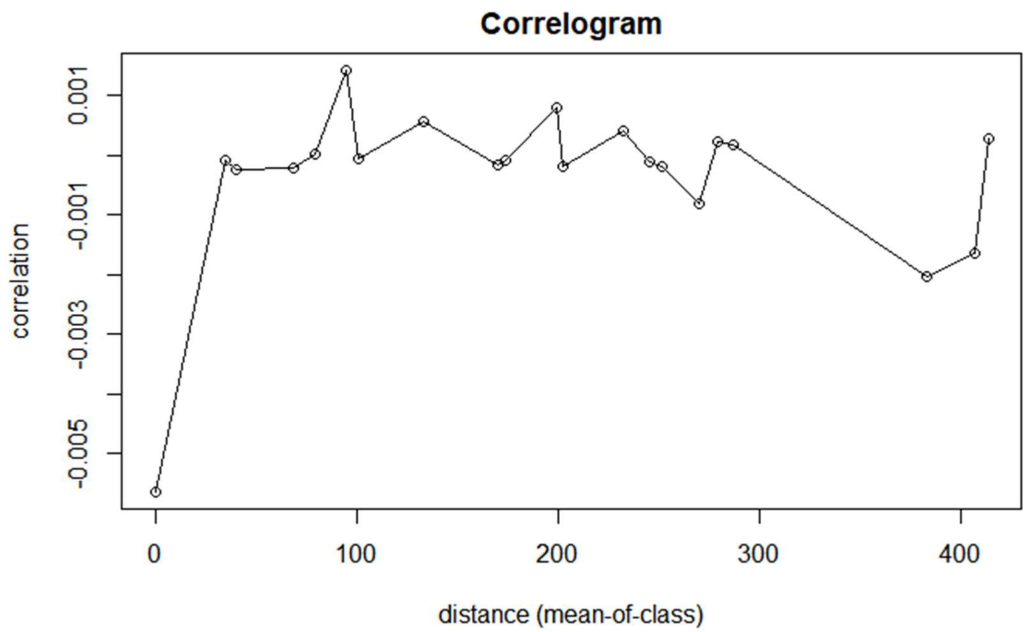

Figure A2.13 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and commercial food provider density in 1km landscapes. Moran I statistic = -4.17e-3, p-value = 0.92.

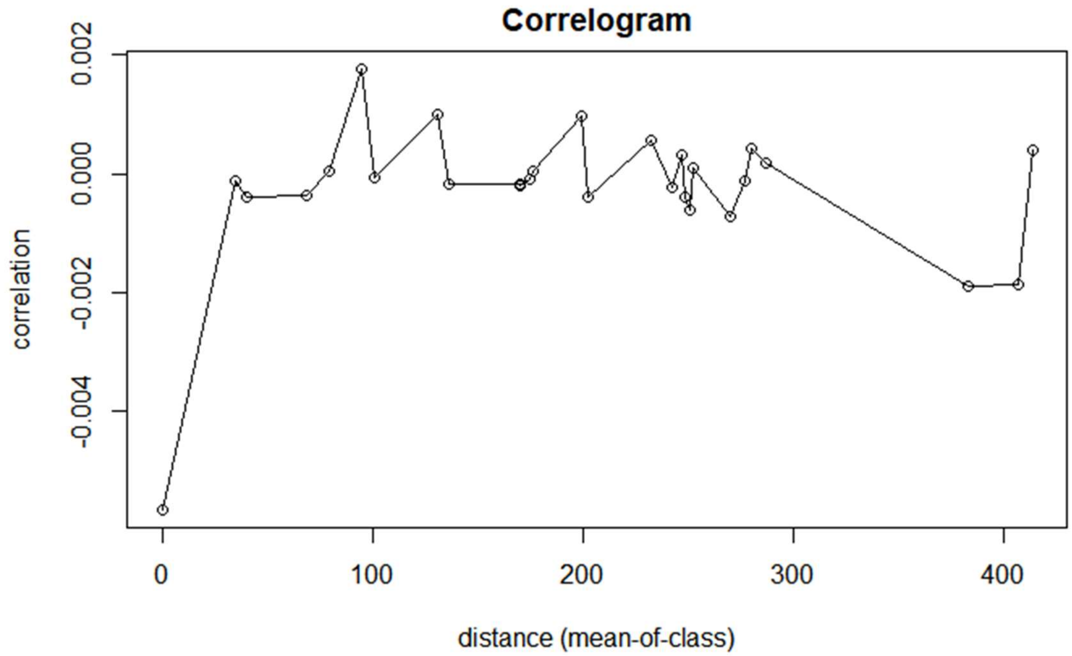

Figure A2.14 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and commercial food provider density in 2km landscapes. Moran I statistic = -4.23e-3, p-value = 0.92.

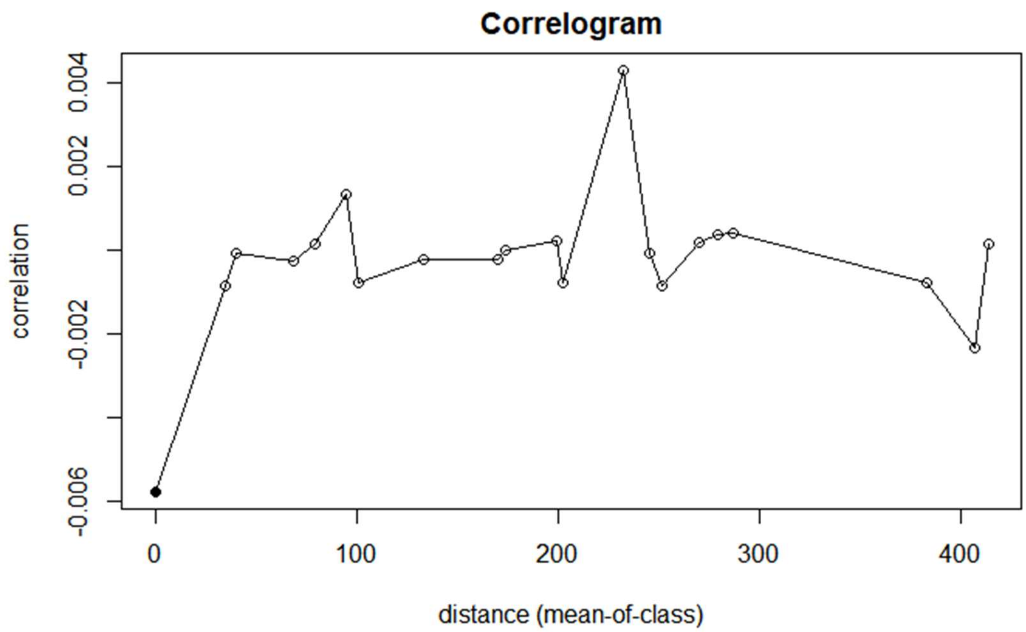

Figure A2.15 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and commercial food provider density and livestock and game producer density in 3km landscapes. Moran I statistic = -4.36e-3, p-value = 0.93.

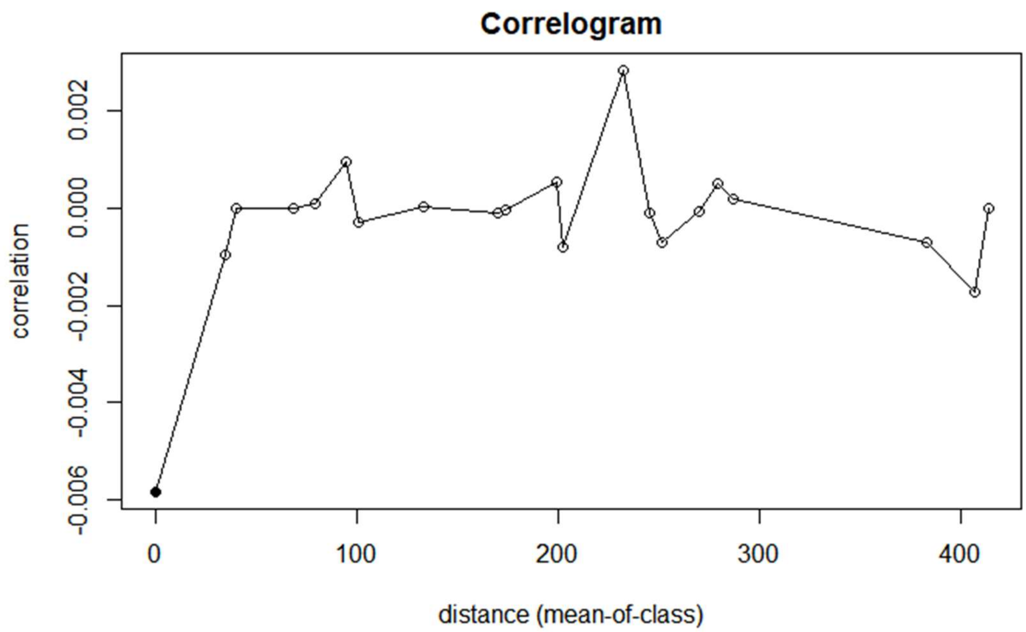

Figure A2.16 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and commercial food provider density and livestock and game producer density in 4km landscapes. Moran I statistic = -4.42e-3, p-value = 0.94.

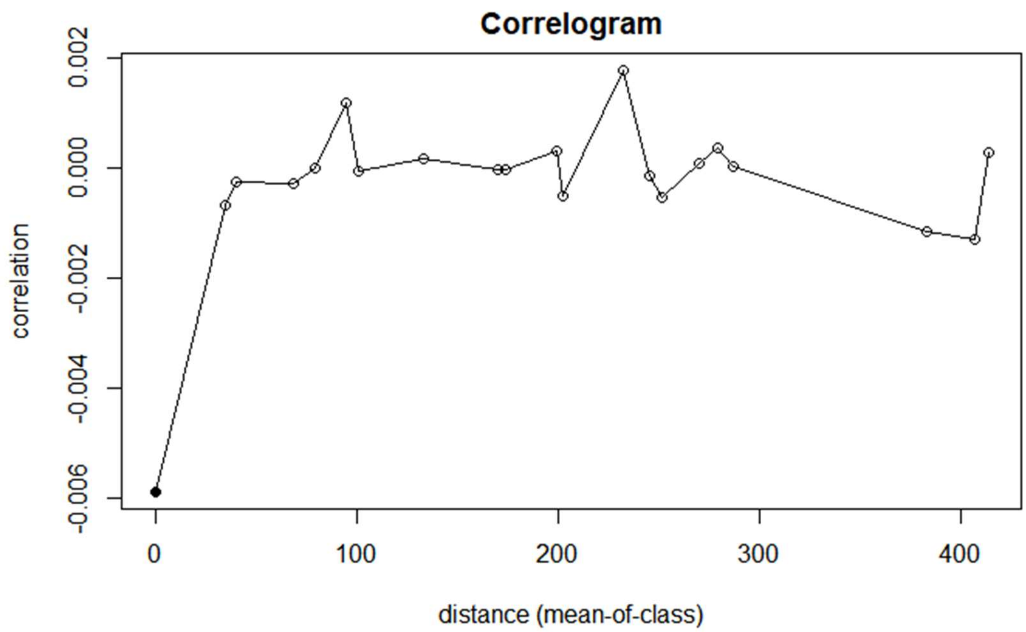

Figure A2.17 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and commercial food provider density and livestock and game producer density in 5km landscapes. Moran I statistic = -4.46e-3, p-value = 0.94.

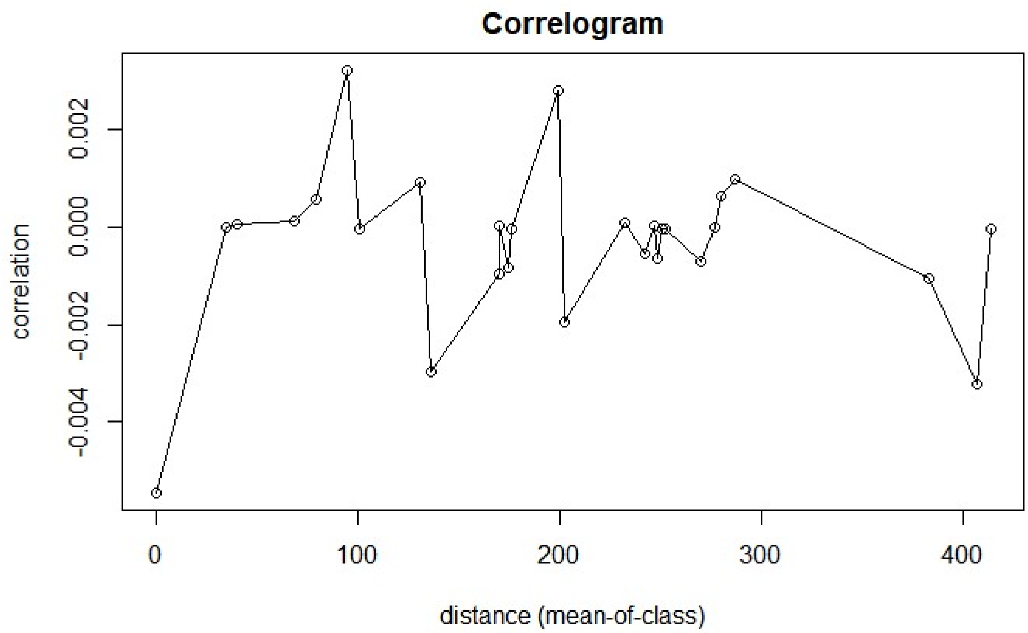

Figure A2.18 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and commercial food provider density in 10km landscapes. Moran I statistic = -3.94e-3, p-value = 0.91.

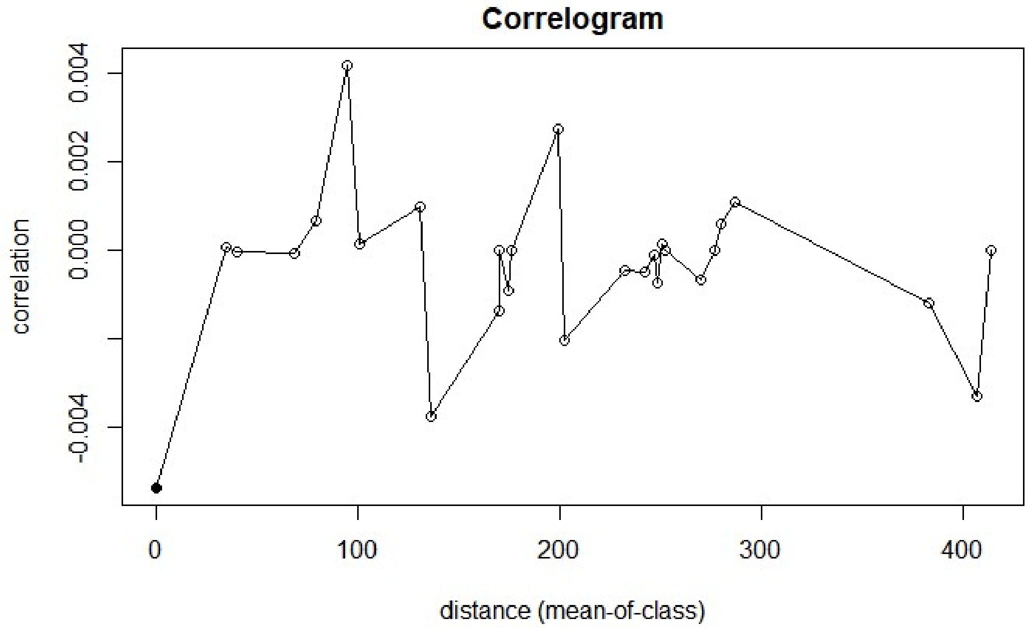

Figure A2.19 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and commercial food provider density in 15km landscapes. Moran I statistic = -3.89e-3, p-value = 0.90.

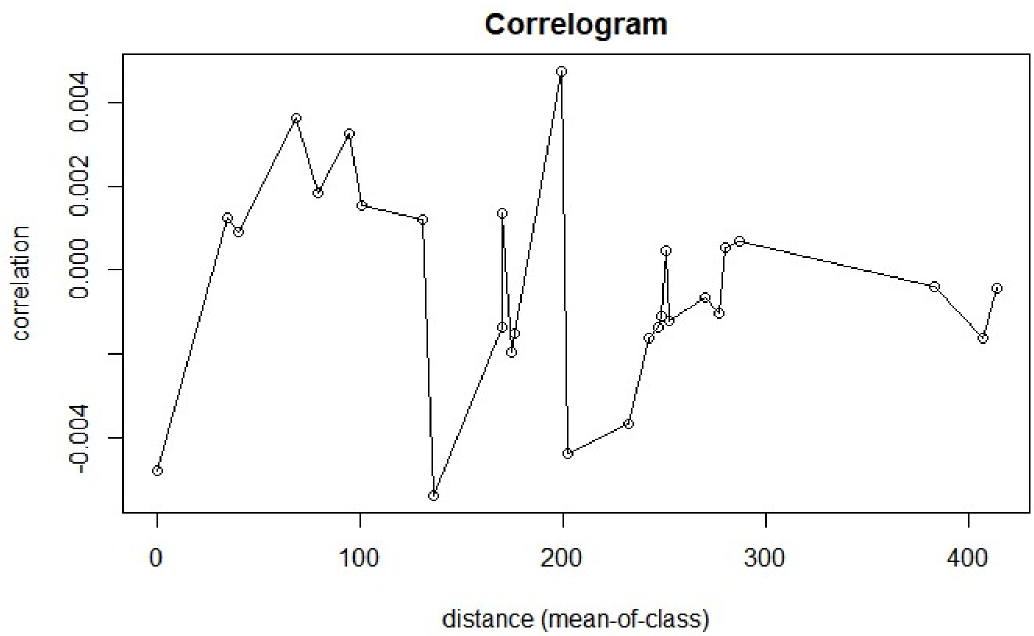

Figure A2.20 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and commercial food provider density in 20km landscapes. Moran I statistic = -3.04e-3, p-value = 0.82.

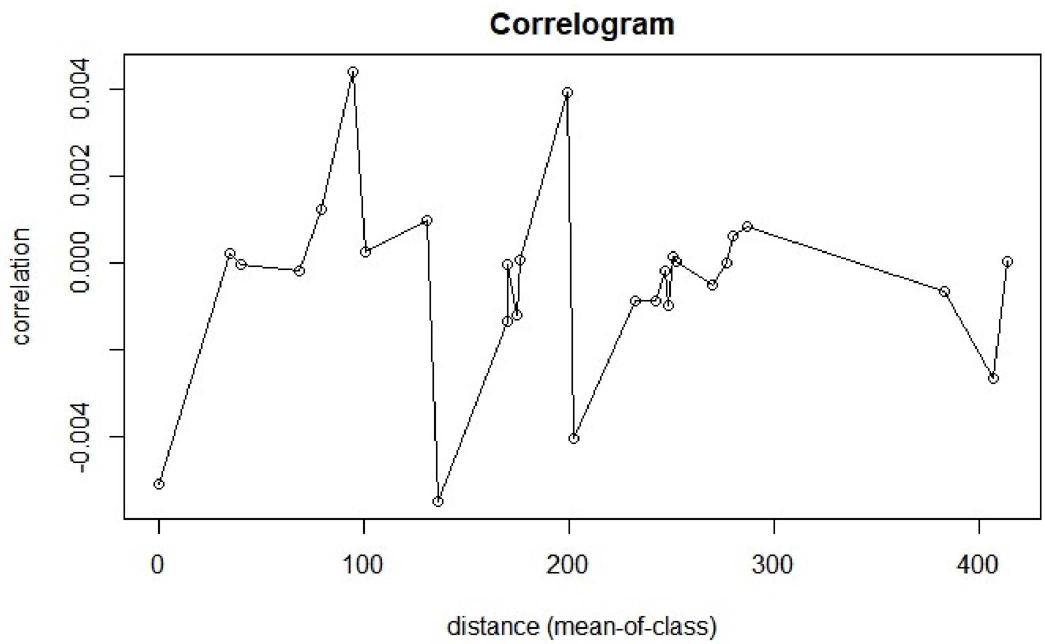

Figure A2.21 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and developed landcover in 10km landscapes. Moran I statistic = -3.65e-3, p-value = 0.88.

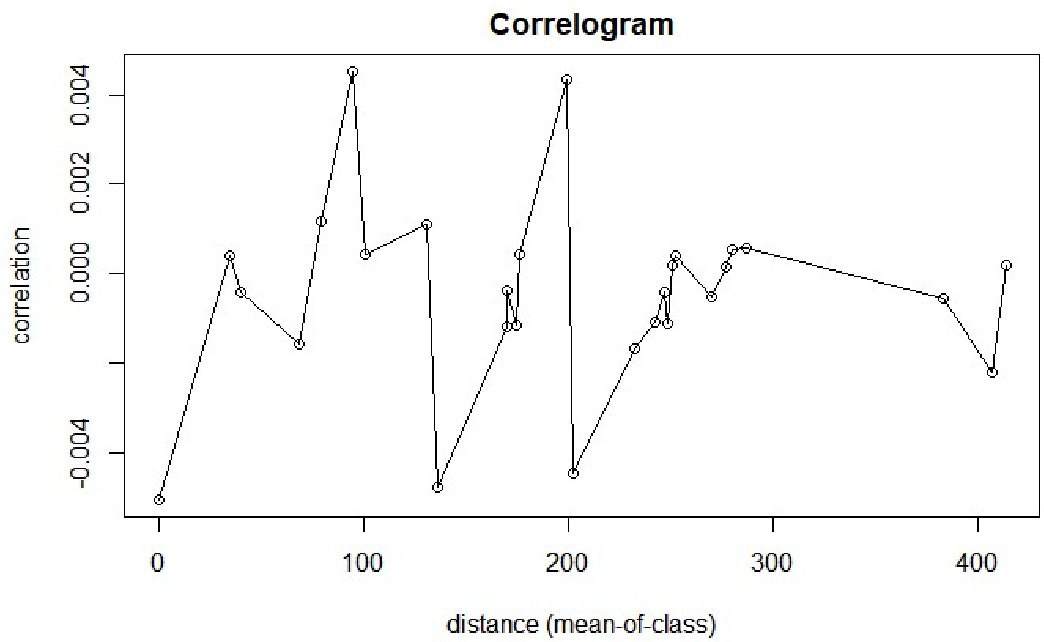

Figure A2.22 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and developed landcover in 15km landscapes. Moran I statistic = -3.74e-3, p-value = 0.89.

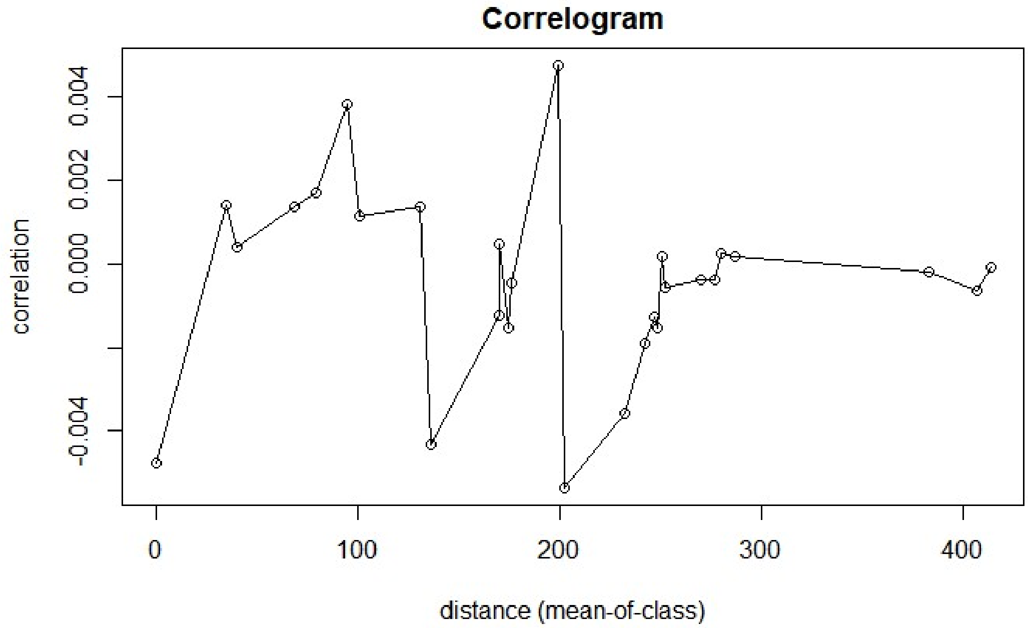

Figure A2.23 Correlogram of residuals from a model of plastic composition of vulture pellets with respect to date, distance to a landfill, and developed landcover in 20km landscapes. Moran I statistic = -3.25e-3, p-value = 0.84.

CHAPTER 3: THE UTILITY OF SPATIAL DECISION SUPPORT SYSTEMS TO WILDLIFE REHABILITATION AND RELEASE: A CASE STUDY FOCUSING ON RAPTORS IN THE CHARLOTTE METROPOLITAN AREA, USA

Abstract

Wildlife rehabilitation is increasing in practice, with thousands of individuals and organizations nationwide rehabilitating injured or sick wildlife. An important part of post-rehabilitation survival of wildlife is release – which includes selecting a location with suitable habitat, at the right time of year, using the most appropriate release methods, and so on. Yet, it can be difficult for wildlife rehabilitators to select suitable release locations with many unknowns regarding the spatial ecology of the species and various threats and resources in the area. Using six raptor species (i.e., birds of prey) as a case study, I created the first spatial decision support system for post-rehabilitation release site selection of raptors, called the RaPTR online GIS. Release suitability maps were created for the study species using the following variables: landcover type, habitat edge density, distance to streams and/or water, canopy height, tree canopy cover, road density, landcover change vulnerability, species density, and rehabilitation admission density. It is also important to consider logistic and organizational constraints for wildlife rehabilitators. As such, potential release sites were selected that were safe and accessible for releasers, network analyses were conducted to show all areas accessible within specified driving times, and the areas with the highest average release suitability were identified to ease ideal site selection. This tool is available online for wildlife rehabilitation organizations to use in the release site selection of rehabilitation raptors – aiming to improve the chances of post-release survival in the study species while minimizing the time and effort required from rehabilitators and releasers. By creating

similar tools and making them publicly accessible, we can promote the use of evidence-based strategies for wildlife release and other aspects of wildlife conservation.

Keywords: raptor, rehabilitation, release, habitat suitability, GIS, spatial decision support system

3.1 Introduction

Wildlife rehabilitation has been defined as "the act of providing temporary care for injured, sick or orphaned wildlife with the goal of releasing them back into the wild" (IWRC, 2022). Thousands of wildlife rehabilitation organizations exist worldwide to undertake this work, with nearly 700 licensed rehabilitators functioning in New York, USA alone (Arent et al., 2018; Hanson et al., 2021). There is some evidence that the number of animals admitted for rehabilitation is increasing over time (Hanson et al., 2021; Kwok et al., 2021); this trend will likely continue with human-wildlife interactions occurring more frequently (Abrahms, 2021). Nearly all animal taxa are represented at wildlife rehabilitation organizations, although the most common groups are mammals or birds, followed by reptiles, amphibians, and other groups (Grogan & Kelly, 2013; Hanson et al., 2021; Kelly, 2020; Kwok et al., 2021; Long et al., 2020; Miller et al., 2023). Globally, anthropogenic causes have been found to be responsible for the majority of rehabilitation intakes across all animal groups, with vehicle collisions, oil spills, and gunshots generally accounting for the most common admission causes (Cope et al., 2022; Hanson et al., 2021; Kwok et al., 2021; Long et al., 2020; Miller et al., 2023). While the success of wildlife rehabilitation efforts vary across taxa, location, and admission cause, between 30-50% of admitted animals survive to be released back into the environment

(Grogan & Kelly, 2013; Hanson et al., 2021; Kelly, 2020; Kwok et al., 2021; Miller et al., 2023).

After rehabilitation comes release – an event that presents many stressors to wildlife. An important factor in the survival of rehabilitated wildlife is the suitability of release locations (Badia-Boher et al., 2022; Batson et al., 2015; Cope et al., 2022). Releasing an animal at the same location where it was captured allows the animal to return to established territory with known food and water sources, mates, and knowledge of local hazards and predators (Hall, 2005). Yet, if the cause of the original injury is still present, releasing the animal back into that environment may put it in danger once more. Other features also require consideration when planning a release including the habitat suitability, species abundance, individual factors such as the animals personality, weight, and life history and situational factors such as the length of rehabilitation, release timing, and the existence of human-wildlife conflicts (Cope et al., 2022; Grogan & Kelly, 2013). Releasing wildlife into less than ideal situations may require them to travel long distances, compete with conspecifics, or interact more with humans – all of which decrease their post-release survival (Cope et al., 2022; Fajardo et al., 2000).

It can be difficult for wildlife rehabilitation organizations to select suitable release sites for wildlife with the many considerations required for release. These organizations are often further constrained by: (1) time, as wildlife releases can require significant time commitments to get to the right location and ensure the animal is prepared for release, and (2) staffing, as many wildlife rehabilitation organizations are non-profit organizations that rely greatly on volunteer efforts. Spatial decision support systems (SDSS) can support organizations with these limitations, defined by Crossland (2008) as “a computer-based system that combines conventional data, spatially referenced data and information, and decision logic as a tool for assisting a human decision-maker". In other words, SDSS integrate different data sources to provide a computer-based framework that assists with decision-making for complex spatial problems (Densham, 1991; Sugumaran & Degroote, 2010). These systems are used to analyze and solve problems in nature resource management, business marketing, urban and landscape planning, and public health and hazard analysis, among other fields (Densham, 1991; Tang et al., 2017). Other methods of spatial analysis such as habitat suitability modeling can analyze spatial patterns to inform decisions, but SDSS provides decision-making support that extends past habitat suitability modeling and can offer additional information that addresses the needs of the organization, such as time constraints or accessibility concerns. Habitat suitability maps have been created to select suitable release sites for agile gibbons (*Hylobates agilis albibarbis*) (Cheyne, 2006), roughtail rock agamas (*Stellagama stellio*), and snake-eyed lizards (*Ophisops elegans*) (Mert & Kirac, 2019), and SDSS have been used for the identification of critical habitat in Arkansas (Larson & Sengupta, 2004), for the selection of conservation hotspots in India (Ahmad et al., 2018), for the translocation of Mojave desert tortoises (*Gopherus agassizii*) (Heaton et al., 2008), and for the use of tourists at Great Smoky Mountains National Park (Dye & Shaw, 2007). All of these models allow the releaser to identify species-appropriate habitats across the landscape, but to my knowledge, no similar models have been created or published that identify suitable habitat for many rehabilitated species, nor have any similar models incorporated additional features aiming to reduce the time and staffing constraints on rehabilitation organizations (Batson et al., 2015; Cope et al., 2022).

Globally, many raptor species (i.e., birds of prey) are becoming more prevalent in cities (Boal & Dykstra, 2018), such as peregrine falcons (*Falco peregrinus*), red-tailed hawks (*Buteo jamaicensis*), and osprey (*Pandion haliaetus*) (Boal, 2018; Mannan & Steidl, 2018). This may be because urban areas provide more favorable environmental conditions than natural habitat for these species, along with sustainable policies and lower rates of predation that may lead to higher reproductive success and juvenile survival (Gehlbach, 1996; Love & Bird, 2000; Mannan & Steidl, 2018). However, urban areas are also littered with threats to raptor populations such as building and automobile collisions, electrocution, toxic materials, disease, and domestic predators – all of which contribute to a significant proportion of urban raptor mortalities (Dwyer et al., 2018). Raptors are a good case study for an SDSS that identifies suitable release habitat for rehabilitated individuals and incorporates features addressing organizational constraints, as these populations are increasing in urban areas, are commonly admitted to wildlife rehabilitation organizations (Cope et al., 2022; Hanson et al., 2021), and are often well-liked by urban residents (Bjerke & Østdahl, 2004; Muñoz-Pedreros et al., 2018).

In this study, I designed the first SDSS for rehabilitated raptor release with the incorporation of elements that are expected to improve the use by wildlife rehabilitation organizations, including accessibility metrics for releasers. I identified the opportunity to create the Raptor Placement Tool for Release (RaPTR) through discussions with a raptor rehabilitation organization. I created release suitability maps and an online GIS for six raptor species that commonly occur in the Charlotte Metropolitan Area, USA. The RaPTR online GIS tool allows the user to identify areas of high release suitability, aiming to maximize long-term chances of survival while minimizing the time required by the rehabilitation organization and the releaser. While I expect that such a tool exists in private use, to my knowledge, there have been no similar tools created or published that address the release of wildlife, especially not the release of rehabilitated raptor species into urban environments that incorporate additional features including accessibility metrics for releasers.

3.2 Methods

3.2.1 Raptor rehabilitation case study

I worked in collaboration with a raptor rehabilitation organization, creating this tool through discussions with them and relying on their expert guidance and feedback throughout. The raptor rehabilitation organization is a non-profit organization located near Charlotte, NC that has been rehabilitating raptor species for several decades. They treat hundreds of raptors each year with 66% of admitted raptors released (this does not include raptors that die within the first 24 hours). With this number of intakes and releases each year, it can be difficult to select ideal release sites for each bird with so many unknowns regarding the landscape associations of the species, local raptor abundance, and accessible and appropriate release sites in the area. As such, releases may be on an ad hoc basis with release locations selected based on best estimates of suitable habitat and the availability of staff or volunteers to transport and release the raptor. The creation of this tool provided the opportunity for the organization to ensure that raptors would be released in the most suitable locations and provide guidance to staff and volunteers on locations at which to go to release the raptors – thus, saving a great deal of time on their part while likely benefiting the raptors survival post-release.

3.2.1.2 Study species

I prepared release suitability maps for six raptor species that commonly occur in the study area and are most often admitted to the organization. The study species include red-tailed hawks (*Buteo jamaicensis*), red-shouldered hawks (*Buteo lineatus*), barred owls (*Strix varia*), great horned owls (*Bubo virginianus*), eastern screech owls (*Megascops asio*), and osprey (*Pandion haliaetus*). In total, these six species accounted for ~75% of admissions to the organization and ~95% of releases.

3.2.1.3 Study area

This research is situated within the Charlotte Metropolitan Area, USA (CMA), an urban area in North Carolina and South Carolina surrounding the city of Charlotte, NC. The CMA is a quickly growing area with sprawling urban landcover dominated by single-family housing. In addition to developed land cover, the CMA is composed of forested and agricultural land cover (Dewitz & United States Geological Survey, 2021) which offer a wide variety of habitats and resources for raptor populations. In this study, I used two different classifications of the CMA to accommodate the needs of different raptor species. The smaller CMA classification includes Iredell, Rowan, Catawba, Lincoln, Gaston, Mecklenburg, Cabarrus, Union, and Stanly counties within North Carolina and York and Lancaster counties within South Carolina. This smaller area is more suitable for raptor species that do poorly with extended periods of time in vehicles. The larger CMA classification includes all counties within the smaller classification in addition to Alexander, Davie, Davidson, Cleveland, Montgomery, Anson, and Richmond counties in North Carolina and Cherokee, Chester, and Chesterfield counties in South Carolina.

3.2.2 Modeling and spatial decision support system creation

Here, I provide an overview of the methods related to this research. This study included multiple species with different study areas, variables, and methods, and as such, the methods section does not provide specifics on each species. All species-specific information can be found in the supplementary materials.

3.2.2.1 Variables

Environmental variables were selected for each species based on habitat and landscape requirements and threats from humans and predators (Tables 3.1-3.3, Figure 3.1). Habitat and landscape variables included landcover, habitat edge density, distance to water or streams, and canopy height and cover. The landcover variable (from the National Land Cover Database) has 20 different landcover classes including water, developed, barren, forested, shrubland, grassland, cultivated, and wetland (Yang et al., 2018). Each species has unique landcover preferences that can be selected for within these categories. For example, red-tailed hawks regularly use a variety of open habitats (such as grassland or cultivated areas) near forested habitats (Preston & Beane, 2020) while red-shouldered hawks rely more on forested areas with wetland and riparian habitats (Dykstra et al., 2020). Some of the study species are also known to use edge habitat (i.e., habitat where two different landcover types meet, such as grassland and forest). Habitat edge density is the amount of edge between relevant landcover classes (Yang et al., 2018) for these species, calculated as the kilometers of habitat edge divided by the area of landscapes equaling the size of the species core area used. The distance to water (Yang et al., 2018) or streams (Esri Inc., 2023b) is valuable for those species that use water more than others, such as osprey, and should be released in areas closer to water. Finally, canopy height (Lang et al., 2022) and tree canopy cover (Yang et al., 2018) are important as species select for different types of forested habitat that are not captured in other variables. For example, barred owls select for more dense, old-growth forests and as such would prefer a higher percentage of canopy cover and taller canopy height (Mazur & James, 2021).

Several variables were selected that indicated threats to the raptor, including road density, species density, rehabilitation admission density, and landcover change vulnerability. Road density represents a significant threat to many of the study species as they often forage near roadways and subsequently collide with vehicles (Boal & Dykstra, 2018). This was calculated as the distance of all roadways (United States Census Bureau, 2021) divided by the area of landscapes equaling the size of the species home range. Species density shows the abundance of raptors of that species within landscapes, allowing us to avoid releasing raptors into landscapes with a high density of individuals already present and likely defending territory. The species density was calculated as the number of individual raptors from complete eBird checklists (Fink et al., 2021) within landscapes equaling the size of the species home range, adjusted for birding intensity by dividing by the average number of complete checklists within the average distance traveled by birders (De Salvo et al., 2020). Similarly, rehabilitation admission density is a measure of the number of raptors admitted to the organization, allowing us to select against areas that may be presenting more threats to raptors. The first portion of this metric was the same as species density (# of individuals/home range area) but was then adjusted for human population density by dividing by the population of the landscape. As many raptors are long-lived, long-term threats are important as well. Landcover change vulnerability is a long-term threat metric that shows the vulnerability that the landcover of an area will change by 2050 (Esri Inc., 2021). This variable allows us to select for areas that are not expected to change significantly from natural habitat in the coming decades.

As each variable may not be important to a species, only relevant variables were selected based on the species life history and requirements. For example, there is evidence that red-tailed hawks use edge habitat between open and forested landcover (Preston & Beane, 2020) and as such, habitat edge density was included as a variable for red-tailed hawks. However, there is no evidence that barred owls (Mazur & James, 2021) or osprey (Bierregaard et al., 2020) are similarly reliant on edge habitat and so this variable was not used for these species. Details on each variable and sources can be found in Tables 3.1 and 3.2.

3.2.2.2 Variable weights

Each variable was assigned a percentage weight based on estimated importance of the variable to the species (Tables A3.1-A3.12). All variables combined equaled 100% and a variables weight determined how much it influenced the resulting suitability map. Percentage weights were used to ensure that resulting suitability maps for each species were set to the same scale to improve public usability. The variable weights were chosen based on previous literature on the species ecology and expert advice from the organization (Table 3.2). Generally, habitat features (such as landcover type and edge density) were weighted as more important than major threats (such as road density), which were weighted as more important than minor threats (such as species or rehabilitation admission densities) – i.e., habitat features > major threats > minor threats. For example, red-tailed hawks have known landcover associations and use edge habitat between open and forested areas (Preston & Beane, 2020). As these associations are well discussed in the literature, each variable received a weight of 20%. Additionally, there is some evidence that red-tailed hawks prefer specific tree canopy cover amounts, so this variable received a weight of 17%. Roads are a major, immediate threat to this species while landcover change vulnerability is a minor, long term threat, and as such, these variables received weights of 17% and 10%, respectively. Finally, species density and rehabilitation admission density are both minor threats as well and received weights of 8% each.

3.2.2.3 Suitability scores

The values of each variable were assigned suitability scores within categories of very low, low, medium, high, and very high suitability for the species (Tables A3.1-A3.6). The chosen suitability scores were chosen based on previous literature on the species ecology and expert advice from the organization (Table 3.2). For example, moderate and high intensity developed landcover were assigned a very low suitability score for eastern screech owls while forested landcover was assigned a very high suitability score, as eastern screech owls require forested habitats but are not often found in heavily developed landscapes (Ritchison et al., 2020). As water is important to eastern screech owls and as the organization prefers to release this species near water, areas within 0.5km of water were scored as very highly suitable, with decreasing suitability as distance to water increased.

3.2.2.4 Release site selection

I created a layer of suitable release sites that were (1) on public property (i.e., nature preserves, state parks, city parks, etc.), (2) had a variety of habitats nearby, (3) were not within densely populated areas, (4) provide a safe place to park and release the bird. Sites were selected manually by viewing public property within the CMA and identifying the locations that fit the parameters listed above. These points were not selected for specific species and do not include any required permissions, they simply provide public property sites that the releaser can contact to request permission to release the bird. Additionally, network analyses were conducted using ArcGIS Pro 3.1.3 (Esri Inc., 2023a). Polygons were created showing all areas accessible within a 15, 30, 45, and 60 minute drive of the organization and all suitable release sites were identified within these time periods. These layers can help the releaser identify suitable release sites based on their time availability for release and on the amount of time the raptor can safely spend in transportation.

3.2.2.5 Release suitability map creation

Release suitability maps were created for each study species using the Suitability Modeler from ArcGIS Pro 3.1.3 (Figure 3.2) (Esri Inc., 2023a). Each release suitability map was made by modeling the cells suitability based on the variables that were important to the species, with the variable weights indicating how much influence each variable had and the variable suitability scores indicating the suitability of each cell for that variable (Table 3.1). The model outputs were weighted on a suitability scale ranging from 1-5, with one representing very low suitability areas and five representing very high suitability areas. The final release suitability maps had suitability grouped into four categories: 2 = very low-low suitability (1-2 suitability scores), 3 = low-medium suitability (2-3 suitability scores), 4 = medium-high suitability (3-4 suitability scores), and 5 = high-very high suitability (4-5 suitability scores). As release suitability visualization was the primary objective for the models, I created the models using the smallest cell size of the layers. Each release suitability model was shared as a web map using ArcGIS Pro 3.1.3 and ArcGIS Online. Finally, the eight areas with the highest average release suitability were located as the most suitable release areas to target for releases.

3.2.2.6 Sensitivity Analyses

Finally, sensitivity analyses were completed on each map to evaluate the sensitivity of the map to changes in variable weights (Li & Wu, 2006; Theuerkauf et al., 2019). I created four different sub-maps for each species release suitability map: (1) the original map with selected weights, (2) a map with the most important habitat variables increased in weight, (3) a map with the most important habitat variables decreased in weight, and (4) a map with all variables weighted equally (Tables A3.7-A3.12). The variable percentage weights were converted to multiplier weights (weighted influence) for each original map. These multiplier weights were then adjusted for the suitability analysis sub-maps for adding or subtracting variable weight as stated. Then, the new multiplier weights were converted back to percentage weights for each sub-map prior to conducting the analyses. This process ensured that the species sub-maps were adjusted in the same way and represent similar transformations. The suitability analysis sub-maps were created using the largest cell size of the layers to ensure accuracy of the analyses. Graphs were created for each species that shows the percentage of cells occupying each suitability category (2: very low-low 3: low-medium, 4: medium-high, and 5: high-very high) for each sensitivity analysis sub-map.

3.2.3 RaPTR Online GIS

The RaPTR online GIS tool has eight layers for each species that allow the user to view (1) the projected species release suitability map for the CMA, (2) the areas with the highest average suitability, (3) all high-very high suitability areas, (4) potential release sites on public land that are safe and accessible, (5) the areas accessible within a 15, 30, 45, and 60 minute drive of the organization, and (6-8) the potential release sites reachable within a 30, 45, and 60 minute drive of the organization (Figure 3.3). There is no layer showing potential release sites reachable within a 15 minute drive of the organization because none of the selected sites exist within that area. The RaPTR Online GIS tool is available at www.raptrmaps.com and is accompanied by a User Guide describing the available layers and the opportunities for use.

3.3 Results

3.3.1 Release suitability maps

Red-tailed hawks have medium-high and high-very high release suitability across much of the study area (Figure 3.4). The innermost portion of the City of Charlotte has lower suitability scores due to the high amounts of developed landcover and higher road densities, paired with lower amounts of edge density between open and forested areas and a higher density of red-tailed hawks admitted to the organization when compared to other locations in the study area. The most suitable release areas identified are all in suburban and rural landscapes with forested and agricultural landcovers interspersed, creating more edge habitat.

Red-shouldered hawks have medium-high release suitability across most of the study area, with only small portions showing high-very high release suitability (Figure 3.5). As with the red-tailed hawk release suitability map, there are lower levels of release suitability in the more urban areas within and around the City of Charlotte as these areas have more developed landcover and road density with less edge habitat and higher rehabilitation admission rates. The lower amounts of high-very high release suitability for this species is driven primarily by the edge density of forested and wetland habitats. This type of habitat is available near the Carolina Sandhills National Wildlife Refuge and extending north to Uwharrie National Forest, but is largely lacking elsewhere in the study area. All of the most suitable release areas identified are those that offer this habitat feature. Some wetland habitats were likely too small or covered by forest canopy to be captured and as such, the edge density between forested and wetland habitats may be an underrepresentation of actually available habitat. While the most suitable release areas should be used when possible, areas with medium-high suitability likely offer this habitat feature to some extent as well.

Similar to red-tailed hawks, barred owls have medium-high and high-very high suitability across most of the study area, with the exception of the more urban portions where we see lower release suitability scores (Figure 3.6). The high-very high suitability areas are located in landscapes with more old-growth forests with high percentages of tree canopy cover and streams nearby for foraging. As such, the most suitable release areas are located near the Uwharrie National Forest, the Carolina Sandhills National

Wildlife Refuge, and Kings Mountain State Park where there is significant natural forested land and water sources.

Great horned owls have large areas of high-very high release suitability, surrounded by areas of medium-high release suitability (Figure 3.7). When compared to the three previous species, great horned owls have a much larger area with low-very low release suitability within and surrounding the City of Charlotte, nearly completely covering the area inside of the I-485 loop. The most suitable release areas are those with forested landcover with high levels of edge density between open and forested habitats, and low road densities – in this case, that includes many of the more rural landscapes with a mixture of forested and open, agricultural habitats.

Eastern screech owls have release suitability similar to that of great horned owls, with high-very high release suitability in the more rural forested landscapes and a larger area of low release suitability comprising the City of Charlotte (Figure 3.8). Areas of high release suitability are driven primarily by forested landcover with moderate levels of edge density between forested and open habitats, with low road density, and near water sources. This leads to the most suitable release areas being those outside of the urban landscapes and in the southern and eastern portions of the study area near significant water sources such as High Rock Lake and Lake Wylie.

Finally, osprey have large areas of high-very high release suitability across the study area and large areas of low release suitability in the urban areas, similar to great horned owls and eastern screech owls (Figure 3.9). The higher suitability areas are those with more forested habitats and few roads that are very close to water sources, as osprey require water to forage. This selection for water availability is visible in the release suitability map, with the appearance of many smaller circular areas of high-very high suitability being those areas immediately surrounding water sources.

3.3.2 Sensitivity analyses

Of the six species, the sensitivity analyses of four species (barred owl, great horned owl, eastern screech owl, and osprey) revealed low levels of variation in release suitability across sub-maps (Figure 3.10c-f). In other words, each of these outputs rate suitability level in a similar way, regardless of changes in the most important habitat variables. Each of the resulting sub-maps for these four species show the largest proportion of cells holding values between 3-4 (medium to high suitability), with fewer cells holding other values. For the other two species (red-tailed hawk and red-shouldered hawk), the sensitivity analyses show moderate levels of variation between sub-maps (Figure 3.10a-b). Despite the variation in these two species analyses, the original map used represents a middle ground at all levels.

3.4 Discussion

The RaPTR online GIS tool was developed to provide a way for raptor rehabilitators to select release sites for rehabilitated raptors while taking into consideration the habitat quality, potential threats, species density, and accessibility for releasers. This tool allows the user to identify areas of high release suitability (i.e., suitable habitat with a low density of threats), view the driving distance from the organization, and find safe and accessible release sites for rehabilitated raptors across the study area. I delivered the RaPTR online GIS tool to the organization in October 2023, provided training on how to use the tool, and discussed opportunities for improvement. As of now, the organization can use this tool in a few different ways: (1) to select specific release sites to send releasers to, (2) to select general areas within which releasers can select a specific location using the tool online, or (3) to allow releasers to select release sites using the tool and confirm site selections with organization. The incorporation of network analyses and accessible release sites promote each of these uses by providing logistical information to the organization and the releaser to support the selection of release sites that meet the needs of the raptors and the humans. The tool will continue to grow and improve in the future. Currently, I am adding points for all past releases and incorporating a way to automatically map future releases around the study area so release site selection can incorporate a consideration for previous release sites. Additionally, I am creating a suitability model widget with ArcGIS Online for each species that allows the user to adjust each variable weight and suitability score and thus, to prioritize different variables depending on the needs of the individual bird to be released. In the future, this methodology could also be built as a geoprocessing model using ArcGIS Pro ModelBuilder so it can be shared and replicated worldwide. This process also allows for the potential to incorporate other opportunities and threats impacting species such as plastic pollution and ingestion potential as discussed in Chapter 2 or spatial data showing the existence of conflict areas.

With wildlife rehabilitation increasing and raptors becoming more prevalent in urban areas, this tool offers the opportunity to improve the post-rehabilitation chances of survival once raptors are released back into the environment. Generally, the first four weeks after release are critical, as the animal must struggle for territory, find food and water sources, and avoid predation and anthropogenic harm – both of which account for a significant portion of post-release mortalities of rehabilitated wildlife (Cope et al., 2022).

After the first several weeks, some species have survival rates similar to wild, unrehabilitated individuals (such as peregrine falcons (*Falco peregrinus*); Sweeney (1997)) while other species consistently show lower survival rates throughout their life (such as Cape vultures (*Gyps coprotheres*); Monadjem et al. (2014)). By incorporating not only habitat suitability into the release suitability maps, but also several features that address major threats to post-release survival, I expect that releasing raptors into areas identified by this tool as having high or very high suitability may increase their chances of survival within the first critical weeks. Additionally, the RaPTR online GIS tool allows the user to target or avoid specific areas for raptor release. With the highly pathogenic avian influenza (HPAI) continuing to impact raptor populations nationwide, this tool allows the user to select sites that target high suitability release areas while avoiding known areas with HPAI occurrence, potentially further increasing the chances of survival post-release.

While this tool has many strengths, it does have limitations to its use as well. As the RaPTR tool is currently only available for a select number of species across a small area, it could be expanded to include additional species within the CMA and other areas with active raptor rehabilitation programs. Additionally, the variable weights incorporated into these models represent my best estimates of variable importance to species based on previous literature and expert guidance, but there is little known about many species exact needs regarding habitat and landscape features such as amount of canopy cover, distance to water, or the density of edge habitats. This is especially important when considering the red-shouldered hawk release suitability map. Edge habitat was weighted as an important feature for the species, yet edges between wetland

and forested habitats are not especially abundant in the study area and thus led to few very high suitability areas identified. With more research focusing on the spatial ecology of these raptor species, the maps could be based on more scientific evidence.

There are several opportunities for future research that focus on the individual-level impacts, the population-level impacts, and the human impacts of this tool and others like it. First, by changing where we release rehabilitated raptors across the landscape, we may see different impacts to the individual birds. The goal of this tool is to maximize chances of survival by releasing raptors into highly suitable habitat with fewer threats. By releasing raptors fixed with GPS trackers, the success and survival of raptors released in areas with different suitability levels could be tracked to validate the tool. Second, the widespread use of tools such as this one could lead to population-level impacts on wildlife species. With more raptors being released into specific areas, we may see higher rates of competition and starvation. A higher post-release survival rate could also lead to population-level impacts due to altered conspecific and interspecific interactions (Paterson et al., 2021). Future research could explore the impact of wildlife rehabilitation and release on populations across landscapes to explore long-term impacts such as these. Finally, future research could evaluate the human impacts of this tool, specifically focusing on how organizations and individuals use these tools, how much time is saved, and the value that they believe is contributed to their work.

3.5 Conclusion

Some raptor species have adapted to survive in urban areas, with access to unique habitats, food sources, climates, and potentially lower rates of predation. However, urban environments present many threats to raptor species as well, including collisions with anthropogenic structures, electrocution, disease, and human-wildlife conflicts. Wildlife rehabilitation organizations treat injured raptors and release them back into the environment post-rehabilitation. Yet, without knowledge of species habitat and landscape associations, the distribution of threats, or the accessibility of release sites, it can be difficult for wildlife rehabilitation organizations to select the most suitable release sites for rehabilitated raptors. I created the Raptor Placement Tool for Release (RaPTR). This is an online GIS tool that provides release suitability maps, network analyses, and potential release sites to aid rehabilitators and releasers in easily and efficiently selecting high quality release sites that maximize the chances of survival of the released raptor. This tool can be used to select release sites for six different species within the Charlotte Metropolitan Area, USA and allows the user to prioritize factors such as habitat quality, transportation time, or direction. Future iterations will improve the tool by adding past and future releases and by creating a suitability model widget that allows the user to adjust variable weights and values depending on the individual needs of the raptor. By creating similar tools and making them publicly accessible, we can promote the use of evidence-based strategies for various aspects of wildlife conservation.

Table 3.1 (continued on next page) Environmental variables used in release suitability modeling for rehabilitated red-tailed hawks (*Buteo jamaicensis*), red-shouldered hawks (*Buteo lineatus*), barred owls (*Strix varia*), great horned owls (*Bubo virginianus*), eastern screech owls (*Megascops asio*), and osprey (*Pandion haliaetus*) within the Charlotte Metropolitan Area, USA.

Environmental variable	**Description**	**Cell size (m)**	**Source**
Land cover classifications (categorical)	Categorical variable describing land use and land cover.	30	2016 National Land Cover Database (Yang et al., 2018)
Edge density (km/km^2)	The amount of edge within the landscape, calculated as the length of edge between relevant habitats[3] within the species core area used[4]	Variable[4]	2016 National Land Cover Database (Yang et al., 2018); ArcGIS Pro 3.1.3 (Esri Inc., 2023a)
Distance to streams (km)	The distance, in kilometers, to streams.	1,350	Esri Inc. (Esri Inc., 2023b)
Distance to water (km)	The distance, in kilometers, to open water landcover.	35	2016 National Land Cover Database (Yang et al., 2018); ArcGIS Pro 3.1.3 (Esri Inc., 2023a)
Canopy height (m)	The height, in meters, of the canopy.	10	EcoVision Lab (Lang et al., 2022)
Tree canopy cover (%)	The percentage of tree canopy cover.	30	2016 National Land Cover Database Tree Canopy Cover (Yang et al., 2018)
Road density (km/km^2)	The distance of all roadways, in kilometers, divided by area of the species home range[1], in square kilometers.	2,200	Census Bureau TIGER/Line (United States Census Bureau, 2021); ArcGIS Pro 3.1.3 (Esri Inc., 2023a)
Landcover change vulnerability	The vulnerability to landcover change by 2050, with high values indicating high vulnerability to change and low values indicating little vulnerability to change.	300	Esri Inc. (Esri Inc., 2021) from Clark University

Table 3.1 (continued) Environmental variables used in release suitability modeling for rehabilitated red-tailed hawks (*Buteo jamaicensis*), red-shouldered hawks (*Buteo lineatus*), barred owls (*Strix varia*), great horned owls (*Bubo virginianus*), eastern screech owls (*Megascops asio*), and osprey (*Pandion haliaetus*) within the Charlotte Metropolitan Area, USA.

Environmental variable	**Description**	**Cell size (m)**	**Source**
Species density	Abundance of the species adjusted for birding intensity, calculated as the # of individuals from complete checklists observed within the species home range area[1], divided by the average number of complete checklists within the average distance traveled by birders[2]	Variable [1]	eBird reports 2017-2022 (Fink et al., 2021); ArcGIS Pro 3.1.3 (Esri Inc., 2023a)
Rehabilitation admission density	Abundance of the species adjusted for population density, calculated as the # of individuals from complete checklists observed within the species home range area[1], divided by the population of the area	Variable [1]	Data provided by the raptor rehabilitation organization; ArcGIS Pro 3.1.3 (Esri Inc., 2023a)

[1]The radii of species home range sizes are as follows: red-tailed hawk – 1.7km (Preston & Beane, 2020); red-shouldered hawk – 1.6km (Dykstra et al., 2020); great horned owl – 9.45km (Frank & Lutz, 1981; Rohner, 1997); osprey – 1km (Bierregaard et al., 2020); eastern screech owl – 1km (Belthoff et al., 1993; Gehlbach, 2008); barred owl – 3.94km (Fuller, 1979; Livezey, 2007).
[2]The average distance traveled by birders was 10.7km per De Salvo et al. (2020), calculated as the average distance traveled for birdwatching (in km/month) divided by average birding trips (number/month).
[3]The relevant habitat edges for the species are as follows: red-tailed hawk – open-forested edge density (Preston & Beane, 2020); red-shouldered hawk – wetland-forested edge density (Dykstra et al., 2020; Dykstra et al., 2001); great-horned owl – open-forested edge density (Artuso et al., 2013; Grossman et al., 2008); eastern screech owl – open-forested edge density (Ritchison et al., 2020; Sparks et al., 1994).
[4]The radii of species core area used are as follows: red-tailed hawk – 0.18km (Morrison et al., 2016; Petersen, 1979; Sexton, 2005); red-shouldered hawk – 0.41km (Bloom et al., 1993; Howell & Chapman, 1997); great horned owl – 0.44km (Bennett & Bloom, 2005); eastern screech owl – 0.29km (Barros & Motta-Junior, 2014; Belthoff et al., 1993; Davis & Weir, 2010; Smith & Gilbert, 1984).

Table 3.2 (continued on next page) Spatial ecology of the six study species included in the RaPTR online GIS.

Species	Spatial ecology	Literature
Red-tailed hawk (*Buteo jamaicensis*)	Across the eastern United States, this species is associated with a variety of open habitats (shrubland, grassland, pastures, etc.) near scattered forested areas. They appear to select for edge habitats between forested and open areas to use the foraging sites in combination with roosting and nesting sites. Prefers forested areas with relatively open canopies, often near foraging areas, and generally avoid dense canopy forests. This species has been found to use core areas of approximately 10.2 hectares in Connecticut, USA and larger areas in the mountainous areas of Puerto Rico. Home range can vary but is often around 150 hectares in size. This species is highly territorial during the breeding season. Average territory sizes have been found to be 2.3km^2 in Oregon, with a diameter of nearly 2km. This species does not appear to be especially territorial outside of the breeding season. This species often forages near roads, which present a significant threat and the distance to roads should be maximized when possible.	Bednarz and Dinsmore (1982) Morrison et al. (2016) Petersen (1979) Preston and Beane (2020) Sexton (2005) Vilella and Nimitz (2012)
Red-shouldered hawk (*Buteo lineatus*)	This species uses a variety of forested habitats including deciduous, coniferous, and mixed forests, as well as suburban parks, greenways, riparian areas, and swamps. They generally appear to prefer mature and old growth forests when compared to younger forest stands. This species appears to select for edge habitat between forests and wetlands when available. This species is often associated with wetlands, stream bottomlands, and small forest openings with wetlands but avoids open water habitats and potentially agricultural areas. They nests near water (averaging 140 meters away) and in areas with canopy cover averaging 27.5% ± 13%. This species defends a territory with home ranges averaging 90-200 hectares in size. Individuals have core areas used of approximately 50 hectares in landscapes in Georgia, although smaller core areas have been seen elsewhere. Roads are a major threat to this species and the distance from roads should be maximized when possible.	Bednarz and Dinsmore (1982) Bloom et al. (1993) Bosakowski and Smith (1997) Bosakowski et al. (1992) Dykstra et al. (2020) Dykstra et al. (2000) Dykstra et al. (2001) Howell and Chapman (1997) Preston et al. (1989)

Table 3.2 (continued) Spatial ecology of the six study species included in the RaPTR online GIS.

Species	Spatial ecology	Literature
Barred owl (*Strix varia*)	This species relies on forested land and uses other adjacent landcover types occasionally. They have been found to prefer large, old growth forests when compared to younger forests. This species is also associated with water sources, often using riparian areas and wetlands year round for foraging. This species maintains territories with an average territory size of approximately 250-300 hectares in size although territories as large as 1,200 hectares have been recorded. As they are territorial, we should avoid releasing this species into areas with more individuals present. Roads present a major threat to this species and the distance from roads should be maximized when possible.	Allen (1987) Boxall and PHR (1982) Elody and Sloan (1985) Fuller (1979) Gagné et al. (2015) Harrold (2003) Livezey (2007) Mason (2004) Mazur and James (2021) Mazur et al. (1998) McGarigal and Fraser (1984) Nicholls and Warner (1972)
Great horned owl (*Bubo virginianus*)	This species uses a variety of habitat including forests (deciduous, coniferous, and mixed forests), swamps, and agricultural areas. Their territories often have some open habitat available such as fields, pastures, or croplands. This species has been found to be associated with urban and suburban areas although other research has found that they avoid areas with human activity. Generally, developed landcover should be avoided to minimize risks. They have been found to be common in highly heterogeneous landscapes with more forest-nonforest edge habitat. This species maintains territories year round with home ranges recorded between $4.8km^2$ and $69.4km^2$, although core area used has been found to be much smaller, averaging less than $1km^2$. Roads present a major threat to this species and the distance from roads should be maximized when possible.	Artuso et al. (2013) Bennett and Bloom (2005) Bierregaard (2018) Dwyer et al. (2018) Frank and Lutz (1981) Franks and Warnock (1969) Grossman et al. (2008) Minor et al. (1993) Rohner (1997)

Table 3.2 (continued) Spatial ecology of the six study species included in the RaPTR online GIS.

Species	Spatial ecology	Literature
Eastern screech owl (*Megascops asio*)	This species relies on tree-dominated landscapes of any type, including deciduous, coniferous, and mixed forests, and either early successional or mature forests. They will also use riparian forested areas, suburban yards, parks, and greenways. Uses pastures and fields less than expected. This species like edge habitat between forests and other landcover types. They prefer to have running water nearby and prefer forests with minimal shrub cover. This species is not especially territorial and defends only immediate roosting and nesting sites. They maintain home ranges of 20-70 hectares in size with some research finding a nightly home range ("core area used") of 26.5 hectares in size. Roads present a major threat to this species and the distance from roads should be maximized when possible. Barred owls are a predator and occupy a similar niche, this species has been found to be less common in areas with more barred owls.	Barros and Motta-Junior (2014) Belthoff et al. (1993) Davis and Weir (2010) Dwyer et al. (2018) Gehlbach (2008) Leonard et al. (2015) Ritchison et al. (2020) Smith and Gilbert (1984) Sparks et al. (1994)
Osprey (*Pandion haliaetus*)	The habitat used by this species varies greatly but the important features are an adequate supply of fish within 10-20 kilometers of nests and open nesting sites without significant predator presence. It is very important for this species to be near water as they use open water for fishing. They often nest in forested areas near open water. This species appears to only defend the nesting site and not foraging areas. Roads present a threat to this species and the distance from roads should be maximized when possible.	Bider and Bird (1983) Bierregaard et al. (2020) Bretagnolle and Thibault (1993) Stocek and Pearce (1983)

Table 3.3 Environmental variables used in each species release suitability model. The species are as follows: RTHA (red-tailed hawk, *Buteo* jamaicensis), RSHA (red-shouldered hawk, *Buteo lineatus*), BDOW (barred owl, *Strix varia*), GHOW (great horned owl, *Bubo virginianus*), EASO (eastern screech owl, *Megascops asio*), and OSPR (osprey, *Pandion haliaetus*). Gray shading shows the variables included in each species model; white shading indicates variables that were not included in the species model.

Environmental variable	**RTHA**	**RSHA**	**BDOW**	**GHOW**	**EASO**	**OSPR**
Study area size[1]	Large	Large	Large	Small	Small	Small
Land cover classifications (categorical)						
Edge density (km/km^2)						
Distance to streams (km)						
Distance to water (km)						
Canopy height (m)						
Tree canopy cover (%)						
Road density (km/km^2)						
Landcover change vulnerability						
Species density						
Predator species density						
Rehabilitation admission density						

[1]See Methods

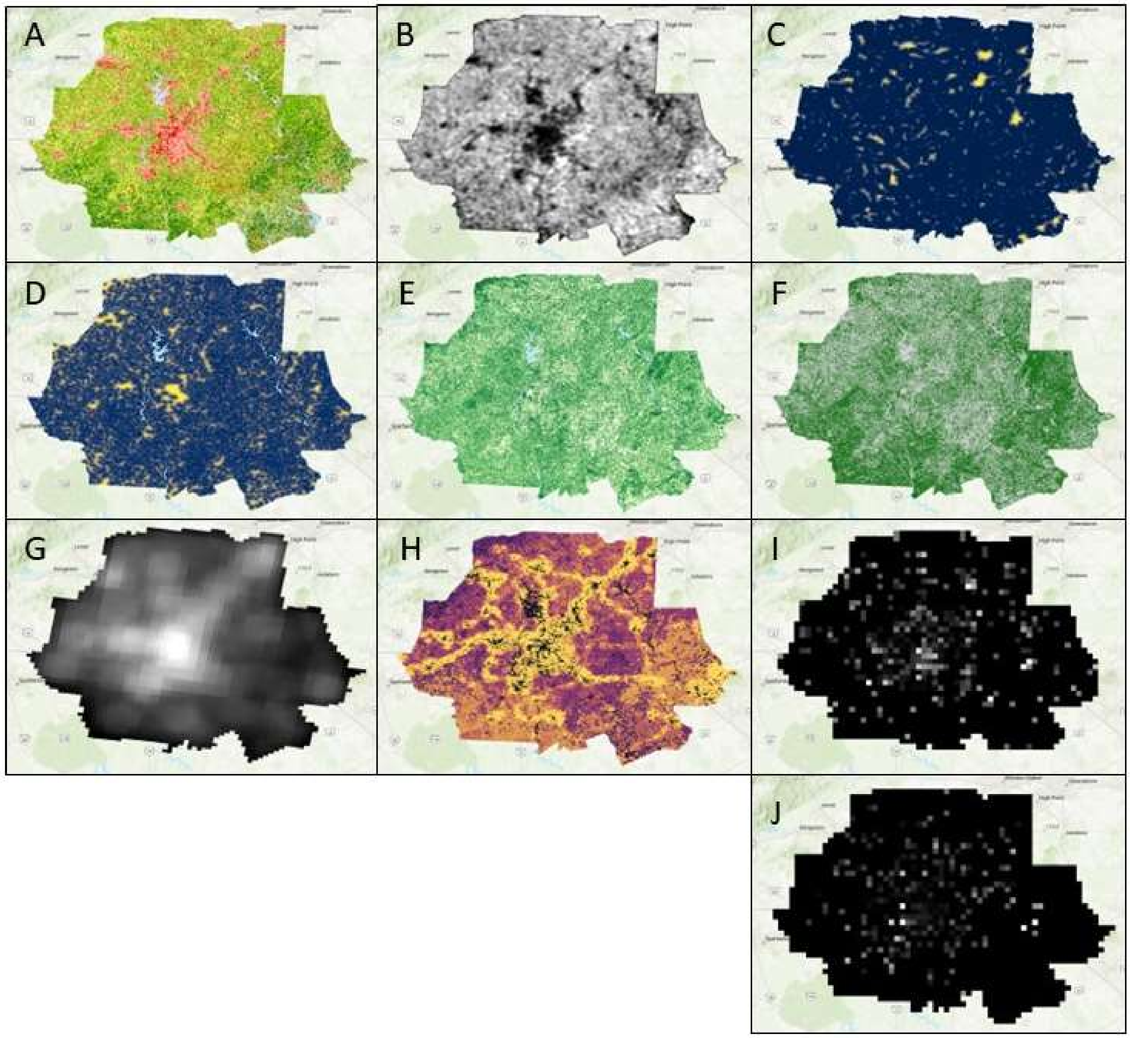

Figure 3.1 Variables combined to create the RaPTR online GIS for rehabilitated raptor release site selection. (a) Landcover data from the 2016 National Land Cover Database (Yang et al., 2018), (b) edge density between species-relevant landcover types, (c) the distance from streams (Esri Inc., 2023b), (d) the distance from any water source (Yang et al., 2018), (e) canopy height from the EcoVision Lab (Lang et al., 2022), (f) the percentage of canopy cover (Yang et al., 2018), (g) the density of roadways across landscapes of variable sizes (United States Census Bureau, 2021), (h) the vulnerability of the area to landcover change by 2050 (Esri Inc., 2021), (i) the density of eBird observations of the species (Fink et al., 2021), and (j) the density of rehabilitation admissions for the species. This process was completed for six study species. Information on variables and species can be found in Tables 3.1-3.3.

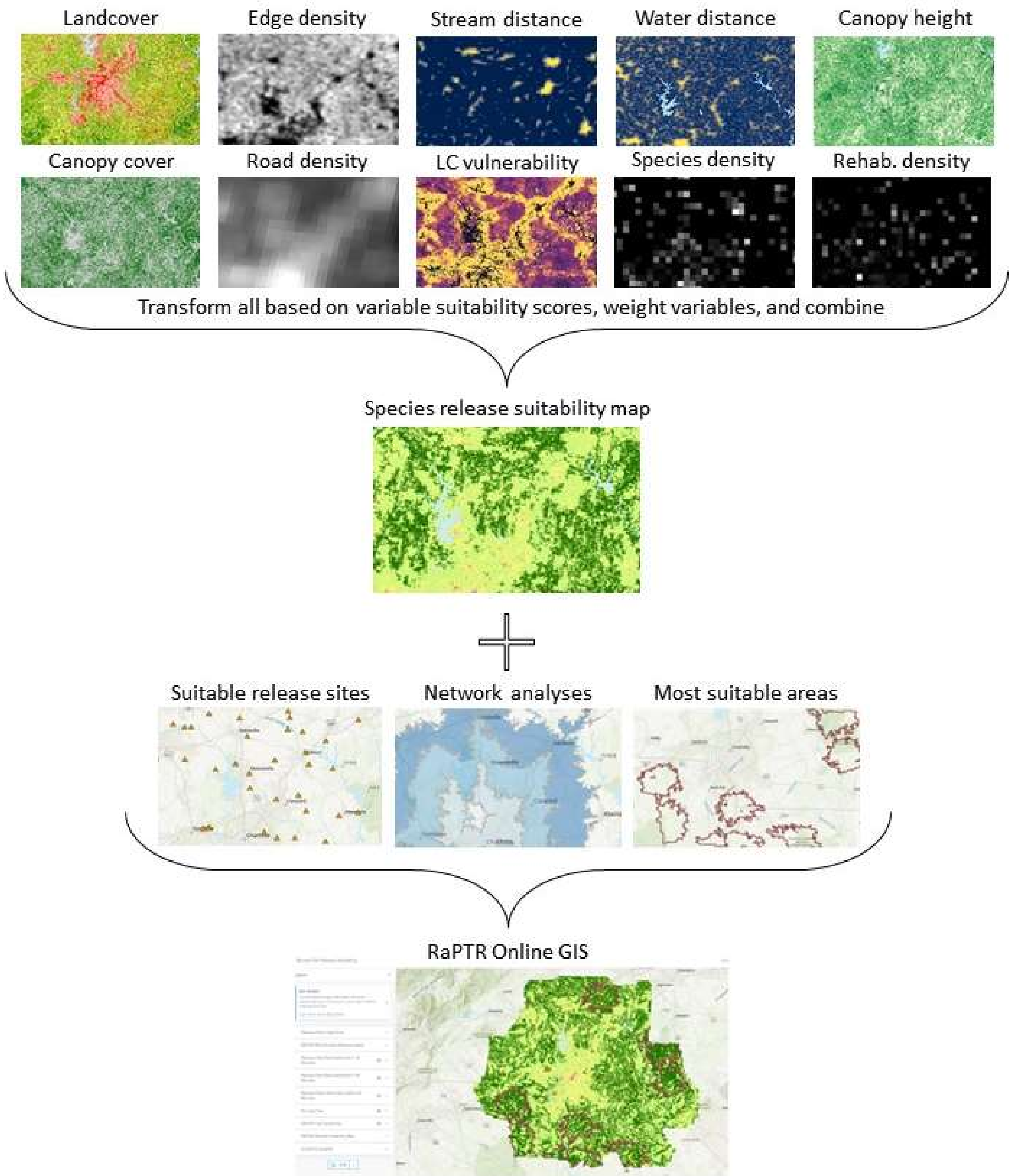

Figure 3.2 Workflow for the creation of the RaPTR online GIS, including the selection of all variables, followed by the variable transformations based on the variable weights and suitability scores. All variables were then combined into the release suitability map (using the ArcGIS Pro Suitability Modeler (Esri Inc., 2023a)). Suitable release sites were selected, network analyses were conducted, and the most suitable release areas were identified. Together with the release suitability map, these were combined to create the RaPTR online GIS for rehabilitated raptor release site selection. This process was completed for six study species. Information on variables and species can be found in Tables 3.1-3.3.

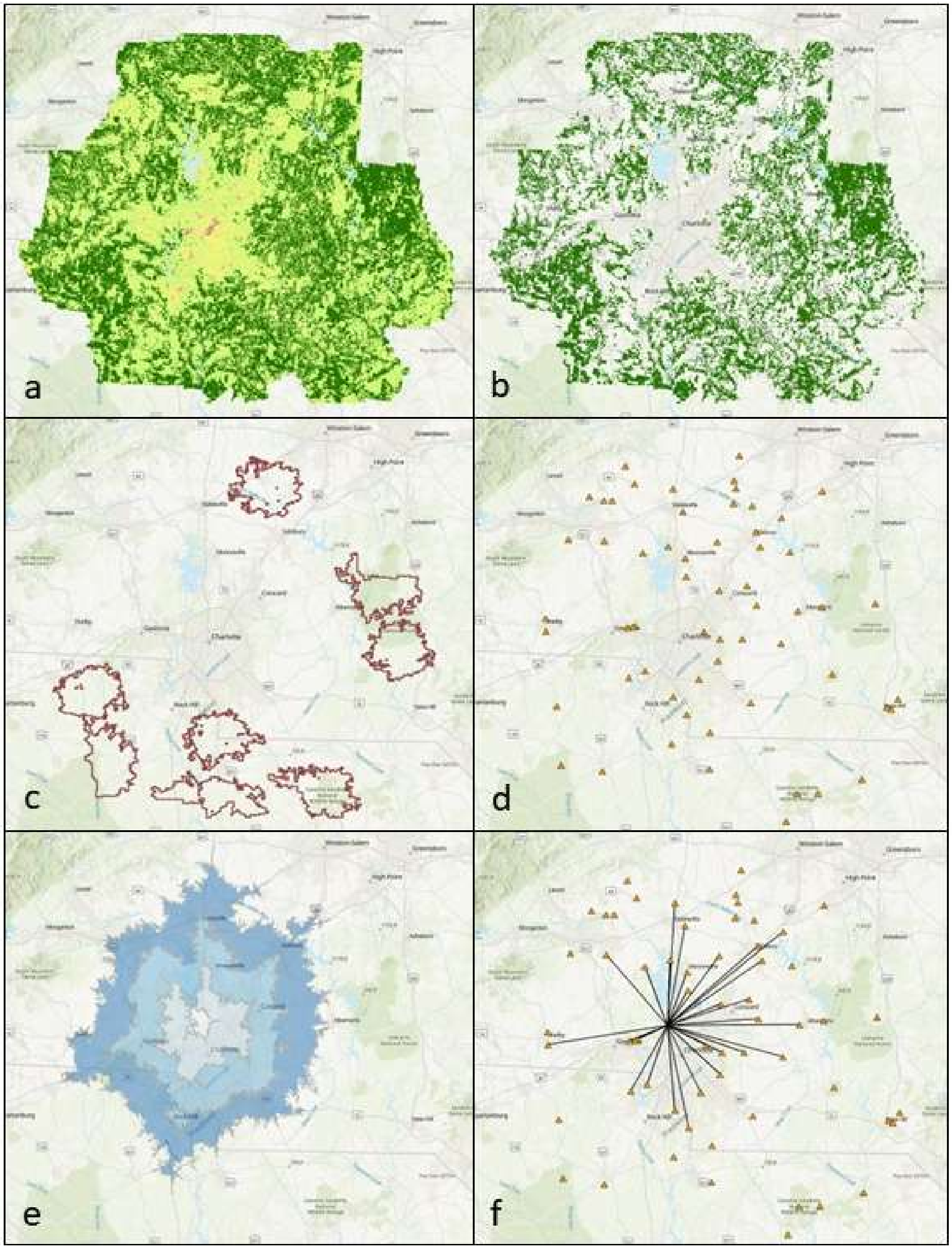

Figure 3.3 All layers included in the RaPTR online GIS for each of the six raptor study species (Table 3.2). (a) species-specific release suitability map with greens showing high release suitability and red and yellow showing low release suitability, (b) all areas of high-very high release suitability for the species, (c) the most suitable release areas, identified as the areas with the highest average suitability, (d) potential release sites within the study area that are safe and accessible, (e) network analyses showing driving time from the raptor rehabilitation organization in 15-minute increments, and (f) all potential release sites reachable within a 30, 45, and 60-minute drivetime (shown with the potential release sites layer for clarity).

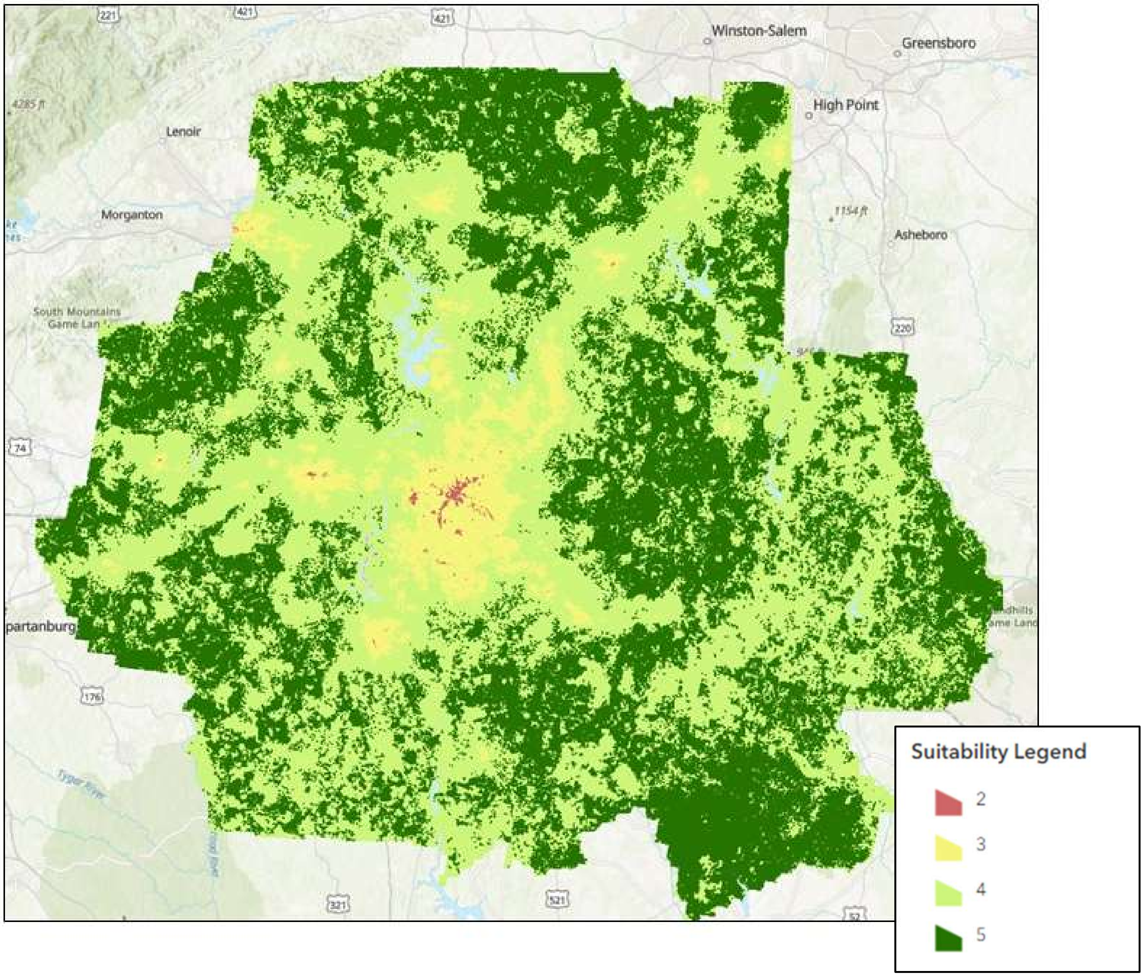

Figure 3.4 Release suitability map for rehabilitated red-tailed hawks (*Buteo jamaicensis*) in the Charlotte Metropolitan Area, USA with four levels of suitability: 2 – very low-low suitability, 3 – low-medium suitability, 4 – medium-high suitability, and 5 – high-very high suitability. Release suitability map created using the ArcGIS Pro Suitability Modeler (Esri Inc., 2023a) and the following variables (Table 3.1): landcover type, open-forested edge density, tree canopy cover, road density, landcover change vulnerability, species density, and rehabilitation admission density.

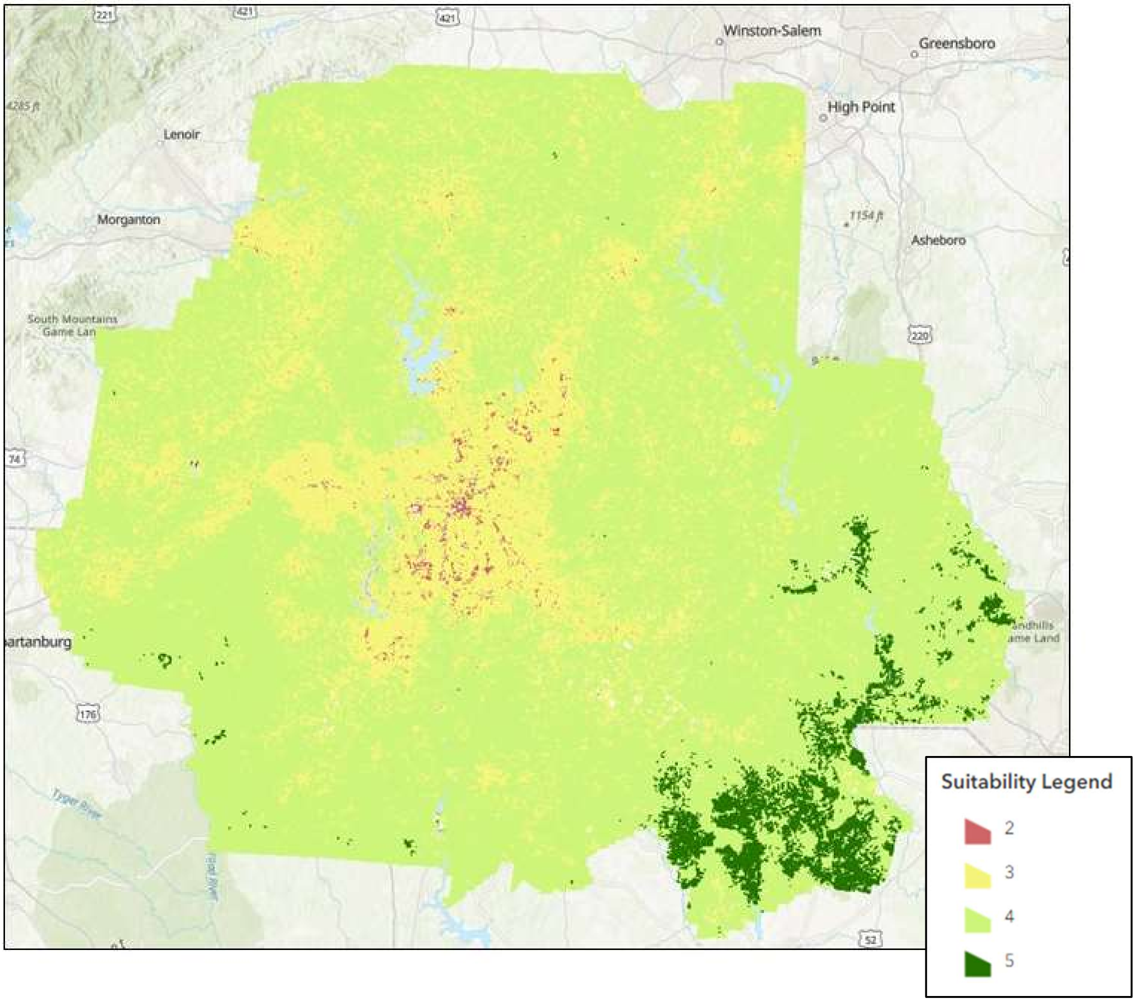

Figure 3.5 Release suitability map for rehabilitated red-shouldered hawks (*Buteo lineatus*) in the Charlotte Metropolitan Area, USA with four levels of suitability: 2 – very low-low suitability, 3 – low-medium suitability, 4 – medium-high suitability, and 5 – high-very high suitability. Release suitability map created using the ArcGIS Pro Suitability Modeler (Esri Inc., 2023a) and the following variables (Table 3.1): landcover type, forested-wetland edge density, canopy height, road density, landcover change vulnerability, species density, and rehabilitation admission density.

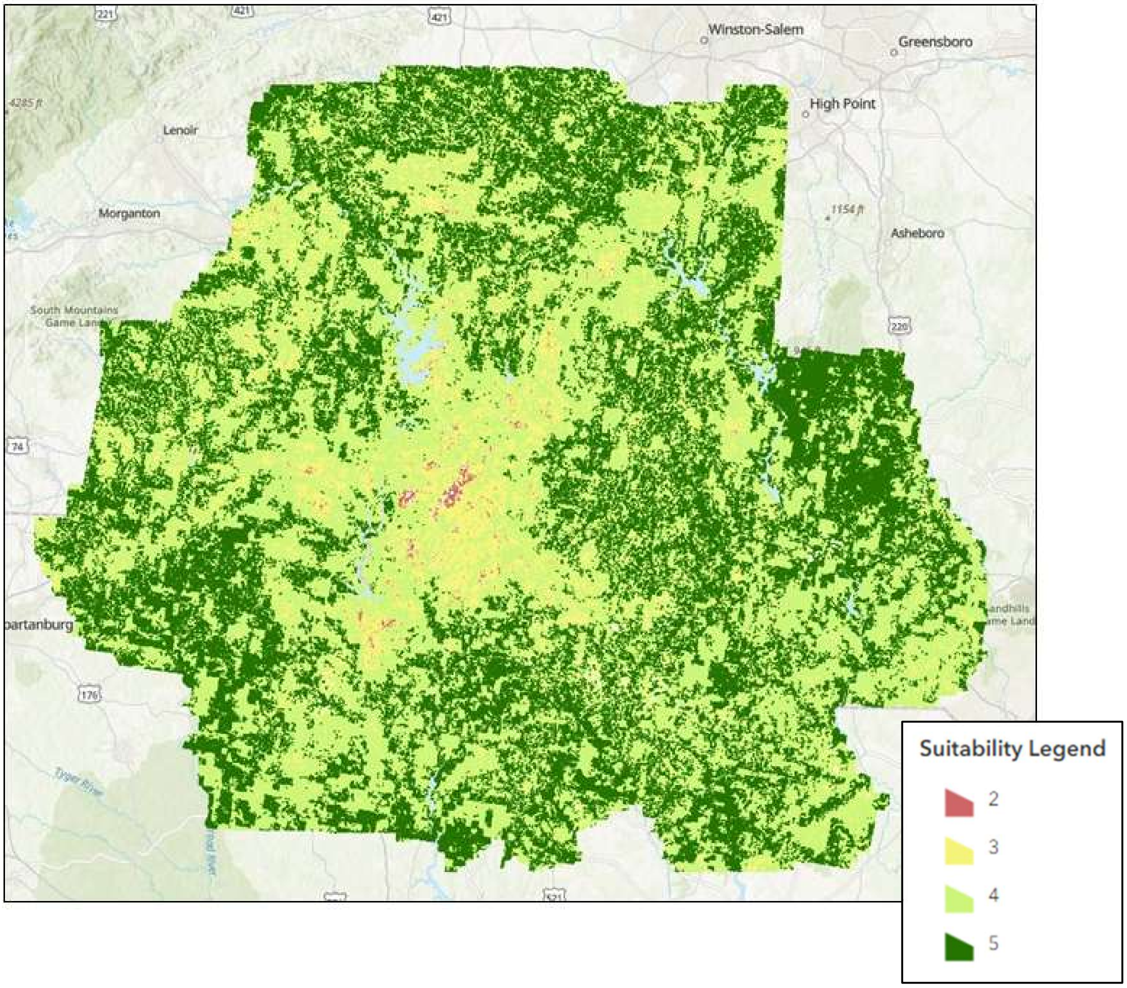

Figure 3.6 Release suitability map for rehabilitated barred owls (*Strix varia*) in the Charlotte Metropolitan Area, USA with four levels of suitability: 2 – very low-low suitability, 3 – low-medium suitability, 4 – medium-high suitability, and 5 – high-very high suitability. Release suitability map created using the ArcGIS Pro Suitability Modeler (Esri Inc., 2023a) and the following variables (Table 3.1): landcover type, distance to streams, canopy height, tree canopy cover, road density, landcover change vulnerability, species density, and rehabilitation admission density.

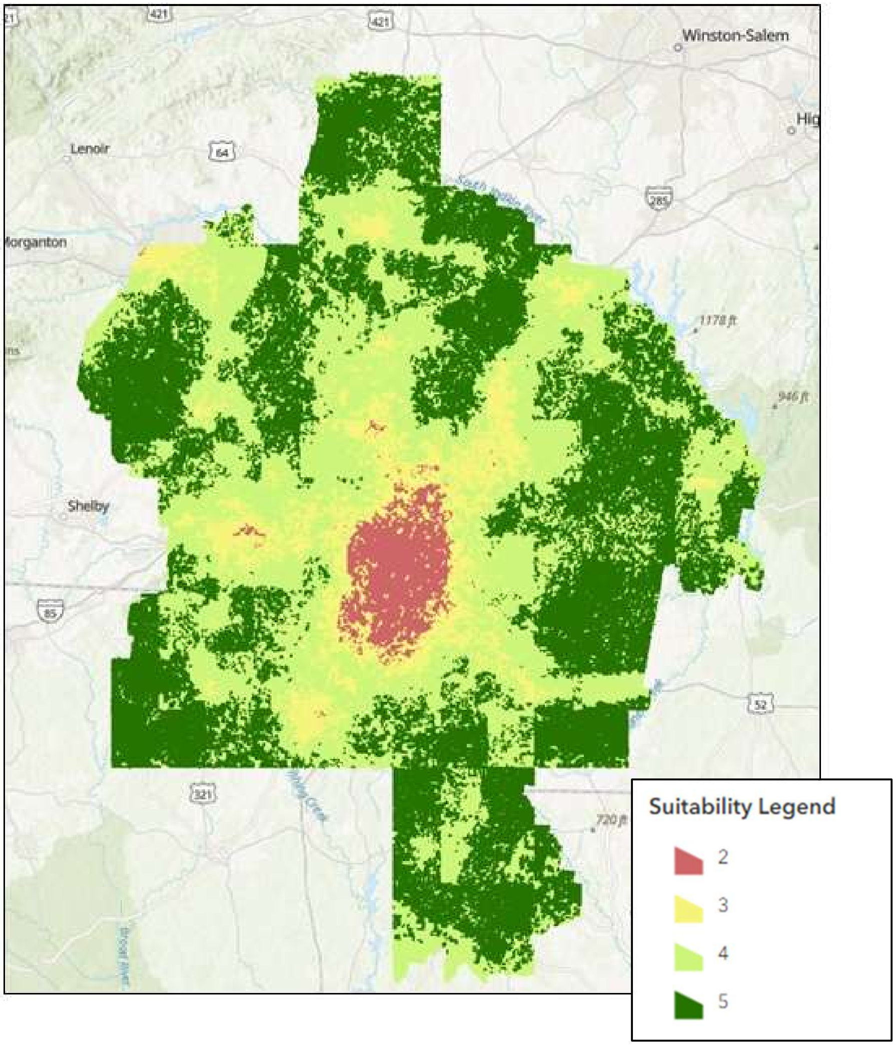

Figure 3.7 Release suitability map for rehabilitated great horned owls (*Bubo virginianus*) in the Charlotte Metropolitan Area, USA with four levels of suitability: 2 – very low-low suitability, 3 – low-medium suitability, 4 – medium-high suitability, and 5 – high-very high suitability. Release suitability map created using the ArcGIS Pro Suitability Modeler (Esri Inc., 2023a) and the following variables (Table 3.1): landcover type, open-forested edge density, road density, landcover change vulnerability, species density, and rehabilitation admission density.

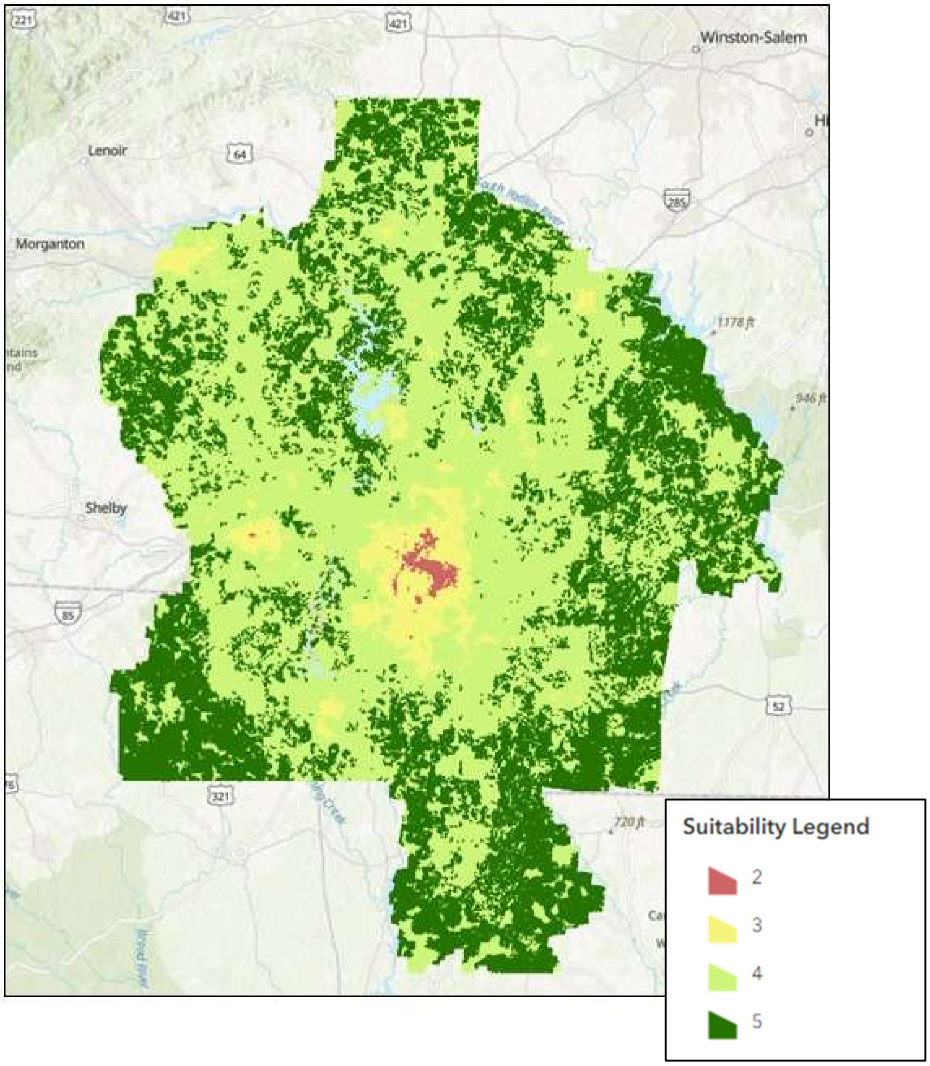

Figure 3.8 Release suitability map for rehabilitated eastern screech owls (*Megascops asio*) in the Charlotte Metropolitan Area, USA with four levels of suitability: 2 – very low-low suitability, 3 – low-medium suitability, 4 – medium-high suitability, and 5 – high-very high suitability. Release suitability map created using the ArcGIS Pro Suitability Modeler (Esri Inc., 2023a) and the following variables (Table 3.1): landcover type, open-forested edge density, distance to water, road density, landcover change vulnerability, species density, barred owl (*Strix varia*) species density, and rehabilitation admission density.

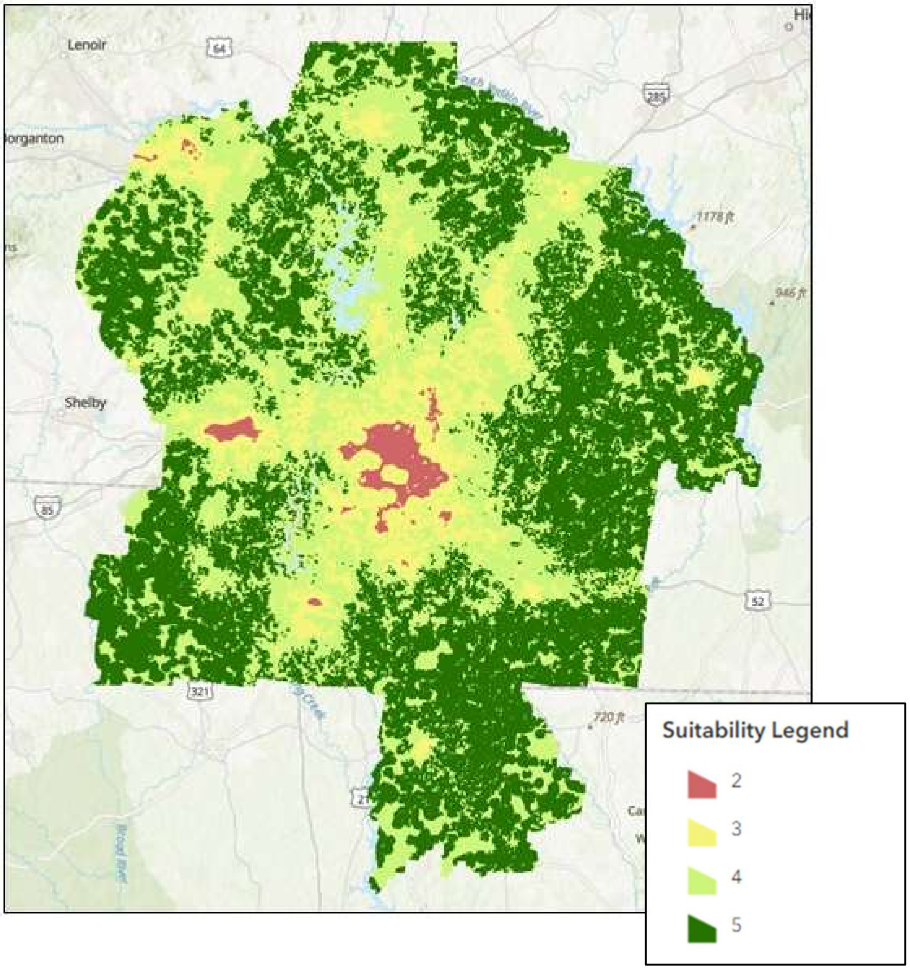

Figure 3.9 Release suitability map for rehabilitated osprey (*Pandion haliaetus*) in the Charlotte Metropolitan Area, USA with four levels of suitability: 2 – very low-low suitability, 3 – low-medium suitability, 4 – medium-high suitability, and 5 – high-very high suitability. Release suitability map created using the ArcGIS Pro Suitability Modeler (Esri Inc., 2023a) and the following variables (Table 3.1): landcover type, distance to water, road density, landcover change vulnerability, species density, and rehabilitation admission density.

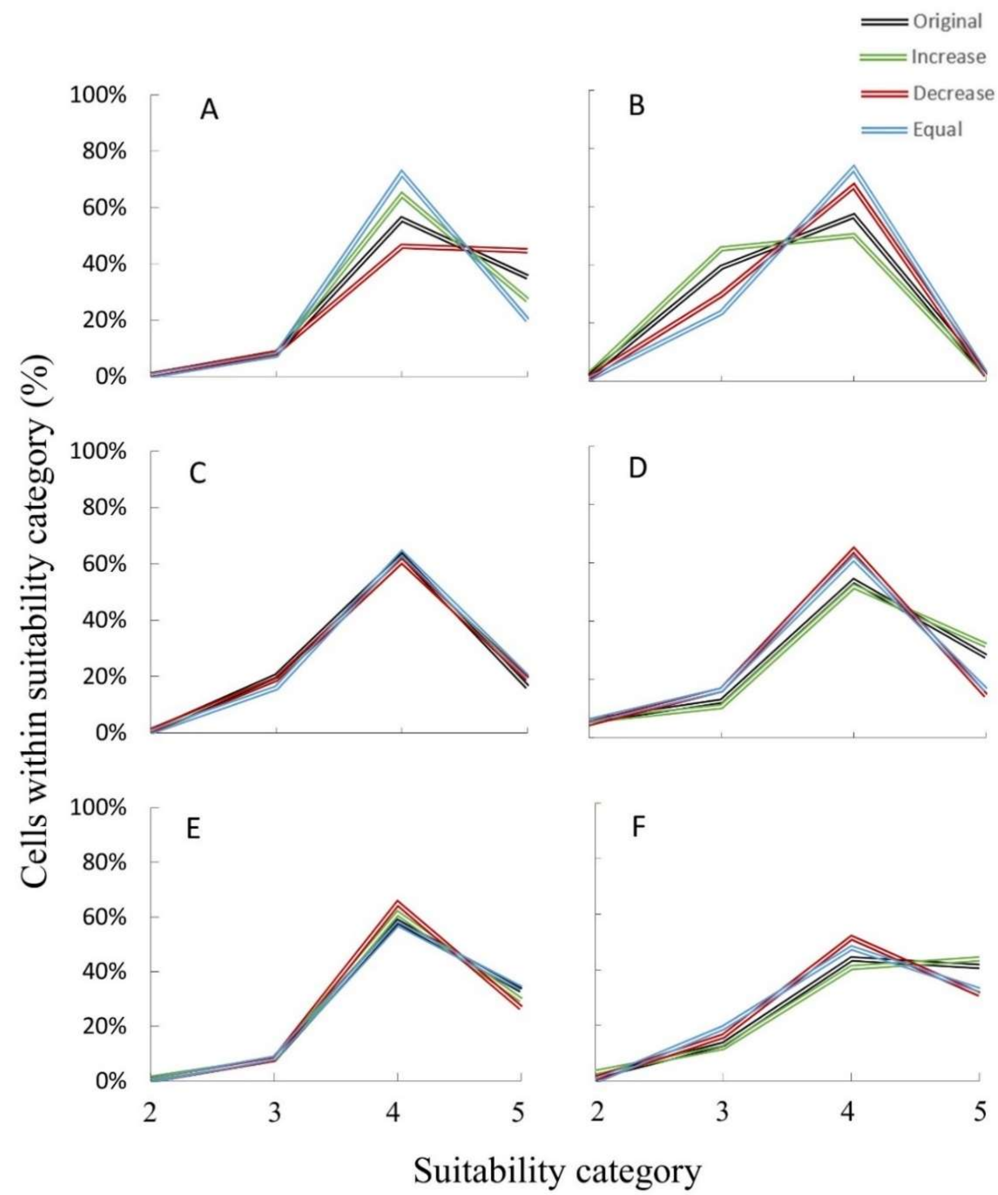

Figure 3.10 Sensitivity analyses of release habitat suitability models for red-tailed hawks (A, *Buteo jamaicensis*), red shouldered hawks (B, *Buteo lineatus*), barred owls (C, *Strix varia*), great horned owls (D, *Bubo virginianus*), eastern screech owls (E, *Megascops asio*), and osprey (F, *Pandion haliaetus*). Each line shows one model and the percent of cells in each suitability class: (2) Very Low-Low, (3) Low-Medium, (4) Medium-High, and (5) High-Very High. The "original" model is the model with variable weights based on the literature and expert advice. "Increase" models were adjusted by increasing the weight of the most important habitat variables by one, and "decrease" models decreased the weights by one. "Equal" models were made with all variables having the same weight.

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3.7 Appendix

Table A3.1 Variables, weights, and suitability scores for a release suitability model for rehabilitated red-tailed hawks (*Buteo jamaicensis*) in the Charlotte Metropolitan Area, USA. Variable descriptions and sources can be found in Table 3.1.

Variable	Weight	Weighted Influence (%)	Suitability Criteria	Sub Criteria
Landcover	2.5	20	Very High	Deciduous, Evergreen, Mixed Forest Woody Wetlands Grassland Pasture/Hay Cultivated Crops Shrub/Scrub Emergent Herbaceous Wetlands
			High	Barren Land
			Medium	Developed Open Space
			Low	Developed, Low Intensity
			Very Low	Developed, Medium and High Intensity
Open-Forested edge density (km/km2)	2.5	20	Very High	0.9+
			High	0.6-0.9
			Medium	0.4-0.6
			Low	0.1-0.4
			Very Low	Less than 0.1
Tree Canopy Cover (%)	2.125	17	Very High	20-60
			High	10-20 60-80
			Medium	0-10 80-100
			Low	
			Very Low	
Road density (km/km2)	2.125	17	Very High	0-2
			High	2-4
			Medium	4-6
			Low	6-8
			Very Low	8-10
Landcover change vulnerability	1.125	10	Very High	0.4-0.6
			High	0.3-0.4 0.6-0.7
			Medium	0.2-0.3 0.7-0.8
			Low	0.1-0.2 0.8-0.9
			Very Low	0-0.1 0.9-1
Species density	1	8	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile
Rehabilitation admission density	1	8	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile

Table A3.2 Variables, weights, and suitability scores for a release suitability model for rehabilitated red-shouldered hawks (*Buteo lineatus*) in the Charlotte Metropolitan Area, USA. Variable descriptions and sources can be found in Table 3.1.

Variable	Weight	Weighted Influence (%)	Suitability Criteria	Sub Criteria
Landcover	2.33	21	Very High	Deciduous, Evergreen, Mixed Forest
				Woody Wetlands
				Emergent Herbaceous Wetlands
			High	Shrub/Scrub
				Grassland/Herbaceous
			Medium	Developed Open Space
				Barren Land
				Pasture/Hay
				Cultivated Crops
			Low	Developed, Low Intensity
			Very Low	Developed, Medium and High Intensity
Wetland-Forested edge density (km/km2)	2.33	21	Very High	0.35-0.45
			High	0.25-0.35
				0.45+
			Medium	0.2-0.25
			Low	0.1-0.2
			Very Low	0-0.1
Canopy height (m)	1.78	16	Very High	30+
			High	24-30
			Medium	16-24
			Low	10-16
			Very Low	Less than 10
Road density (km/km2)	1.44	13	Very High	0-2
			High	2-4
			Medium	4-6
			Low	6-8
			Very Low	8-10
Landcover change vulnerability	1.22	11	Very High	0.4-0.6
			High	0.3-0.4
				0.6-0.7
			Medium	0.2-0.3
				0.7-0.8
			Low	0.1-0.2
				0.8-0.9
			Very Low	0-0.1
				0.9-1
Species density	1	9	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile
Rehabilitation admission density	1	9	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile

Table A3.3 Variables, weights, and suitability scores for a release suitability model for rehabilitated barred owls (*Strix varia*) in the Charlotte Metropolitan Area, USA. Variable descriptions and sources can be found in Table 3.1.

Variable	Weight	Weighted Influence (%)	Suitability Criteria	Sub Criteria
Landcover	2.125	17	Very High	Deciduous, Evergreen, Mixed Forest
			High	Woody Wetlands
			Medium	Shrub/Scrub Grassland/Herbaceous Pasture/Hay Cultivated Crops Emergent Herbaceous Wetlands
			Low	Barren Land Developed Open Space
			Very Low	Developed, Low, Medium, High Intensity
Distance to streams (km)	2.125	17	Very High	Less than 0.5
			High	0.5-0.8
			Medium	0.8-1.5
			Low	1.5-2.0
			Very Low	2.0+
Canopy height (m)	1.5	12	Very High	30+
			High	24-30
			Medium	16-24
			Low	10-16
			Very Low	Less than 10
Tree canopy cover (m)	2	16	Very High	70-100
			High	50-70
			Medium	30-50
			Low	20-30
			Very Low	0-20
Road density (km/km2)	1.5	12	Very High	0-2
			High	2-4
			Medium	4-6
			Low	6-8
			Very Low	8-10
Landcover change vulnerability	1.25	10	Very High	0.4-0.6
			High	0.3-0.4 0.6-0.7
			Medium	0.2-0.3 0.7-0.8
			Low	0.1-0.2 0.8-0.9
			Very Low	0-0.1 0.9-1
Species density	1	8	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile
Rehabilitation admission density	1	8	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile

Table A3.4 Variables, weights, and suitability scores for a release suitability model for rehabilitated great horned owls (*Bubo virginianus*) in the Charlotte Metropolitan Area, USA. Variable descriptions and sources can be found in Table 3.1.

Variable	Weight	Weighted Influence (%)	Suitability Criteria	Sub Criteria
Landcover	2.4	24	Very High	Deciduous, Evergreen, Mixed Forest
			High	Woody Wetlands
				Shrub/Scrub
				Grassland/Herbaceous
				Pasture/Hay
				Cultivated Crops
				Emergent Herbaceous Wetlands
			Medium	Barren Land
			Low	Developed Open Space
			Very Low	Developed, Low, Medium, High Intensity
Open-Forested edge density (km/km2)	2.4	24	Very High	0.6-0.8
			High	0.5-0.6
				0.8-0.9
			Medium	0.4-0.5
			Low	0.2-0.4
			Very Low	0-0.2
Road density (km/km2)	1.7	17	Very High	0-2
			High	2-4
			Medium	4-6
			Low	6-8
			Very Low	8-10
Landcover change vulnerability	1.5	15	Very High	0.4-0.6
			High	0.3-0.4
				0.6-0.7
			Medium	0.2-0.3
				0.7-0.8
			Low	0.1-0.2
				0.8-0.9
			Very Low	0-0.1
				0.9-1
Species density	1	10	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile
Rehabilitation admission density	1	10	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile

Table A3.5 Variables, weights, and suitability scores for a release suitability model for rehabilitated eastern screech owls (*Megascops asio*) in the Charlotte Metropolitan Area, USA. Variable descriptions and sources can be found in Table 3.1.

Variable	Weight	Weighted Influence (%)	Suitability Criteria	Sub Criteria
Landcover	1.89	17	Very High	Deciduous, Evergreen, Mixed Forest
			High	Woody Wetlands Emergent Herbaceous Wetlands Shrub/Scrub
			Medium	Grassland/Herbaceous Pasture/Hay Cultivated Crops Barren Land Developed Open Space
			Low	Developed Low Intensity
			Very Low	Developed, Medium and High Intensity
Open-Forested edge density (km/km2)	1.89	17	Very High	0.5-0.6
			High	0.6-0.7 0.4-0.5
			Medium	0.7-0.8 0.3-0.4
			Low	0.8-0.9 0.2-0.3
			Very Low	0.9+ 0-0.2
Distance to water (km)	1.89	17	Very High	Less than 0.5
			High	0.5-1.0
			Medium	1.0-1.5
			Low	1.5-2.5
			Very Low	2.5+
Road density (km/km2)	1.44	13	Very High	0-2
			High	2-4
			Medium	4-6
			Low	6-8
			Very Low	8-10
Landcover change vulnerability	1	9	Very High	0.4-0.6
			High	0.3-0.4 0.6-0.7
			Medium	0.2-0.3 0.7-0.8
			Low	0.1-0.2 0.8-0.9
			Very Low	0-0.1 0.9-1
Species density	1	9	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile
Rehabilitation admission density	1	9	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile
Barred owl species density	1	9	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile

Table A3.6 Variables, weights, and suitability scores for a release suitability model for rehabilitated ospreys (*Pandion haliaetus*) in the Charlotte Metropolitan Area, USA. Variable descriptions and sources can be found in Table 3.1.

Variable	Weight	Weighted Influence (%)	Suitability Criteria	Sub Criteria
Landcover	2.1	21	Very High	Deciduous, Evergreen, Mixed Forest
			High	Woody Wetlands
			Medium	Emergent Herbaceous Wetlands Grassland/Herbaceous Pasture/Hay Cultivated Crops Shrub/Scrub
			Low	Barren Land
			Very Low	Developed, Open, Low, Medium, High Intensity
Distance to water (km)	3.1	31	Very High	Less than 0.1
			High	0.1-0.5
			Medium	0.5-1.0
			Low	1.0-2.0
			Very Low	2.0+
Road density (km/km2)	1.6	16	Very High	0-2
			High	2-4
			Medium	4-6
			Low	6-8
			Very Low	8-10
Landcover change vulnerability	1.2	12	Very High	0.4-0.6
			High	0.3-0.4 0.6-0.7
			Medium	0.2-0.3 0.7-0.8
			Low	0.1-0.2 0.8-0.9
			Very Low	0-0.1 0.9-1
Species density	1	10	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile
Rehabilitation admission density	1	10	Very High	Lowest quantile
			High	
			Medium	
			Low	
			Very Low	Highest quantile

Table A3.7 Variables and weights (weighted percentages in parentheses) for release suitability model sensitivity analyses for rehabilitated red-tailed hawks (*Buteo jamaicensis*) in the Charlotte Metropolitan Area, USA. The most important habitat variables (italicized) were adjusted in the increase and decrease models, while all variables were set to equal weights in the equal model. Note that all variable weighted percentages changed slightly in the increase and decrease models to ensure all weights equaled 1. See the Methods: Sensitivity Analysis section for discussion of this.

Environmental variable	**Original model weights**	**Increase model weights**	**Decrease model weights**	**Equal model weights**
Landcover	2.5 (0.20)	3.5 (0.24)	1.5 (0.14)	1 (0.143)
Open-Forested edge density	2.5 (0.20)	3.5 (0.24)	1.5 (0.14)	1 (0.143)
Tree canopy cover	2.125 (0.17)	2.125 (0.15)	2.125 (0.20)	1 (0.143)
Road density	2.125 (0.17)	2.125 (0.15)	2.125 (0.20)	1 (0.143)
Landcover change vulnerability	1.125 (0.10)	1.125 (0.08)	1.125 (0.12)	1 (0.143)
Species density	1 (0.08)	1 (0.07)	1 (0.10)	1 (0.143)
Rehabilitation admission density	1 (0.08)	1 (0.07)	1 (0.10)	1 (0.143)

Table A3.8 Variables and weights (weighted percentages in parentheses) for release suitability model sensitivity analyses for rehabilitated red-shouldered hawks (*Buteo lineatus*) in the Charlotte Metropolitan Area, USA. The most important habitat variables (italicized) were adjusted in the increase and decrease models, while all variables were set to equal weights in the equal model. Note that all variable weighted percentages changed slightly in the increase and decrease models to ensure all weights equaled 1. See the Methods: Sensitivity Analysis section for discussion of this.

Environmental variable	**Original model weights**	**Increase model weights**	**Decrease model weights**	**Equal model weights**
Landcover	2.33 (0.21)	3.33 (0.24)	1.33 (0.16)	1 (0.143)
Wetland-Forested edge density	2.33 (0.21)	3.33 (0.24)	1.33 (0.16)	1 (0.143)
Canopy height	1.78 (0.16)	2.78 (0.20)	0.78 (0.10)	1 (0.143)
Road density	1.44 (0.13)	1.44 (0.10)	1.44 (0.18)	1 (0.143)
Landcover change vulnerability	1.22 (0.11)	1.22 (0.09)	1.22 (0.15)	1 (0.143)
Species density	1 (0.09)	1 (0.07)	1 (0.12)	1 (0.143)
Rehabilitation admission density	1 (0.09)	1 (0.07)	1 (0.12)	1 (0.143)

Table A3.9 Variables and weights (weighted percentages in parentheses) for release suitability model sensitivity analyses for rehabilitated barred owls (*Strix varia*) in the Charlotte Metropolitan Area, USA. The most important habitat variables (italicized) were adjusted in the increase and decrease models, while all variables were set to equal weights in the equal model. Note that all variable weighted percentages changed slightly in the increase and decrease models to ensure all weights equaled 1. See the Methods: Sensitivity Analysis section for discussion of this.

Environmental variable	**Original model weights**	**Increase model weights**	**Decrease model weights**	**Equal model weights**
Landcover	2.125 (0.17)	3.125 (0.20)	1.125 (0.12)	1 (0.125)
Distance to streams	2.125 (0.17)	3.125 (0.20)	1.125 (0.12)	1 (0.125)
Tree canopy cover	2 (0.16)	3 (0.19)	1 (0.11)	1 (0.125)
Canopy height	1.5 (0.12)	1.5 (0.10)	1.5 (0.16)	1 (0.125)
Road density	1.5 (0.12)	1.5 (0.10)	1.5 (0.15)	1 (0.125)
Landcover change vulnerability	1.25 (0.10)	1.25 (0.08)	1.25 (0.12)	1 (0.125)
Species density	1 (0.08)	1 (0.06)	1 (0.11)	1 (0.125)
Rehabilitation admission density	1 (0.08)	1 (0.06)	1 (0.11)	1 (0.125)

Table A3.10 Variables and weights (weighted percentages in parentheses) for release suitability model sensitivity analyses for rehabilitated great horned owls (*Bubo virginianus*) in the Charlotte Metropolitan Area, USA. The most important habitat variables (italicized) were adjusted in the increase and decrease models, while all variables were set to equal weights in the equal model. Note that all variable weighted percentages changed slightly in the increase and decrease models to ensure all weights equaled 1. See the Methods: Sensitivity Analysis section for discussion of this.

Environmental variable	**Original model weights**	**Increase model weights**	**Decrease model weights**	**Equal model weights**
Landcover	2.4 (0.24)	3.4 (0.28)	1.4 (0.18)	1 (0.167)
Open-Forested edge density	2.4 (0.24)	3.4 (0.28)	1.4 (0.18)	1 (0.167)
Road density	1.7 (0.17)	1.7 (0.14)	1.7 (0.20)	1 (0.167)
Landcover change vulnerability	1.5 (0.15)	1.5 (0.14)	1.5 (0.18)	1 (0.167)
Species density	1 (0.10)	1 (0.08)	1 (0.13)	1 (0.167)
Rehabilitation admission density	1 (0.10)	1 (0.08)	1 (0.13)	1 (0.165)

Table A3.11 Variables and weights (weighted percentages in parentheses) for release suitability model sensitivity analyses for rehabilitated eastern screech owls (*Megascops asio*) in the Charlotte Metropolitan Area, USA. BDOW indicates barred owl (*Strix varia*) species density. The most important habitat variables (italicized) were adjusted in the increase and decrease models, while all variables were set to equal weights in the equal model. Note that all variable weighted percentages changed slightly in the increase and decrease models to ensure all weights equaled 1. See the Methods: Sensitivity Analysis section for discussion of this.

Environmental variable	**Original model weights**	**Increase model weights**	**Decrease model weights**	**Equal model weights**
Landcover	1.89 (0.17)	2.89 (0.20)	0.89 (0.11)	1 (0.125)
Open-Forested edge density	1.89 (0.17)	2.89 (0.20)	0.89 (0.11)	1 (0.125)
Distance to water	1.89 (0.17)	2.89 (0.20)	0.89 (0.11)	1 (0.125)
Road density	1.44 (0.13)	1.44 (0.11)	1.44 (0.18)	1 (0.125)
Landcover change vulnerability	1 (0.09)	1 (0.08)	1 (0.13)	1 (0.125)
Species density	1 (0.09)	1 (0.07)	1 (0.12)	1 (0.125)
Rehabilitation admission density	1 (0.09)	1 (0.07)	1 (0.12)	1 (0.125)
BDOW species density	1 (0.09)	1 (0.07)	1 (0.12)	1 (0.125)

Table A3.12 Variables and weights (weighted percentages in parentheses) for release suitability model sensitivity analyses for rehabilitated ospreys (*Pandion haliaetus*) in the Charlotte Metropolitan Area, USA. The most important habitat variables (italicized) were adjusted in the increase and decrease models, while all variables were set to equal weights in the equal model. Note that all variable weighted percentages changed slightly in the increase and decrease models to ensure all weights equaled 1. See the Methods: Sensitivity Analysis section for discussion of this.

Environmental variable	**Original model weights**	**Increase model weights**	**Decrease model weights**	**Equal model weights**
Landcover	2.1 (0.21)	3.1 (0.26)	1.1 (0.14)	1 (0.167)
Distance to water	3.1 (0.31)	4.1 (0.35)	2.1 (0.25)	1 (0.167)
Road density	1.6 (0.16)	1.6 (0.13)	1.6 (0.20)	1 (0.167)
Landcover change vulnerability	1.2 (0.12)	1.2 (0.10)	1.2 (0.15)	1 (0.167)
Species density	1 (0.10)	1 (0.08)	1 (0.13)	1 (0.167)
Rehabilitation admission density	1 (0.10)	1 (0.08)	1 (0.13)	1 (0.165)

CHAPTER 4: HUMAN ADAPTATION IS KEY TO MANAGING CONFLICTS WITH BLACK VULTURES (*CORAGYPS ATRATUS*)

Abstract

1. Human-wildlife conflicts are increasing and have significant implications for human and wildlife populations worldwide. Black vultures (*Coragyps atratus*) provide a good example – they are a species whose range is expanding into new areas and are involved in frequent conflicts, often regarding concerns over depredation of domestic and captive wild animals (i.e., livestock, farmed or kept wildlife).

2. Instigated by a conflict at a local organization, I sought to (1) evaluate the environmental and social drivers of human-black vulture conflicts involving captive animals, and (2) identify the best management strategies that lead to long-term coexistence between humans and black vultures. I conducted in-depth semi-structured interviews of 14 researchers and practitioners across North and South America that had previous experience with black vulture conflicts.

3. My analyses reveal that the black vulture conflicts are primarily caused by resource availability, generally a food source, and are ultimately solved by human adaptation, often by way of resource restriction. I present a framework based on these results that describes the progression of conflicts to coexistence, illustrated by the case study that initiated the research.

4. *Synthesis and applications*: To coexist with black vultures, we must strive to identify the root causes of conflicts and promote human adaptation to, and tolerance for, black vulture populations.

Keywords: black vulture, human-wildlife conflict, livestock, management, coexistence

4.1 Introduction

Humans and wildlife are sharing more land worldwide, leading to more frequent human-wildlife conflicts (Abrahms, 2021; Frank & Glikman, 2019; Soulsbury & White, 2015). Human-wildlife conflicts can lead to direct physical impacts such as injury, illness, and death for humans and wildlife, but also indirect impacts including opportunity costs, diminished wellbeing, and the disruption of livelihoods for individuals involved in conflicts (Nyhus, 2016). Further, human-wildlife conflict is a major cause of biodiversity loss and can contribute to the disruption of ecosystem-wide functions such as pollination, seed dispersal, and nutrient cycling (Dirzo et al., 2014; Nyhus, 2016). The relationship between human development and conflicts with wildlife is complex and situational, with different types of human-wildlife conflict existing across the urban-to-rural gradient.

Many vultures within the Cathartidae family have adapted to survive in close proximity to humans, using the many resources that we provide and adapting to the threats present in developed landscapes (Bildstein & Therrien, 2018). Black vultures (*Coragyps atratus*) are one species of Cathartid vulture that ranges across large portions of North and South America, and are involved in multiple types of human-wildlife conflicts (Buckley et al., 2022; Kluever et al., 2020). In recent decades, their range across North America has expanded, spreading into the midwestern United States, among other areas (Buckley et al., 2022; Zimmerman et al., 2019). Black vulture populations have also rebounded from declines in the late 1900's, and are now experiencing population increases estimated between 5-10% annually (Avery, 2004; Blackwell et al., 2007; Kluever et al., 2020; Zimmerman et al., 2019).

With black vulture populations increasing and spreading into the midwestern United States, conflicts have spread with them. Livestock depredation is one conflict currently receiving a great deal of attention – reports of black vultures attacking and killing livestock (primarily neonatal cows, sheep, goats, and horses) have increased significantly since the 1990's (Avery & Cummings, 2004; Kluever et al., 2020; Quinby et al., 2022; Zimmerman et al., 2019). Black vultures will occasionally prey upon livestock, especially when weak, injured, or otherwise vulnerable (such as newborns) (Buckley et al., 2022; Kluever et al., 2020). The concerns about black vulture depredation also apply to domestic animals and captive wildlife, such as those in zoos, farms, or other facilities (Buckley et al., 2022; Lowney, 1999) as these offer concentrations of animals with a high likelihood of vulnerable individuals, especially in the case of zoos or wildlife rehabilitation centers.

Despite the increasing frequency of reports, these conflicts are understudied with only one study evaluating the environmental factors associated with depredation risk (Quinby et al., 2022) and just a select few studies evaluating the perceptions of livestock producers (Ballejo et al., 2020; Duriez et al., 2019; Wahl et al., 2023) or estimating the true rate of depredation events (Ballejo et al., 2020; Humphrey et al., 2004). Additionally, while more research in recent years has focused on black vulture livestock depredation (Avery & Cummings, 2004; Duriez et al., 2019; Wahl et al., 2023), to my knowledge, none has focused on other facilities (such as zoos or wildlife rehabilitation centers) despite the relevancy of conflicts and the opportunity to identify the drivers and solutions. Adding further importance to future research on human-black vulture conflicts is the threat of policy change that could negatively impact black vulture populations and alter human-vulture interactions across large scales. This includes policies such as the Black Vulture Relief Act of 2023 (United States House of Representatives bill introduced in the 118th Congress) that would reduce federal protections for black vultures and authorize livestock producers to perform lethal management without a permit ("Black Vulture Relief Act of 2023 ", 2023).

Given the significance of human-wildlife conflicts to human wellbeing and ecosystem functioning, it is important to understand the drivers of conflict and management strategies that promote long-term coexistence. My objective with this research was to evaluate the drivers of human-black vulture conflicts and management strategies for conflicts involving captive animal populations. This research was motivated by a conflict at a wildlife rehabilitation facility in the North Carolina piedmont region. The facility was experiencing black vulture depredation of captive animals, paired with property damage and community complaints. In the context of this case study, I sought to answer the following questions: (1) what environmental and social features drive black vulture conflicts involving captive animals, and (2) how can we manage these conflicts in a way that is appropriate for both humans and black vultures? In this article, I present the findings from in-depth interviews conducted with researchers and practitioners across the black vulture range, a framework conceptualizing black vulture conflicts and coexistence, and the application of the framework to the case study. My research is the first to highlight black vulture depredation conflicts at a wildlife rehabilitation facility and synthesize the current understanding of human-black vulture conflicts using interviews with researchers and practitioners across North and South America. This approach provides insight to this understudied phenomenon by identifying drivers and solutions for black vulture conflicts involving a diversity of captive animal populations (rather than livestock only), as well as providing lessons that can help us understand human-wildlife conflicts across similar generalist species worldwide.

4.2 Methods

4.2.1 Case study and impetus for research

This research was guided by a case of black vulture conflict at a wildlife rehabilitation facility in the North Carolina piedmont region. The facility housed animals indoors and outdoors and left food outdoors. In 2019, as many as 1,000 black vultures began congregating at the site on any given day. The black vultures ate the food meant for the rehabilitated animals, attacked injured or weak animals, consumed dead animals, and destroyed materials across the facility. I aimed to assist with this conflict and gain a deeper understanding of similar situations that could inform future black vulture conflicts across the black vulture range. To do this, I conducted interviews of researchers and practitioners who had worked with similar black vulture conflicts worldwide and with community members located near the case study conflict[1].

4.2.2 Researcher and practitioner interviews

I conducted in-depth semi-structured interviews with researchers and practitioners worldwide who have been involved in cases of black vulture conflict. Potential

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[1]I conducted interviews of community members located near the black vulture conflict case study. The interviews were structured around characteristics of the conflict, the social and environmental contexts, management strategies and success, and the perceptions and impacts to the community (Table 4.1). This research was approved by the IRB as Exempt with Limited Review under study # IRB-23-0414. While these interviews with community members contributed to our broader understanding of the issue, they are not the key method analyzed in this paper as I was unable to recruit a large number of participants. The results and discussion focus only on interviews conducted with researchers and practitioners.

interviewees were contacted if they had authored articles or books discussing black vulture conflicts and management strategies, were affiliated with organizations that manage black vulture conflicts (such as the United States Department of Agriculture), were reported through news articles as having been involved in conflicts, or were referred by other potential interviewees. I interviewed 14 researchers and practitioners regarding their experience with black vulture conflict (Figure 4.1). The participants were spread across North America (n=12, 85.7%) and South America (n=2, 14.3%) and worked in the zoological field (n=4, 28.6%; zoological parks, rehabilitation, animal care, etc.), as academic/private researchers (n=4, 28.6%), with government agencies (n=3, 21.4%), with other private businesses (n=1, 7.1%), or were not currently affiliated with any organization (n=2, 14.3%). Participants were also working or living across the black vulture range including within the established range (n=9, 64.3%) and along the range edges (n=5, 35.7%). This sample of researchers and practitioners spans multiple industries, two continents, and different parts of the black vulture range. Because of this, I consider it representative of the current state of knowledge of black vulture-human conflicts and therefore adequate as a basis for generalizable conclusions.

Interviews lasted approximately 30-60 minutes and discussed characteristics of the conflict, social and environmental contexts, management strategies and success, and the perceptions and impacts to the surrounding community (Table 4.1). Interviews occurred between April 2022 and June 2023 and were conducted in a confidential manner over Zoom or in-person within the Charlotte, NC area, depending on interviewee location and preference. This research was approved by the Institutional Review Board (IRB) as Exempt with Limited Review (Study # IRB-22-0594).

4.2.3 Analyses

With the interviewee's consent, the interviews were audio recorded. Interviews were transcribed using Otter.ai (*Otter.ai*, 2023) and analyzed using NVivo 13 (*NVivo*, 2020) to explore themes and connections. I coded the interviews for themes that were informed by an in-depth literature review, author experiences, and expert opinions. The themes captured (a) broad conditions associated with conflict, (b) conflict type, (c) cause of conflict, (d) management strategies used, and (e) consequences of management (Table 4.2). The use of semi-structured interviews allowed for unique ideas to emerge from the conversations while also providing the interviewer with relevant background information and context that supported the ideas. To address my research objectives, I evaluated the coded interviews within each theme for key ideas present across participants. I also collected the number of participants that discussed each theme to evaluate how frequently each was raised.

4.3 Results and Discussion

4.3.1 Researcher and practitioner interviews

Here, I present and discuss the results from these interviews structured by the major theme categories: (1) broad conditions associated with conflict, (2) conflict type, (3) cause of conflict, and (4) management strategies used and consequences.

4.3.1.1 Broad conditions associated with conflict

There are many social and environmental conditions associated with black vulture conflicts. Here, I discuss perceptions of black vultures (like, dislike, or neutrality towards black vultures; whether they are viewed as intelligent or valuable), the landscape composition, threats at the site of conflict, and concerns or confusion about new black vulture presence. Among participants, there was an overall fondness towards black vultures (n=10, 71.4%; Figure 4.2a). The interviews were conducted with those that worked closely with black vultures who may be more likely to appreciate the species. Despite their personal fondness, many participants believed that other people have a dislike or fear of black vultures, especially when involved in a conflict (n=7, 50%), and several participants saw or experienced concerns or confusion about new black vulture presence (n=4, 28.6%).

Vultures are often portrayed poorly in media, which likely contributes to the perceived negative views about vultures (Lambertucci et al., 2021). Yet, research on some vulture species has found generally positive perceptions due to the cultural and ecological services they provide (Craig et al., 2018; Mashele et al., 2021; Phuyal et al., 2016). Participants often believed that negative perceptions of black vultures contribute to the occurrence of conflicts, as is supported by recent literature on human-vulture conflict (Ballejo et al., 2020; Lambertucci et al., 2021), and that these negative perceptions, rather than evidence of damage or threat, may be used as an excuse to push for management. For example, one participant stated:

> "*I think…people have not a very positive view of vultures to begin with. It's just that they think about death and about mortality and think about it coming for me... And they're biased against them*." – Interview participant #11, academic researcher, 2022

This quote shows that the true conflict with black vulture populations may exist in the perceptions of humans regarding vultures, rather than in actual evidence of damage.

Participants discussed conflicts occurring in urban (n=3, 21.4%), mixed (n=3, 21.4%), and rural (n=4, 28.6%) landscapes in approximately equal numbers (Figure 4.2a). Based on these results, there does not appear to be any relationship between black vulture conflicts and landcover, with conflicts occurring across various urban, rural, and mixed landscapes. This is supported by existing research, with black vulture conflicts occurring or predicted to occur across diverse landscapes (Kluever et al., 2020; Quinby et al., 2022; Wahl et al., 2023; Washburn, 2018). The idea that locations with conflicts have fewer threats to the black vultures was mentioned by some participants (n=4, 28.6%). Wildlife naturally balance trade-offs between opportunity and risk and conflicts may be more likely to occur at sites that offer resources with fewer threats than surrounding areas.

4.3.1.2 Conflict type

Participants discussed black vulture conflicts of all types – perceived threats, property damage, livestock depredation, and unwanted or nuisance congregations (Figure 4.2b). Among these, property damage was the most commonly discussed with many having experience with these conflicts (n=11, 78.6%). This was followed by unwanted congregations (n=8, 57.1%), livestock depredation (n=7, 50%), and perceived threats (n=3, 21.4%).

While livestock depredation has gained attention in recent years (Lambertucci et al., 2021), property damage is still the most common conflict reported, accounting for 46% of reports to the United States Department of Agricultural (USDA) Animal & Plant Health Inspection Service (APHIS) in 2022 compared to 38.5% of reports as threats to agriculture and livestock (USDA, 2022). Based on previous literature and USDA APHIS reports, these conflicts appear to occur across the black vulture range, with instances of property damage, livestock depredation, and unwanted or nuisance congregations within the established range and along the edges (APHIS, 2021; Buckley et al., 2022; Kluever et al., 2020; Tillman et al., 2002).

4.3.1.3 Cause of conflict

Nearly all participants (n=12, 85.7%) viewed conflicts as caused by food availability (Figure 4.2c). Conflicts caused by new developments and habitat changes were discussed as well (n=3, 21.4%; n=1, 7.1%, respectively), but the overwhelming response from those interviewed was that conflicts were nearly always associated with an available food source.

Most vulture species, including the black vulture, are habitat generalists and opportunistic foragers (Bildstein & Therrien, 2018; Buckley et al., 2022; Richard et al., 2022; van Overveld et al., 2022), taking advantage of available food sources. Other opportunistic foraging species, such as black bears (*Ursus americanus*) and raccoons (*Procyon lotor*) are frequent subjects of conflicts with humans centered around food (Barden et al., 1993; Lackey et al., 2018). One participant echoed this idea, stating:

> *"A lot of animals adapt their behavior based on the seasonality of [humans]… We've seen that in bears. We see it in raccoons… and a lot of those animals that are opportunists…come in spring and hang around…until the [humans] leave and the food source leaves with them."* – Interview participant #10, industry practitioner, 2022

This quote shows the similar behaviors and the adaptation to human patterns that we see in habitat generalists and opportunistic foraging species.

Black vulture foraging includes live or dying animals, often those that are young and vulnerable (Buckley et al., 2022). While more research is critically needed on the rate and context of depredation incidents by black vultures, there are certainly credible reports of black vultures attacking and killing animals including hatchling sea turtles, skunks, opossums, and newborn livestock (Hagopian, 1947; McIlhenny, 1939; Mrosovsky, 1971; Wahl et al., 2023). Black vultures also view birthing livestock as a potential food source, as discussed by one participant:

> *"There's no question that vultures are very attracted to cattle that are going to give birth or to a horse that's going to give birth or sheep, etc. It's very well documented, they will hang around and they're waiting for the afterbirth… They associate a cow doing what a cows doing before she's about to give birth. And they know that there's going to be a nice little feast on the way reliably fairly soon. And they're perfectly happy to sit contently and wait."* – Interview participant #11, academic researcher, 2022

This quote supports the black vulture use of birthing livestock at a food source, but highlights the idea that often, the black vultures are targeting the afterbirth rather than the newborn animal. However, when animals are stillborn, injured, or sick, the black vultures may view them as a food source as well.

These results, paired with previous literature, demonstrate how adaptable black vultures are in their foraging strategies. Birthing livestock are simply another food source to which black vultures have adapted – the vultures know when the livestock will be giving birth, and they are present for the meal. This extends to human patterns as well (van Overveld et al., 2022), black vultures understand when and where food will be available from sources such as farms, garbage, and slaughterhouses, and adapt their behavior to take advantage of the food source.

4.3.1.4 Management strategies used and consequences

Interviews were analyzed for management strategies including scare tactics, lethal tactics, education, translocation, and human adaptation to the black vulture presence. All management strategies were discussed in the interviews, except for translocation of black vultures (Figure 4.2d).

Human adaptation was the most commonly discussed management strategy (n=12, 85.7%), and nearly always with the human adaptation centered around limiting a food source. As one participant discussed, we will adapt to them just as much as they have adapted to us. Participants described situations in which they had limited access to food sources by transitioning captive animals to feeding indoors, clearing roadkill and dead fish regularly, switching from composting to garbage compacting, and educating employees and visitors about securing garbage and food. Interview participants described these strategies as largely effective when done consistently.

The literature on black vulture conflicts also emphasizes the importance of human adaptation as a management strategy, with management recommendations primarily focusing on habitat management and the elimination of food attractants (APHIS, n.d.; Killam et al., 2022; Kluever et al., 2020; Wildlife Services, 2010). This extends to ensuring that livestock and other animals are safe and protected, especially when weak or vulnerable. We have adapted to many other species involved in resource-driven conflicts over time, and the solutions often lie in human adaptation through altering human behavior and animal husbandry practices (Lackey et al., 2018; Rush et al., 2023; Shivik, 2004). Previous research has found that birthing livestock are safe from black vulture depredation when kept in barns or smaller pastures (Wahl et al., 2023) but face greater risks when left unprotected in larger pastures, as is true for other predator species such as bears, coyotes, and wolves (Shivik, 2004). One participant discussed the use of barns and similar structures to protect birthing and vulnerable livestock from black vultures:

> *"It is because of those factors that the practice is to build these [barns]…where the sows going when they're going to give birth, and they're protected, they're covered, and they're shielded. It's on you, the human, to make the changes that are necessary to protect yours from the natural instincts of those animals, to take advantage of a food source sitting there unprotected.*" – Interview participant #3, academic researcher, 2022

This quote shows the importance of human adaptation to managing conflicts with black vulture populations, as well as other wildlife. In many of these cases, black vultures are following their instincts and humans may need to alter behaviors and husbandry practices to coexist with the species.

While human adaptation was the most commonly discussed management strategy in my interviews, the other strategies were discussed frequently as well. The use of scare tactics including hanging effigies, making loud noises, shining lasers, and deploying inflatable stick figures were discussed in many interviews (n=9, 64.3%). Lethal tactics were discussed frequently as well (n=8, 57.1%), generally as a secondary method to address problematic black vulture congregations that persist after scare tactics were employed. However, several participants raised the question of when and if we should be using lethal management in response to black vulture conflicts at all (n=5, 35.7%). Retaliation against predators is common worldwide (Dickman, 2010; Woodroffe et al., 2005), but lethal management of black vultures simply may not have the same effect as it does on other species. Black vultures form large congregations, and it may be difficult to identify specific problem individuals within congregations, making lethal management much less effective.

> *"If you come across an animal that's moribund, and the vultures are feeding, it's pretty nasty. I completely understand the reaction, but it doesn't justify doing whatever you want in response to it…*
> *Unfortunately, the solution is, 'Oh, we've got to shoot a bunch of vultures'… You've got a bear that gets into the habit of waiting for calves? In that case, you could probably identify the individual bear who's determined, who's developed a taste for calves. But that's not ever going to be the case when you're trying to apply the same solution to vultures."* – Interview participant #11, academic researcher, 2022

This quote shows the gruesome nature of black vulture attacks on animals, while also highlighting the idea that lethal management may not have the same effect on black vultures as it does on other species. Even if individual black vultures were more likely to attack livestock, it would be very difficult to use lethal management on selected individuals within large congregations.

Finally, many of the participants discussed the use of education for those involved in conflict as a management strategy (n=7, 50%). While education was discussed less frequently than the other strategies, several participants believed it to be one of the most important and valuable strategies to use, as discussed by one participant:

> *"That's what we want to be here for is if people are having troubles with that human-wildlife conflict, we can educate them. Hopefully provide them with enough information so that they can have some respect for the bird. And then that way, they'll be more inclined to work towards a better solution to figuring out the problem… Even if you can't figure out their problem or solve it for them, they just want to talk to somebody."* – Interview participant #9, zoological practitioner, 2022

Many of the practitioners from the zoological fields echoed this idea – education is very important in managing human-wildlife conflict. This quote shows that education can help individuals understand and have more respect for the species, which may lead to them working to find better long-term solutions rather than quick fixes. Other times, individuals just want to have their frustrations heard and understood, even if there is no easy solution. Education and communication can help individuals involved in conflicts not only evaluate all of the options available to them, but also understand the value of the organism (Cortés-Avizanda et al., 2018; Duriez et al., 2019; Lambertucci et al., 2021). Several participants (n=5, 35.7%) reported having created educational materials for employees, visitors, or those involved in conflicts, with positive responses. Education programs for other predatory species have clear potential to reduce human-wildlife conflicts and are often a highly recommended management tool for conflicts worldwide (Cailly Arnulphi et al., 2017; Duriez et al., 2019; Gore et al., 2006; Johansson et al., 2016).

Yet, educational campaigns are not always sufficient to cause human behavioral change, especially with conflicts causing property damage or livestock depredation (Baruch-Mordo et al., 2011; Espinosa & Jacobson, 2012). Programs that provide education on the conflict-causing species and target human behavioral changes (through fines or enforcement) to address the conflict can be fundamental tools in turning conflict into coexistence (Baruch-Mordo et al., 2009, 2011; Espinosa & Jacobson, 2012; Manfredo & Dayer, 2004).

Regardless of the management strategies used, participants generally reported mixed success with equal numbers of participants reporting conflicts continuing, being solved, or moving to a different area (n=5, 35.7% for each; Figure 4.2e). There were no clear associations between specific management strategies and success over time. For example, hanging effigies was reported as successful by several participants, but with some seeing diminishing success after the first year. This sentiment was repeated for other scare tactics discussed, such as loud noises or lights, with some immediate success that diminished once the black vultures became accustomed to the tactics. Lethal tactics were met with early success as well, but two participants argued that culling simply created space for new vultures and thus, was largely ineffective long-term. Both scare tactics and lethal tactics often resulted in black vultures moving to a different area due to altered resource availability – shifting the conflict rather than solving it. These reports are supported by previous research that found variable rates of success for the use of guard animals, lethal control, translocation, and scare tactics (Avery & Lowney, 2016; Evans, 2013; Humphrey et al., 2000; Kluever et al., 2020; Milleson et al., 2006; Scasta et al., 2017; Tillman et al., 2002; Wahl et al., 2023). As stated in Woodroffe et al. (2005) – "there is no silver bullet" for black vulture management.

4.3.2 A framework and case study of black vulture conflict

In this section, I present a framework for black vulture conflicts and coexistence based on my results and discuss insights from the application of the framework to the case study motivating this research.

4.3.2.1 Framework for black vulture conflicts and coexistence

With human adaptation to species and management of the root causes of conflict, we can gradually move towards coexistence with the populations (Lackey et al., 2018). In all of the situations discussed in this article, the participants involved have used various lethal and nonlethal management techniques, but the ultimate coexistence was due to their ability to adapt to the black vultures, to identify the resources used by the vultures and the materials threatened by them, and to change what they were doing in response.

This framework shows that black vulture conflicts are driven by resource availability, are ultimately solved by human adaptation, and gradually move towards coexistence (Figure 4.3). Over 85% of interview participants identified black vulture conflicts as being caused by resource availability, generally food sources, which is supported by previous research (Avery & Cummings, 2004; Ballejo et al., 2020; Kluever et al., 2020; Quinby et al., 2022; Wahl et al., 2023). Once black vultures have identified the available resource, they begin congregating in the area and conflicts with humans arise. The conflicts may result from black vulture use of the available resource (e.g., predation upon vulnerable animals), the impacts to the area (e.g., property damage), or simply the presence of the species (unsightly, nuisance, perceived threat). To address the resulting conflicts, various management strategies may be used. Over 85% of interview participants identified human adaptation as the most promising long-term management strategy, which is further supported by existing literature on human-wildlife conflicts (Avery & Cummings, 2004; Kluever et al., 2020; Lackey et al., 2018; Shivik, 2004; Wahl et al., 2023). Human adaptation often involved limiting the availability of resources at the heart of conflicts. With this adaptation, I hypothesize that less management of the black vultures is necessary, and the relationship ultimately moves closer to coexistence. However, if new resources become available, conflicts may arise once more and begin the process anew.

This framework has broad applicability to conflicts between humans and common, generalist wildlife species. Conflicts between humans and gray wolves (*Canis lupus*), black bears and grizzly bears (*Ursus arctos horribilis*), coyotes (*Canis latrans*), monkeys such as macaques (*Macaca tonkeana*), and Canada geese (*Branta canadensis*) are typically resource-driven and best managed long-term through human adaptation (Alexander & Draper, 2019; Cope et al., 2005; Lackey et al., 2018; Riley, 2019; Shivik, 2004). In the words of Lackey et al. (2018): "ultimately human behavior must change by reducing anthropogenic resources" (p. 1). As long as the resource is accessible, the conflicts will continue. To truly manage many human-wildlife conflicts and promote coexistence, we must use adaptive management to coexist with this species by continually adapting management strategies to changing resources and species occurrence.

4.3.2.2 Case study

In 2019, hundreds of black vultures began congregating at the wildlife rehabilitation facility after finding available resources, specifically multiple food sources and roosting sites (Figure 4.3: Resource availability and black vulture presence). When conflicts began at the facility, various management strategies were used (Figure 4.3: Management strategies used). The facility hung effigies, made loud noises to scare the black vultures off, and used lasers to disturb them from roosting. Despite the management strategies implemented, they were largely unsuccessful, and the conflicts continued. At this point, there were also apparent conflicts with the black vultures and residents in the surrounding community. Complaints were received, videos of the black vulture congregations were posted online, and some black vultures arrived sick and dying at the facility, suspected of poisonings.

In early 2023, I interviewed community members in the area surrounding the facility about conflicts with black vultures. Despite previous reports of conflicts and suspected poisonings in the community, little conflict was identified through my informal discussions and formal interviews with community members. Upon revisiting the wildlife rehabilitation facility that initiated this research in May 2023, the situation had changed drastically over the previous 3-4 years, in ways that illustrate the findings above. There were still black vultures at the facility, although the population decreased to ~300 black vultures on a normal day compared to ~1,000 originally. This is likely in part due to the highly pathogenic avian influenza (HPAI) that reached the United States in January 2022 and significantly impacted black vultures (Harvey et al., 2023; Stokstad, 2022).

However, HPAI was not the only change over this time period – the facility made many changes to their own behaviors and patterns (Figure 4.3: Human adaptation to black vultures). After conflicts began and management was largely unsuccessful, they began feeding many animals in enclosures to minimize the available food. The more vulnerable animals were transitioned to stay in enclosures rather than free ranging to limit the threat of depredation. Enclosures and pools were built with different materials to reduce the threat of damage from black vultures. At this point in 2023, management strategies were largely unused as the facility had adapted to the black vultures presence and were coexisting with the species, as demonstrated by the quote below (Figure 4.3: Coexistence between humans and black vultures).

> *"They're everywhere but they don't bother us… We've vulture-proofed everything."*
> – Wildlife rehabilitation facility, 2023

This quote shows that a state of coexistence has been reached. While the staff and volunteers were frustrated with the black vultures in 2019, they stated in 2023 that the black vultures no longer bothered them because they have adapted to their presence. If new resources were to become available, the black vultures may once again begin conflicting with humans and require new management strategies and adaptation to reach a new state of coexistence.

4.4 Conclusion

In this article, I argue that black vulture conflicts are largely resource-driven and best managed by human adaptation. While this adds valuable discussion on black vulture conflicts, there is a need for additional research on black vulture conflicts that evaluates the true rate of livestock depredation by this species, whether that varies across their range or between seasons, and the nationwide perceptions of black vultures from various stakeholders to provide insight into the social and environmental drivers of tolerance and coexistence with black vulture populations.

To work towards coexistence between humans and black vultures, we must be considering the human factor of the relationship, as human-wildlife coexistence, similar to conservation, “is a goal that can *only* be achieved by changing behavior” as Schultz (2011) stated (p. 1080). Coexistence does not mean blindly discarding all grievances against a species, rather, in the words of Frank (2016): “existing together” (p. 739). To reach this goal, we must strive to identify the root causes of the conflicts that we experience, and promote human adaptation to and tolerance for the black vulture presence, rather than conflict, exclusion, and domination (Frank & Glikman, 2019).

Table 4.1 Researcher and practitioner interview questions used to investigate the social and environmental drivers and management strategies for black vulture (*Coragyps atratus*) conflicts.

Questions
In what ways have you worked with black vulture populations?
Have you studied or encountered conflict between black vultures and humans?
If so, what was the cause of the conflict? For example – livestock depredation, property damage, or a nuisance.
Has the conflict been ongoing or was it a recent development?
For situations of black vulture conflicts, what landscapes did the black vultures reside in and what resources did they use?
Have there been recent changes in that landscape that might impact the conflict?
How did the conflict impact people living and working in the area?
Did those impacted attempt to improve the conflict in any way?
How did people impacted feel about the black vultures and how did they perceive the problem?
Were any management techniques used to control the population? If so, what, when, and how?
Were the management techniques successful? If so, to what extent and for how long?
Did the perceptions towards black vultures of those impacted change after management strategies were implemented?
Did the perceptions of those impacted by black vulture populations extend to other vulture species, regardless of conflict with that species?
Is there anything else that you would like to share?

Table 4.2 Themes used to code interviews with researchers and practitioners.

(a) Broad conditions associated with conflict
Perceptions of black vultures (like, dislike, neutral, intelligent, valuable)
Landscape composition (urban, rural, mixed)
Conflict occurring in a "safe" location with few threats
New presence (confusion, concerns)
(b) Conflict type
Perceived threat
Property damage
Livestock depredation
Unwanted presence/congregation
(c) Cause of conflict
Food source
New development
Habitat changes
(d) Management strategies used
Scare tactics
Lethal tactics
Education
Translocation of vultures
Human adaptation
(e) Consequences of management
Conflict continued, solved, or moved

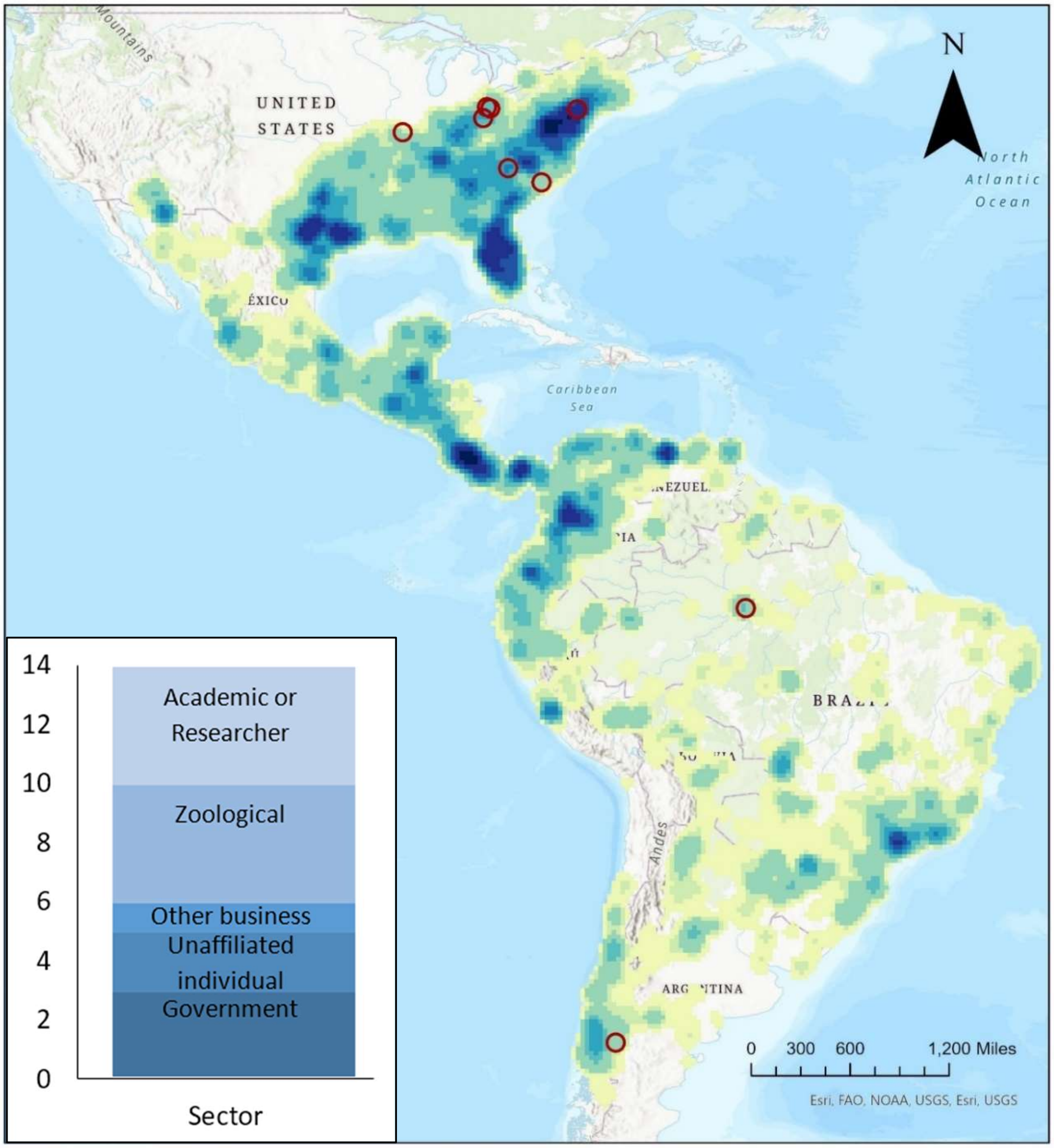

Figure 4.1 The locations and sectors of 14 researchers and practitioners interviewed to evaluate the global drivers and management strategies for black vulture (*Coragyps atratus*) conflicts. Shown on the map are the locations of interviewees (red circles) and the black vulture range shown by population density using 2022 eBird reports (Fink et al., 2021). The chart shows the sectors in which interviewees work.

a

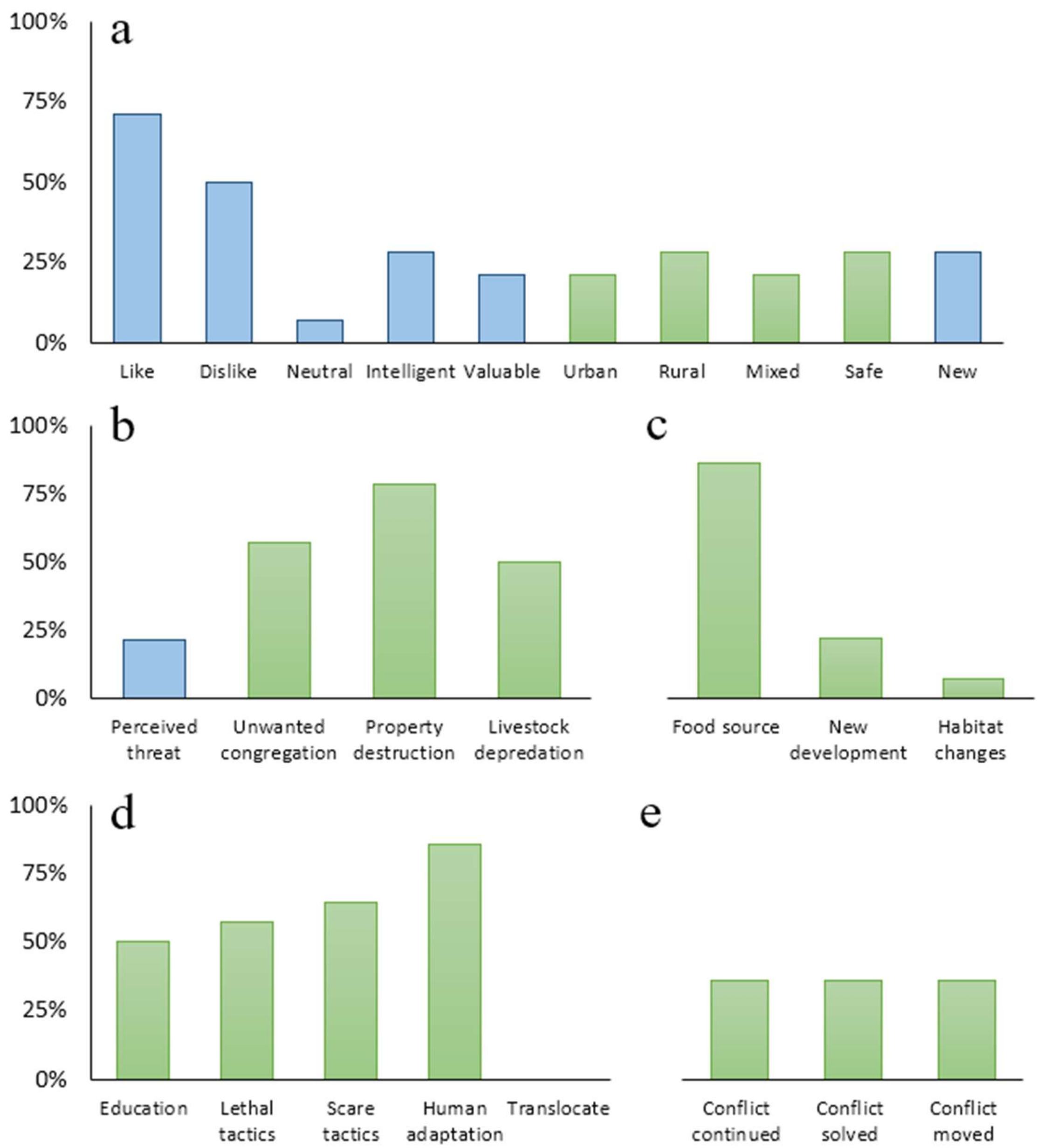

Figure 4.2 The percentage of researcher and practitioner interviews (n=14) regarding black vulture (*Coragyps atratus*) conflicts in which themes appeared. Themes grouped into the following: (a) broad conditions associated with conflict, (b) conflict type, (c) conflict cause, (d) management strategies used, and (e) success of management strategies used. Humans perceptions are indicated by blue shading.

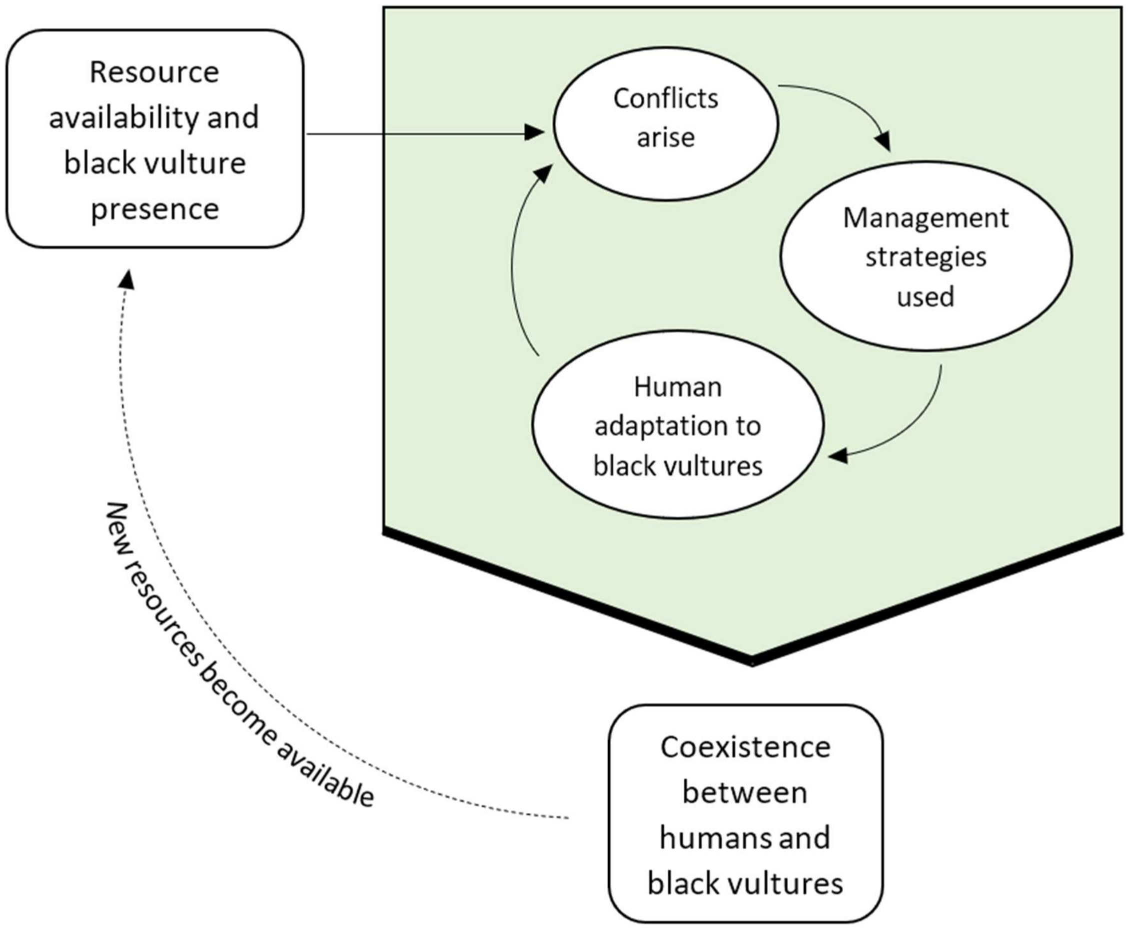

Figure 4.3 A framework showing the progression from the beginning of a black vulture (*Coragyps atratus*) conflict to coexistence. The presence of black vultures begin with resource availability, and conflicts arise. Once a conflict begins, various lethal and nonlethal management strategies are generally used, but with human adaptation to the black vulture presence, management use declines. This cycle continues over time, but eventually, will likely lead to coexistence between humans and black vultures. However, new resources can be made available, and conflicts can begin the cycle again.

4.5 References

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CHAPTER 5: DRIVERS OF BLACK VULTURE RANGE EXPANSION ACROSS THE MIDWESTERN UNITED STATES

Abstract

With climate change impacting temperature and precipitation patterns globally, species are adjusting their ranges to find more suitable environments. Changes in species ranges can have significant ecological impacts with altered species interactions, but range changes can also have significant social impacts, leading to more human-wildlife conflicts. The black vulture (*Coragyps atratus*) is a vulture species in North and South America that has experienced range expansions and an increase in human-wildlife conflicts in recent decades. In this study, I analyzed the black vulture distribution across the midwestern United States to explore the features that are associated with the current black vulture range and where the range is projected to expand or contract under a future climate change scenario (SSP3 RCP7.0) by 2100. I used MaxEnt species distribution modeling to evaluate the black vulture relationship with the following variables: average minimum winter temperature, maximum precipitation amount of the wettest month, precipitation seasonality, snow cover days, density of cows, chickens, sheep, and hogs, landcover type, landcover interspersion and juxtaposition, elevation, and net primary productivity. The top model indicated that areas with higher black vulture suitability are those with (1) less precipitation seasonality, (2) warmer winters with fewer snow cover days, (3) more urban landcover, (4) more open water, (5) less agricultural and cropland area, and (6) more heterogeneous landscapes. An ensemble model of five global climate models projects a range contraction of 2.7% across the study area, with expansions in the northern portion of the study area and contractions in the southern portion of the study area. With these projected range changes and a better understanding of black vulture

bioclimatic and landscape associations, we can better prepare for and manage human-wildlife conflicts that arise with new black vulture presence in the midwestern United States.

Keywords: black vulture, *Coragyps atratus*, species distribution model, MaxEnt, range expansion, climate change

5.1 Introduction

Climate plays an important role in ecosystem health and functioning, with large-scale temperature and precipitation patterns leading to significant impacts for species worldwide including changes in density or abundance, reproductive processes, interspecies relationships, and genetics (Saenz-Jimenez et al., 2021). As the climate changes, we have seen impacts on the geographic range of species including birds, mammals, butterflies, and plants (McCarty, 2001; Walther et al., 2002). Species' geographical responses to climate change vary, with some species shifting poleward with rising temperatures, and other species shifting in opposite directions or in response to precipitation patterns rather than temperature patterns (Thomas, 2010). The variable responses to climate change can make it difficult to manage and protect wildlife populations, because we must understand what environmental features are important to the species and how the availability of these resources may change with climate change.

Research globally is working to understand the environmental features important to various groups, including vulture species. The landscape associations of many vulture species from Europe, Africa, and Asia have been analyzed including the Egyptian vulture (*Neophron percnopterus*), whose populations appear to rely on domestic livestock and suitable nesting sites across Spain and Iraq (Khwarahm et al., 2021; Mateo-Tomás &

Olea, 2015). Other research on cinereous vultures (*Aegypius monachus*) and griffon vultures (*Gyps fulvus*) found similar patterns - these species rely on nesting habitat and agricultural land cover (Jha et al., 2022; Jha & Jha, 2021). Other species have more significant relationships with urbanization, forested land cover, deserts, and cropland, as shown by a suite of models produced for vulture species across Ethiopia (Buechley et al., 2021). Black vultures (*Coragyps atratus*) in South America have been found to be impacted by several bioclimatic features including maximum temperature, seasonality of temperature and precipitation, and temperature ranges (Saenz-Jimenez et al., 2021) and it was stated that "a warmer and more seasonal world does not bode well for many vultures" (Bildstein, 2022). Several vulture species in India, Spain, and southern Africa have similarly been found to be impacted by precipitation seasonality and minimum winter temperatures (Jha & Jha, 2020; Phipps et al., 2017) in addition to landcover (Jha et al., 2022; Jha & Jha, 2020) and livestock density (Mateo-Tomás & Olea, 2015; Phipps et al., 2017).

While several threatened and endangered vulture species have received in depth investigation, vultures from North and South America, including those within the Cathartidae family, have received much less attention. The Cathartidae family includes the black vulture, a smaller vulture species that spans North and South America (Avery, 2004; Buckley et al., 2022). The black vulture has been expanding its range across the United States since the 1920s with a range expansion and population growth occurring along the east coast (Buckley et al., 2022). Within the midwestern United States, the range has expanded and contracted over time, perhaps due to changes in land management practices and pesticide use, but in recent decades the range has grown significantly (Buckley et al., 2022; Parmalee, 1954). It is possible that the black vulture range may be expanding in part due to climate change (Buckley et al., 2022) – as climates across North America warm, black vultures may be able to move into regions previously unsuitable due to cold winters. Black vultures have been found to be positively associated with both urban and agricultural land cover, and it is possible that the black vulture range is responding to changes in land cover that provide additional resources that support populations in greater numbers or at different times of year (Campbell, 2014; Evans et al., 2024; Hill et al., 2023; Hill et al., 2021; Quinby et al., 2022). These areas may provide warmer microclimates with more readily available food sources such as garbage and livestock.

Black vultures are of interest across North and South America due to an increasing number of human-wildlife conflicts including property destruction, nuisance congregations, and livestock depredations as discussed in Chapter 4 (Avery & Cummings, 2004; Ballejo et al., 2020; Lowney, 1999). From 2010-2019 in the United States, requests for help with black vulture conflicts increased nearly 3-fold, with the proportion of conflicts involving agriculture and livestock nearly doubling (Kluever et al., 2020). Yet, the black vulture has received little research attention, and to my knowledge, only one study in South America has explored the black vulture range using distribution modeling (Saenz-Jimenez et al., 2021) and no studies have been completed in North America. I aim to fill this gap by analyzing the black vulture distribution across the midwestern United States using bioclimatic and environmental variables to explore what features are associated with the current black vulture range and evaluate range expansions or contractions under future climate change and urbanization scenarios. In this study, I use multiple models at multiple scales, aiming to identify the variables impacting the black vulture range at different spatial scales.

I predict that current black vulture presence across the midwestern United States will be closely tied to food source availability and when available, open, agricultural landscapes near urban areas will be preferred (Campbell, 2014; Evans et al., 2024; Quinby et al., 2022). Under climate change scenarios, I predict that the black vulture range changes will be associated with temperature – expanding into new areas with increasing temperatures and contracting in areas with decreasing or more variable temperatures and precipitation (Buckley et al., 2022; Jha & Jha, 2023; Phipps et al., 2017; Saenz-Jimenez et al., 2021).

5.2 Methods

5.2.1 Study area

I examined the black vulture range within the midwestern United States (Figure 5.1). The study area is comprised of five bird conservation regions (BCR) – central mixed grass prairie (BCR 19), oaks and prairies (BCR 21), eastern tallgrass prairie (BCR 22), central hardwoods (BCR 24), and west gulf coastal plain/Ouachita (BCR 25). This region is dominated by grasslands and agricultural land cover and contains the transition between the eastern temperate forested ecoregion and the great plains ecoregion (Commission for Environmental Cooperation, 1997). There are extensive deciduous forests that transform westward into vast mixed-grass prairies and agricultural and range lands with many rivers, ponds, lakes, and wetlands. This region has a distinct north-south temperature gradient with the northernmost areas experiencing long, cold winters and warm summers while the southernmost areas experience mild winters and hot summers

(Antle et al., 2014). Cities in this region are smaller in size and population than cities in other portions of the black vulture range, with some of the largest urban areas being Chicago, IL, St. Louis, MO, Kansas City, MO, Oklahoma City, OK, Dallas, TX, Indianapolis, IN, and Nashville, TN. Black vultures have continually moved farther northwest into this region and are occupying the great plains area more frequently (Buckley et al., 2022; Latteman, 2019).

5.2.2 Occurrence data

I used black vulture observations from eBird (Fink et al., 2021) from January 1, 2017-December 31, 2022 (Figure 5.2); this timeframe excludes historical records that may be biased, and includes years when eBird use was common across North America and captures the current distribution of black vultures as it has been changing in recent decades and is predicted to continue changing. eBird data has been widely used in MaxEnt models (McQuillan & Rice, 2015; Nixon et al., 2016) and performs well when compared to other data sources such as satellite tracking of birds (Coxen et al., 2017). eBird incorporates a review process that promotes accurate locations and species identifications for observations, limiting false identifications and inaccurate reports (Fink et al., 2021). Misidentifications are unlikely as this species is smaller than other vulture species and the only vulture species across North and South America with full black plumage, head, and legs. Juvenile turkey vultures (*Cathartes aura*) could be misidentified as black vultures given their gray head and dark plumage, but I do not expect these misidentifications to comprise a significant portion of the data as these misidentifications are likely uncommon within the full collection of black vulture observations. To further improve the data quality, I filtered the dataset to remove duplicate, flagged, incidental, and historical reports, and to include only complete checklists within the study area with durations lasting 15-180 minutes (Tanner et al., 2020).

5.2.3 Environmental variables

Based on previous research on vultures, I selected a total of sixteen environmental predictor variables that I used to model the black vulture range (Table 5.1), each of which captures a feature that may be important to black vulture survival and dispersal across the study area.

First, I selected four bioclimatic variables from CHELSA (Karger et al., 2017; Karger et al., 2018) that may be contributing to the black vulture range changes: mean daily minimum air temperature of the coldest month (i.e., minimum winter temperature; bio6), precipitation amount of the wettest month (i.e., maximum precipitation; bio13), precipitation seasonality (bio15), and the number of snow cover days (scd). Each of these variables had present-day data and future projections available for use. Much of the current black vulture wintering range has winter temperatures at or above freezing and it has been hypothesized that temperature and precipitation patterns may be contributing to the black vulture range change (Buckley et al., 2022; Saenz-Jimenez et al., 2021).

Second, I selected four variables describing livestock availability from the United States Geological Survey: the density of sheep, cows, chickens, and hogs (Falcone & LaMotte, 2016). In Africa, the Egyptian vulture range is negatively impacted by the change from small-scale to large-scale ranching practices (Mateo-Tomás & Olea, 2015), but in from the United States, black vultures are attracted to more large-scale ranching practices and areas with a greater density of livestock (Kluever et al., 2020; Quinby et al., 2022). A higher density of these livestock groups may be attracting black vulture populations to new areas with food source attractants (Quinby et al., 2022) – especially for sheep and cows that often roam and birth in large fields (Ballejo et al., 2020).

Finally, I selected several landscape variables that may be of significance to black vulture populations: landcover type, landcover interspersion and juxtaposition (Hesselbarth et al., 2019; Yang et al., 2018), elevation (U.S. Geological Survey, 2023), and net primary productivity (Running et al., 2015). Landcover type includes one categorical landcover variable from the 2016 National Land Cover Database (NLCD) (Yang et al., 2018) and four separate variables describing the amount of urban, range, pasture, and forested landcover from the Land-Use Harmonization (LUH2) project (Hurtt et al., 2020; Popp et al., 2017). The NLCD data was available for present-day only while the LUH2 data was available for present-day and several future scenarios. Black vultures have been found to select for urban, suburban, and agricultural landscapes (Campbell, 2014; Evans et al., 2024; Hill et al., 2023; Quinby et al., 2022), with less interspersion between developed and forested areas (Partridge & Gagné, 2023), although they may prefer heterogeneous landscapes that offer a wide variety of resources (Evans et al., 2024; Hill et al., 2021). Additionally, black vultures generally prefer low elevation areas and potentially areas with moderate levels of net primary productivity that offer enough food resources that are not hidden within forests (as black vultures are often thought to forage more by sight than smell) (Buckley et al., 2022).

To evaluate the black vulture range, I created five present-day models (M1S1, M1S25, M1S100, M2S25, M2S100), each of which was projected to five future scenarios based on global climate models and urbanization scenarios (Table 5.2). Additionally, an ensemble projection was created for each model, which was a combination of the five future scenario projections. This resulted in a total of five present-day models and 30 future projections from those five models. The M1 models (and subsequent projections) included landcover data from the NLCD (Yang et al., 2018) while the M2 models (and subsequent projections) included landcover data from LUH2 (Hurtt et al., 2020).

I investigated the effect of resolution by creating the same models with different resolutions. It can be difficult to select the right scale and resolution with which to study species patterns as species may have different selection criteria for microsites, patches, home ranges, and geographic ranges (Elith & Leathwick, 2009; Meyer, 2007). The selected extent and resolution at which we study landscape ecological patterns can have significant impacts on the results (Luoto et al., 2007; Rahbek, 2005; Wiens, 1989) and studies may benefit from using multi-scale analyses that incorporate different scales used by species (Addicott et al., 1987; Meyer, 2007; Wiens, 1989). The resolutions were selected to capture the different spatial associations of black vultures including their daily area used (Holland, 2015) and different estimates of home range size (Coleman & Fraser, 1989; DeVault et al., 2004; Evans et al., 2023). In this study, the M1S1, M1S25, and M1S100 models all have the same variables and are projected to the same future scenarios. They differ in resolution, represented by the second half of the model name (i.e., M1S1 = 1km cell size; M1S25 = 25km cell size; M1S100 = 100km cell size). The same is true for the M2S25 and M2S100 models as they have the same variables and future projections but differ in resolution.

Each of the five models was projected to SSP3-RCP7.0 (shared socioeconomic pathway #3 and representative concentration pathway 7.0), a climate change scenario that incorporates high challenges to climate change mitigation and adaptation with regional conflicts, through which radiative forcings will reach 7.0 watts/m^2 (Moss et al., 2008; Riahi et al., 2017). The models were projected to the 30-year period of 2071-2100, with separate projections for five different global climate models that represent a range of possible scenarios (Table 5.2). Finally, I created ensemble projections that combine the five global climate model projections into one projection of the black vulture range for each model (Table 5.2).

The correlation among all variables was analyzed using correlation coefficients and variance inflation factors, with acceptable levels of correlation ≤0.70 and variance inflation factor values of ≤10 (Dormann et al., 2013). All variables had acceptable levels of correlation except for those between rangeland and forested landcover in the M2S25 and M2S100 models, and between rangeland and bio15 and pastureland and bio6 in the M2S100 model (0.71-0.79). All variance inflation factor values were acceptable except for that of bio6 in model M2S100 with a VIF of 12.66 (Tables A5.1-A5.6). Despite the higher levels of correlation, these variables were left in the models.

5.2.4 Modeling procedure

I used MaxEnt models to analyze the black vulture range across the midwestern United States region under present-day data and projected climate scenarios.

A target group background selection was used based on all eBird checklists to create a biased background (Kramer-Schadt et al., 2013; Merow et al., 2013; Phillips et al., 2009). Without this background adjustment, models may map sampling effort rather than habitat suitability (Barber et al., 2022). As sufficient cells were available in model M1S1, 10,000 background points were used (Phillips et al., 2009). For the other four models, the number of background points was set to match the number of presence points

(Barbet-Massin et al., 2012), resulting in 1,333 background points for models M1S25 and M2S25 and 117 background points for models M1S100 and M2S100. All background points were sampled from the current black vulture range as the species has not yet dispersed across the entire region (Elith et al., 2011; Merow et al., 2013).

With the selected set of environmental variables for each model, I modeled the black vulture distribution across the study area in R using the dismo (Hijmans et al., 2017) and terra (Hijmans et al., 2022) packages. I used jackknife tests to evaluate the contributions and importance of all variables to the model. Linear, quadratic, and product features and response curves were used to evaluate the different responses to the environmental variables (Phillips et al., 2006). The beta regularization multiplier was set to the default. I evaluated models using cross-validation with ten replicates, with data partitioned into random subsets of 80% for model training and 20% for model testing. Model performance was measured using area under the curve (AUC), an evaluation method that is often considered important to show the accuracy and predictive power of the model, aiming for values ≥ 0.70 (Graf et al., 2005; Luoto et al., 2007; Warren & Seifert, 2011). Range expansions and contractions were measured as the predicted presence across the study area, determined by the probability threshold at which the model maximizes the True Positive Rate and the True Negative Rate (max TPR+TNR).

5.3 Results

The M1S1 model was the top model (AUC = 0.76) describing the present-day black vulture distribution, followed by M1S25 and M2S25 (AUC = 0.60), M1S100 (AUC = 0.52), and M2S100 (AUC = 0.48). In this section, I will focus on the results from the M1S1 model unless stated otherwise. The variable contributions, variable response curves, and changes in black vulture presence for all models are shown in the appendix (Table A5.7, Figures A5.1-A5.3).

The most important variables within the M1S1 model were precipitation seasonality, landcover type, and average minimum winter temperature (variable contributions = 22.4%, 21.2%, and 13.9%, respectively; Figure 5.3). Variable importance varied across scales, although bioclimatic variables were the most important group of variables in all models other than M2S100, in which livestock variables were more important (Figure A5.2). Based on the M1S1 results, areas with higher black vulture suitability are those with (1) less precipitation seasonality, (2) warmer winters with fewer snow cover days, (3) more urban landcover, (4) more open water, (5) less agricultural and cropland area, and (6) more heterogeneous landscapes when compared to other areas (Figure 5.3, A5.1). The M1S1 ensemble projection to 2071-2100 under SSP3 RCP7.0 predicts a contraction of 2.7% in the black vulture range (Table A5.7). However, the global climate model projections that comprise the ensemble projection vary widely, ranging from contractions of 16.6% to expansions of 20.2% (Table A5.7, Figure A5.4).

The black vulture range is projected to change across the study area in different ways (Figure 5.4, 5.5). When comparing the present-day M1S1 model range prediction with the M1S1 ensemble projection to 2071-2100, there are sweeping increases in suitability in the northern portion of the study area (BCR 19 and 22) and more localized decreases in suitability in the southern portion of the study area (BCR 21, 24, and 25) (Figure 5.4). When looking more closely at projected changes in black vulture presence, there are increases in presence in the northern portion of the study area centered around urban areas and water sources (BCR 22 and 24) and clear decreases in presence within the mountainous areas of BCR 24 and 25 and the Interior Plateau south of Nashville, Tennessee in BCR 24 (Figure 5.5). The rest of the study area shows a variety of projected increases and decreases in presence, as well as large areas with no projected changes in presence. While suitability across the northern portion of the study area is projected to increase, the increased suitability values did not meet the max TPR+TNR value for projected presence.

The bioclimatic variables were the most important variables and influenced the projected future black vulture suitability change in several ways (Figure A5.5). By evaluating model projections when all bioclimatic variables were removed except for one, we can understand how different features are impacting range change. Average minimum winter temperatures, precipitation seasonality, and snow cover days appear to be driving suitability increases in the northern portion of the study area, while maximum precipitation and precipitation seasonality are driving suitability decreases in the southern portion of the study area.

Urbanization also appears to be driving future changes in black vulture suitability with clear increases in suitability near urban centers (Figure 5.4, 5.5). There are projected large increases in future black vulture suitability near urban areas such as Davenport, IA, Chicago, IL, and Indianapolis, IN. This is paired with some higher suitability holdouts such as Dallas, TX and Nashville, TN, that are located in areas otherwise experiencing declines in suitability.

5.4 Discussion

The results show that, in present-day, areas with higher black vulture suitability are those with (1) less precipitation seasonality, (2) warmer winters with fewer snow cover days, (3) more urban landcover, (4) more open water, (5) less agricultural and cropland area, and (6) more heterogeneous landscapes when compared to other areas. When projected to 2071-2100, the top model shows a slight contraction in the black vulture range in the study area, comprised of large suitability increases in the northern portion of the study area and more localized suitability declines in the southern portion of the study area. Based on previous research and these results, bioclimatic features are likely the large-scale determinants of black vulture presence while landscape and livestock features drive site selection and suitability at smaller scales. Throughout this section, I will discuss the features impacting the black vulture range and the limitations of this study.

5.4.1 Bioclimatic variables

Species globally are responding to climate change, including several vulture species. Vulture species in India, Africa, and South America are impacted by climate change – specifically by temperature and precipitation metrics similar to those found to be important in this study (Jha & Jha, 2023; Phipps et al., 2017; Saenz-Jimenez et al., 2021). The most compelling previous research is that focused on black vultures in South America, where they are projected to experience significant range contractions due to temperature seasonality, minimum and maximum temperature metrics, and precipitation seasonality (Saenz-Jimenez et al., 2021). Black vultures may select for areas with more consistent rainfall throughout the year, rather than seasons of heavy rain and drought that could alter food availability patterns (Naveda-Rodríguez & Rush, 2023; Santangeli et al., 2022). In this study, I found that black vulture suitability is strongly impacted by minimum winter temperatures, snow cover days, maximum precipitation, and precipitation seasonality – areas that experience warmer temperatures and lower maximum precipitation amounts and precipitation seasonality may see increases in black vulture suitability when compared to other areas. Given the broad scale at which climate change is occurring, paired with the evidence of impacts on similar species, It is likely that temperature and precipitation patterns are the broad-scale determinants of the black vulture range, driving range expansions in some areas and contractions in others.

5.4.2 Landscape and livestock variables

Landscape features, primarily landcover type and livestock availability, have been found to be important drivers of vulture suitability globally (Jha & Jha, 2023; Mateo-Tomás & Olea, 2015; Phipps et al., 2017). Black vultures have been found to select for abundant food sources, urban landcover, forested landcover, landscape heterogeneity, and open water (Anderson, 2001; Evans et al., 2024; Hill et al., 2023; Hill et al., 2021; Novaes & Cintra, 2013, 2015; Partridge & Gagné, 2022). Bioclimatic conditions are impacting black vultures and driving range changes on large scales, but landscape features are likely driving more localized, small-scale range changes within larger, suitable areas.

In this study, I found that black vultures are more positively associated with urban landcover and open water when compared to other landcovers such as forests, grasslands, croplands, and wetlands. Black vultures are known to rely on urban areas and human activities for everyday activities such as roosting, nesting, and foraging (Ballejo et al., 2018; Buckley et al., 2022; Evans et al., 2024; Novaes & Cintra, 2013, 2015; Partridge et al., 2023). Within the study area, black vultures may be expanding their range in colder regions, despite cold winter temperatures, by exploiting urban refugia that offer the resources needed to survive cold nights and winters (Sachanowicz et al., 2019). Across the northern limit of the black vulture range, there are many reports of black vultures now overwintering where they did not previously (Buckley et al., 2022). In my discussions with individuals[2], some birds along the northern range edge are missing toes, potentially due to frostbite when overwintering, and they are regularly witnessed roosting overnight on chimneys and other structures that provide additional heat (Partridge et al., in preparation).

Additionally, I found that black vultures are positively associated with more heterogeneous landscapes and moderate levels of net primary productivity. It is likely that black vultures use resources across various different landcover types – roosting along forest edges or in right-of-way corridors, foraging within urban centers as well as rural, agricultural areas, and nesting in forest fragments. They may be selecting for more heterogeneous landscapes that offer different landcover types and the different resources that go with them (Buckley et al., 2022; Hill et al., 2021). This is further supported by the moderate levels of suitability seen across all landcover types. Black vultures are opportunistic species and are likely able to adapt to a variety of landscapes depending on the available resources (Evans et al., 2023). However, black vultures do not have a well-developed sense of smell (Buckley et al., 2022) and thus may avoid heavily forested areas that make it difficult to find food. Instead, they select more for open landscapes including

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[2] Interviews with researchers and practitioners across North and South America were completed for a related research study evaluating human-black vulture conflicts (see Chapter 4). Those interviewed were individuals who have worked directly with or researched black vulture conflicts. Several individuals located along the black vulture range edge were actively managing conflicts that had arisen when black vultures began appearing in the area more frequently. They noted potential impacts of the colder climates (such as missing toes when overwintering along the edge) and adaptations the vultures had made (such as roosting on heated structures).

urban and suburban areas and grasslands (Buckley et al., 2022). As such, it makes sense that black vulture suitability is highest at moderate levels of net primary productivity, as highly productive landscapes may make it difficult to forage, and more arid areas with lower productivity may not have the biomass to support a population of black vultures.

Finally, I found that black vultures are positively associated with lower densities of cows and hogs, which was unexpected given the prevalence of human-black vulture conflicts regarding livestock as discussed in Chapter 4. The indoor facilities in which hogs are commonly housed (USDA ERS, 2022) may be contributing to the decline in suitability, as black vultures may have learned that there is little food in areas with more hogs present due to protective buildings, intensive land and carcass management, and sanitary practices for slaughter. The similar negative relationship between black vulture suitability and cow density is surprising, given the increasing presence of livestock depredation conflicts across the study area (Kluever et al., 2020). As black vultures are intelligent and opportunistic foragers, they may have learned that a higher density of cows is associated with less food due to more intensive management, as with the hog density. Similar relationships have been seen in Egyptian vultures, which are negatively impacted by large-scale farming practices (Mateo-Tomás & Olea, 2015), this may be true for black vultures as well. Agricultural landscapes as a whole may offer few resources, with specific sites interspersed that offer more resources and attract black vulture populations.

5.4.3 Differences among spatial scales

Slight differences in variable importance and direction can be seen across scales, but there are no clear trends in either direction, with moderate levels of black vulture suitability across variables and scales. Bioclimatic variables are some of the most important variables across all models while livestock and landscape variables are important variables of only select models. However, the model's predictive power and the projected future range change both appear to be scale dependent. The predictive power of the model declined with increasing grain size, perhaps due to the declining number of species records, as has been seen in previous literature (Guisan et al., 2007; Song et al., 2013). The models with a courser grain also projected larger increases in the future black vulture range. These projections should be considered with lower confidence due to the low AUC values and the claims that course grain sizes in species distribution modeling result in "gross overgeneralizations" in ranges (Rahbek, 2005).

5.4.4 Limitations

The moderate levels of suitability across all variables and scales speaks to the adaptability of black vultures, as generalist species have been found to have distribution models with lower accuracy when compared to specialist species (Evangelista et al., 2008; Grenouillet et al., 2011; Saenz-Jimenez et al., 2021). Across North and South America, black vultures have been found to have positive associations with urbanization (Campbell, 2014; Holland et al., 2019; Martínez-Ruiz et al., 2021) as well as negative associations (Ballejo et al., 2018; Novaes & Cintra, 2013). The same confusion exists for water sources (Hill et al., 2021; Novaes & Cintra, 2015; Partridge & Gagné, 2022; Thompson et al., 1990), landscape heterogeneity and habitat fragmentation (Hill et al., 2021; Partridge & Gagné, 2022; Thompson et al., 1990), and food sources (Ballejo et al., 2021; de Araujo et al., 2018; Holland et al., 2019; Kelly et al., 2007; Novaes & Cintra, 2015; Partridge & Gagné, 2022; Plaza & Lambertucci, 2018). While the availability of some sort of food source appears to be a consistent positive predictor, black vultures are adaptable to a wide variety of landscapes, making it difficult to understand their broad landscape associations and predict where, when, and why they will use different landscape features and resources. Throughout these results, it is important to remember the species' generalist nature and intelligence, as this species may learn how to take advantage of new resources in ways that are difficult to predict with this modeling process.

This study was limited in scope, focusing on only one region within the black vulture range, despite this species having a large range encompassing different landscapes and climates. Considering that this is an adaptable species with a large range, it is very possible that different populations worldwide have different bioclimatic and landscape associations with the variables studied here. Thus, these results may not be accurate when applied outside of the midwestern United States region.

Additionally, these models were analyzing black vulture presence rather than black vulture abundance. The use of abundance models may have allowed us to identify bioclimatic and landscape features that black vultures are more strongly associated with based on population size in a given area. With the black vulture range likely shifting and conflicts between humans and black vultures increasing, it will likely become more important to understand what features are associated with black vulture congregations rather than presence.

It is important to note that there do exist significant correlations within the datasets that may make interpretation of some variables difficult. Specifically, minimum winter temperature (bio6) was highly correlated with temperature seasonality (bio4), which I removed from this study as I believed winter temperatures to be a better driver of black vulture suitability. However, it is possible that the association between black vulture suitability and minimum winter temperatures is in part also showing the association with temperature seasonality. The same is true for the few variables within the M2S25 and M2S100 models that had correlation values above the acceptable limits – specifically, pasture landcover, range landcover, forested landcover, and precipitation seasonality (Table A5.4-A5.5).

5.5 Conclusion

The black vulture is an ecologically important species that is experiencing range shifts and an increasing number of human-wildlife conflicts. In order to prevent and manage conflicts, we must understand what features are associated with the black vulture range and how we can expect their range to change in coming years under climate change scenarios. Further, to protect black vulture populations in the event of future population declines, it is critically important to understand exactly which features are being selected for and against and what locations are projected to be most suitable for black vulture populations. In this study, I found that bioclimatic variables are the most important large-scale determinants of the black vulture range, with landcover also playing an important role in black vulture suitability. Local space use and the black vulture range is geared towards available resources, including available habitat, food and water, etc., but this is within areas that have appropriate bioclimatic conditions. As the bioclimatic conditions change with ongoing climate change, the black vulture range will likely shift, expanding in some areas and contracting in others. These models predict that areas of the midwestern United States with less precipitation seasonality, fewer snow cover days, more urban landcover, more open water, less agricultural and cropland area, and more heterogeneous landscapes are more suitable for black vulture populations. With further climate change in the coming decades, black vultures will likely spread into new areas that offer these bioclimatic conditions and resources.

Future research should consider evaluating the black vulture distribution and spatial ecology across multiple, smaller study areas to evaluate fine-scale patterns across space and understand commonalities between regions in North and South America. This could be expanded to project black vulture distribution models to past climates to understand historical associations and changes, and the use of scenario analyses to evaluate the full range of possibilities. Future research should also create abundance models to better understand how environmental features are associated with black vulture population size across their range. Finally, future research should consider how range changes may impact species relationships, especially between black vulture and turkey vulture populations that may be forced to compete for resources in areas without competition previously. With the range projections from this study and future research evaluating the black vulture range, we can be better prepared for black vultures and the conflicts that arise, managing them in a way that is suitable for both humans and black vultures, promoting long-term coexistence with this important species.

Table 5.1 (continued on next page) The sixteen environmental predictor variables used to model the black vulture (*Coragyps atratus*) distribution. The variables for which future climate scenario projections were used are italicized. Landcover type includes different variables that were used in separate models – categorical National Land Cover Database (Yang et al., 2018) and continuous Land-Use Harmonization 2 data (Hurtt et al., 2020; Popp et al., 2017).

Variable	**Description**	**Source**
Mean daily minimum air temperature of the coldest month (bio6)	A measure of the lowest temperature of any monthly daily mean minimum. Measured in ºC with an offset of -273.15. Based on data from 1979-2013.	CHELSA V2.x-V1.xx bioclim bio6 layer (Karger et al., 2017; Karger et al., 2018)
Precipitation amount of the wettest month (bio13)	The amount of precipitation of the wettest month. Measured in kg/m^2 with no offset. Based on data from 1979-2013.	CHELSA V2.x-V1.xx bioclim bio13 layer (Karger et al., 2017; Karger et al., 2018)
Precipitation seasonality (bio15)	A measure of precipitation changes over the course of the year; the standard deviation of the monthly mean precipitation. Measured in kg/m^2 with no offset. Based on data from 1979-2013.	CHELSA V2.x-V1.xx bioclim bio15 layer (Karger et al., 2017; Karger et al., 2018)
Snow cover days (scd)	Number of days with snow cover. Based on data from 1979-2013.	CHELSA V2.x-V1.xx bioclim scd layer (Karger et al., 2017; Karger et al., 2018)
Sheep	Sheep inventory based on the 2012 Census of Agriculture statistics.	Sheep inventory layer; United States Geological Survey (Falcone & LaMotte, 2016)
Cows	Cow inventory based on the 2012 Census of Agriculture statistics.	Cow inventory layer; United States Geological Survey (Falcone & LaMotte, 2016)
Chickens	Chicken inventory based on the 2012 Census of Agriculture statistics.	Chicken inventory layer; United States Geological Survey (Falcone & LaMotte, 2016)
Hogs	Hog inventory based on the 2012 Census of Agriculture statistics.	Hog inventory layer; United States Geological Survey (Falcone & LaMotte, 2016)
Landcover type (landcover)	Includes 20 categorical landcover classes from the National Land Cover Database, including developed land, forests, cropland, pastures, and open water.	Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Database (NLCD) 2016 (Yang et al., 2018)

Table 5.1 (continued) The sixteen environmental predictor variables used to model the black vulture (*Coragyps atratus*) distribution. The variables for which future climate scenario projections were used are italicized. Landcover type includes different variables that were used in separate models – categorical National Land Cover Database (Yang et al., 2018) and continuous Land-Use Harmonization 2 data (Hurtt et al., 2020; Popp et al., 2017).

Variable	**Description**	**Source**
Urban land	Projections of urban land based on the World Climate Research Program Coupled Model Intercomparison Project (CMIP6). Includes all urban land.	Land-Use Harmonization 2 (Hurtt et al., 2020; Popp et al., 2017)
Rangeland	Projections of rangeland based on the World Climate Research Program Coupled Model Intercomparison Project (CMIP6). Includes rangeland.	Land-Use Harmonization 2 (Hurtt et al., 2020; Popp et al., 2017)
Pastureland	Projections of pastureland based on the World Climate Research Program Coupled Model Intercomparison Project (CMIP6). Includes pastureland and cropland.	Land-Use Harmonization 2 (Hurtt et al., 2020; Popp et al., 2017)
Forested land	Projections of forested land based on the World Climate Research Program Coupled Model Intercomparison Project (CMIP6). Includes primary and secondary forests.	Land-Use Harmonization 2 (Hurtt et al., 2020; Popp et al., 2017)
Net primary productivity (npp)	Shows annual amount of biomass of carbon produced by primary producers, measured in kg C/m^2.	2016 Annual Net Primary Productivity from Moderate Resolution Imaging Spectroradiometer (MODIS) (Running et al., 2015)
Elevation	10-meter elevation data	3D Elevation Program data from the United States Geological Survey (U.S. Geological Survey, 2023) accessed through AWS Terrain Tiles (AWS, 2023)
Landcover interspersion and juxtaposition (iji)	The interspersion and juxtaposition of landcover types, includes open water, urban landcover, forested landcover, shrub/grassland, pastureland, cropland, wetland, and barren land. Calculated using the R landscapemetrics package (lsm_l_iji metric).	R Program (R Core Team, 2022) and MRLC NLCD 2016 (Hesselbarth et al., 2019; Yang et al., 2018)

Table 5.2 List of models and projections examining the black vulture (*Coragyps atratus*) range in the midwestern United States. Models were created and projected to 2071-2100 under climate scenario SSP3 RCP7.0. The present-day models are listed with future projections italicized and indented underneath. Ensemble projections combined the five global climate model projections into one single projection. See Table 5.1 for variable descriptions.

Model name	**Cell size**	**Year**	**Variables**
M1S1	1km	1979-2013	bio6, bio13, bio15, scd, sheep, cows, chickens, hogs, landcover, npp, elevation, iji
GFDL-ESM4 *IPSL-CM6A-LR* *MPI-ESM1-2-HR* *MRI-ESM2-0* *UKESM1-0-LL* *Ensemble projection*	1km	2071-2100	
M1S25	25km	1979-2013	bio6, bio13, bio15, scd, sheep, cows, chickens, hogs, landcover, npp, elevation, iji
GFDL-ESM4 *IPSL-CM6A-LR* *MPI-ESM1-2-HR* *MRI-ESM2-0* *UKESM1-0-LL* *Ensemble projection*	25km	2071-2100	
M1S100	100km	1979-2013	bio6, bio13, bio15, scd, sheep, cows, chickens, hogs, landcover, npp, elevation, iji
GFDL-ESM4 *IPSL-CM6A-LR* *MPI-ESM1-2-HR* *MRI-ESM2-0* *UKESM1-0-LL* *Ensemble projection*	100km	2071-2100	
M2S25	25km	1979-2013	bio6, bio13, bio15, scd, sheep, cows, chickens, hogs, urban land, rangeland, pastureland, forested land, npp, elevation, iji
GFDL-ESM4 *IPSL-CM6A-LR* *MPI-ESM1-2-HR* *MRI-ESM2-0* *UKESM1-0-LL* *Ensemble projection*	25km	2071-2100	
M2S100	100km	1979-2013	bio6, bio13, bio15, scd, sheep, cows, chickens, hogs, urban land, rangeland, pastureland, forested land, npp, elevation, iji
GFDL-ESM4 *IPSL-CM6A-LR* *MPI-ESM1-2-HR* *MRI-ESM2-0* *UKESM1-0-LL* *Ensemble projection*	100km	2071-2100	

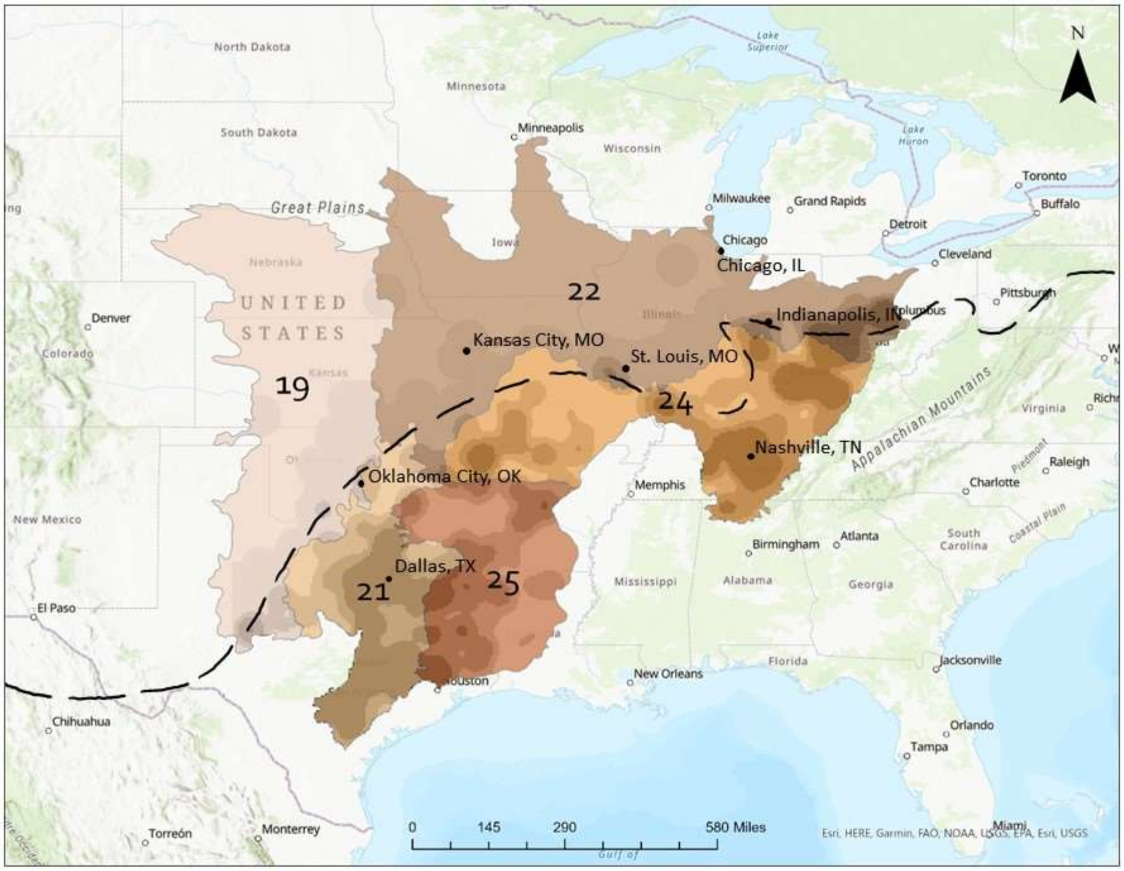

Figure 5.1 Map showing the study area in the midwestern United States for black vulture (*Coragyps atratus*) species distribution modeling. The study area includes five bird conservation regions (BCR) – central mixed grass prairie (BCR 19), oaks and prairies (BCR 21), eastern tallgrass prairie (BCR 22), central hardwoods (BCR 24), and west gulf coastal plain/Ouachita (BCR 25). The density of black vulture eBird reports from 2022 is shown as the dark underlying density layer, with darker areas indicating more reports of black vultures. The black vulture range edge is shown by the black dashed line, with the black vulture range including the southeastern and eastern United States (underneath the dashed line).

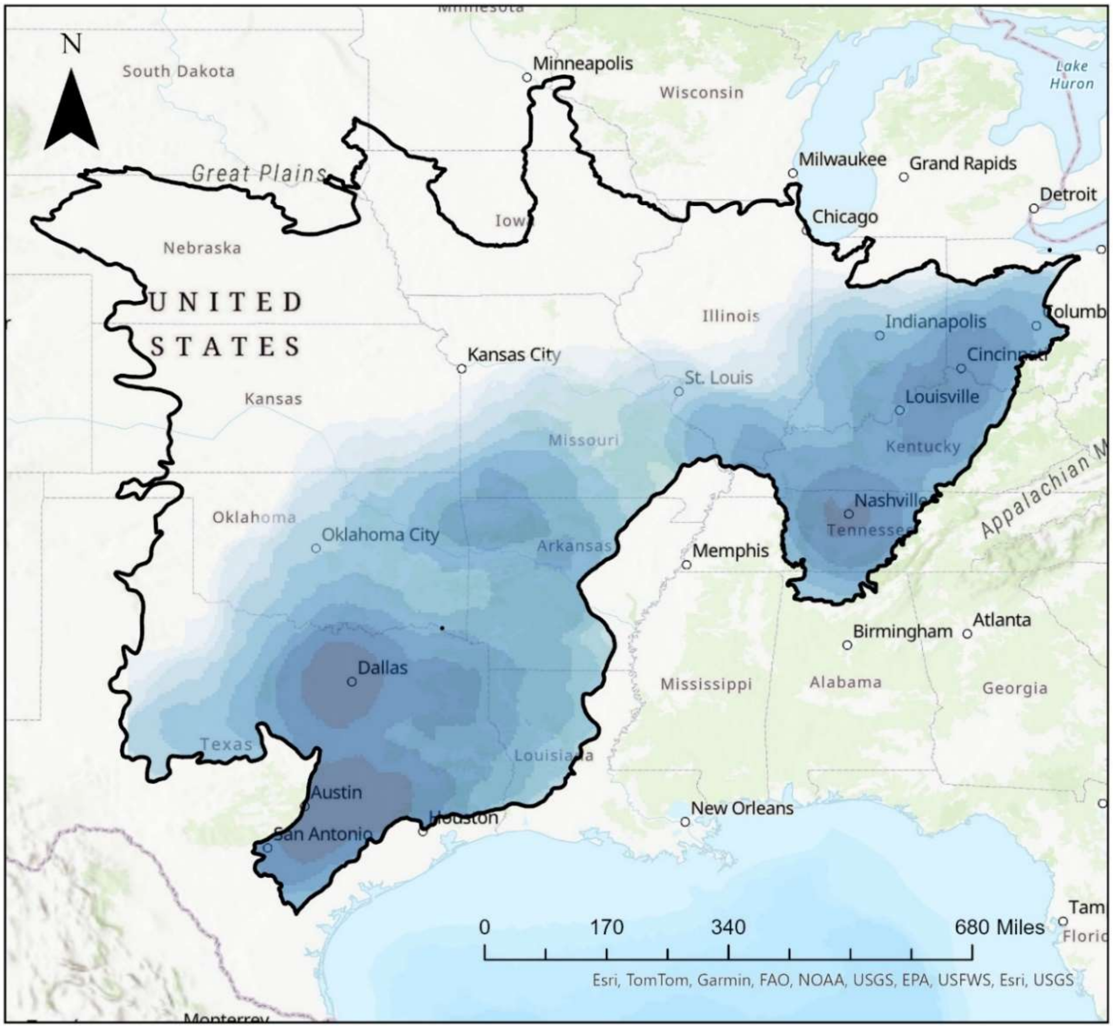

Figure 5.2 Map showing the study area in the midwestern United States for black vulture (*Coragyps atratus*) species distribution modeling with black vulture occurrence data from eBird reports (2017-2022) shown in blue, with darker areas indicating more black vultures observations.

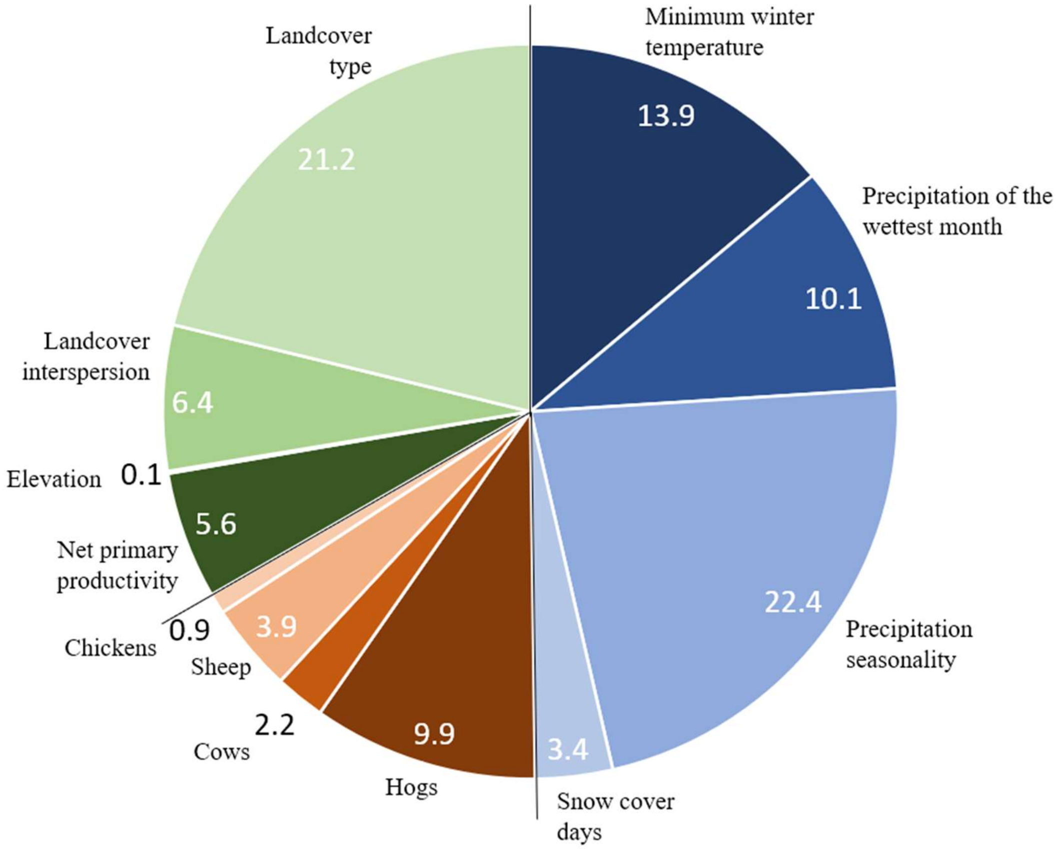

Figure 5.3 Variable contributions as permutation importance normalized to percentages, for the top species distribution model created ((M1S1); see Table 5.1 for variable description and Table 5.2 for model descriptions) for the black vulture (*Coragyps atratus*) in the midwestern United States. Shades of blue denote bioclimatic variables, oranges denote livestock density variables, greens denote landscape variables. All other model variable contributions are shown in Figure A5.2.

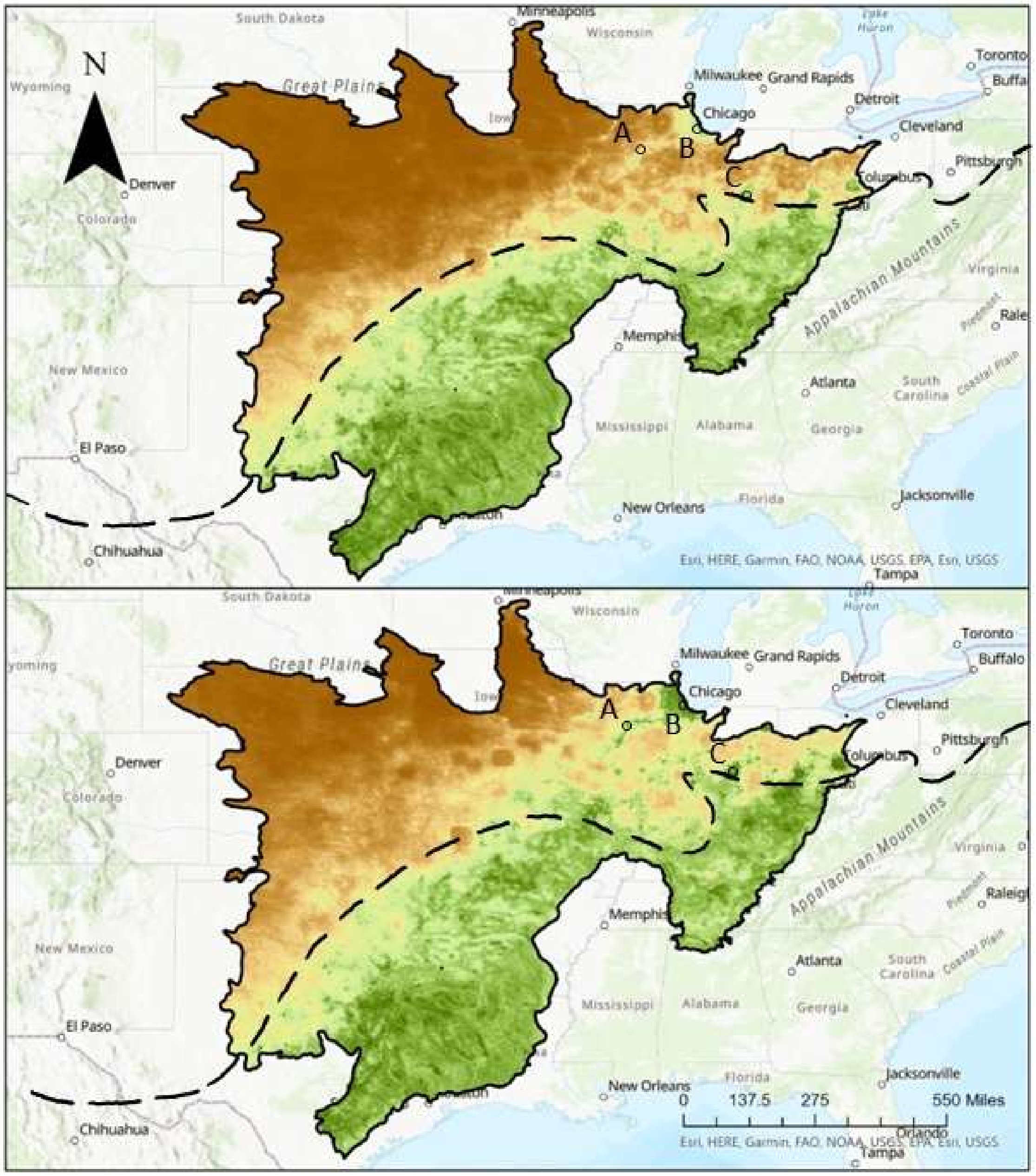

Figure 5.4 Black vulture (*Coragyps atratus*) projected suitability for (a) present-day and (b) model M1S1 for the period 2071-2100 under climate scenario SSP3 RCP7.0, created as an ensemble of five global climate models. Green areas indicate high suitability, orange areas indicate low suitability. Suitability is seen to increase in the northern portion and slightly decrease in the southern portion. See Table 5.1 and Table 5.2 for more information on variables and models. The black vulture range edge is shown by the black dashed line, with the black vulture range including the southeastern and eastern United States (underneath the dashed line). Davenport, IA (A), Chicago, IL (B), and Indianapolis, IN (C) are shown.

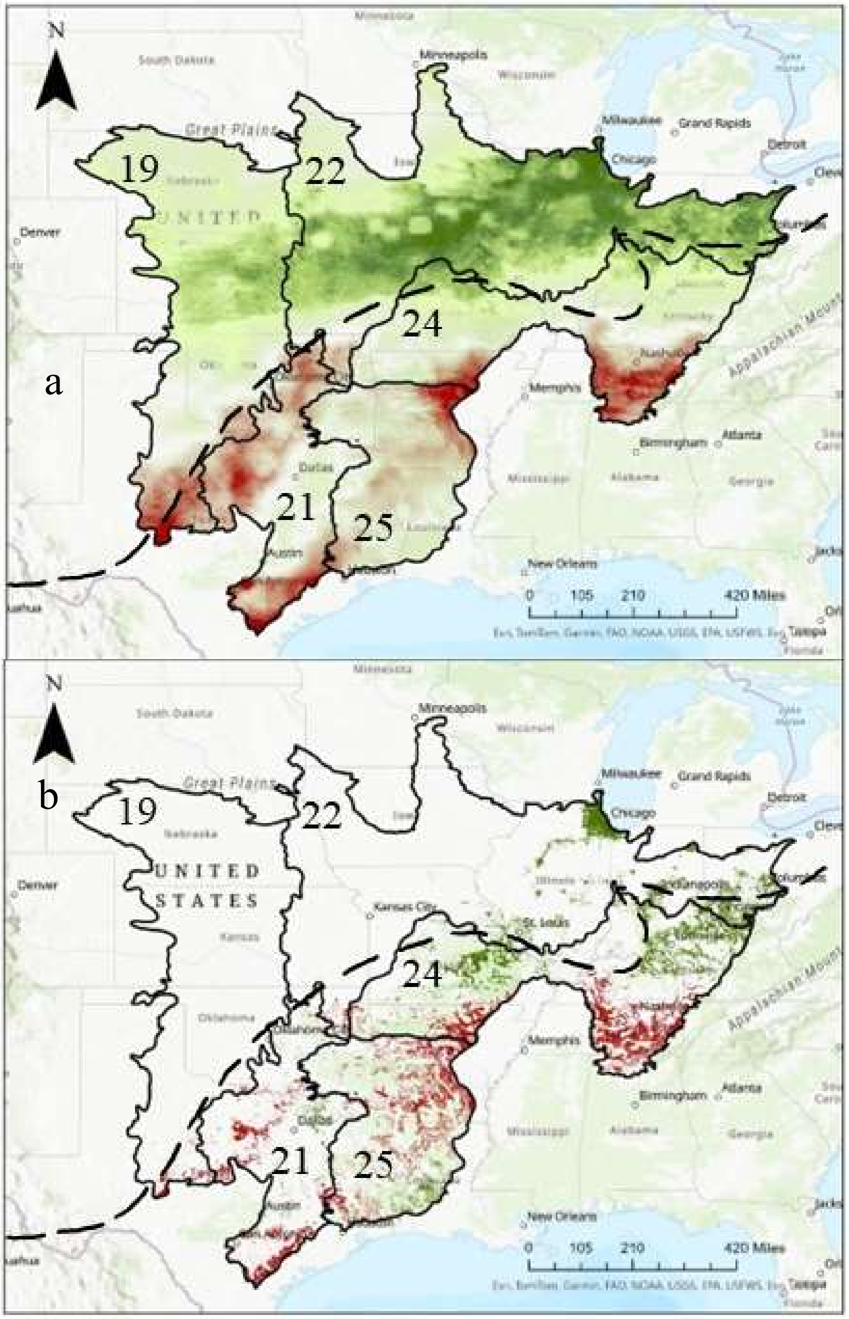

Figure 5.5 Black vulture (*Coragyps atratus*) (a) change in suitability and (b) change in presence between present-day M1S1 model and future projections to 2071-2100 under climate scenario SSP3 RCP7.0, as an ensemble of five global climate models. Green areas indicate increased suitability (a) or new presence (b), red areas indicate decreased suitability (a) or lost presence (b). Suitability is seen to increase in the northern portion and decrease in the southern portion with variable changes in presence. See Table 5.1 and Table 5.2 for more information on variables and models. The black vulture range edge is shown by the black dashed line, with the black vulture range including the southeastern and eastern United States (underneath the dashed line). Bird Conservation Regions within the study area are numbered.

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5.7 Appendix

Table A5.1 Correlation coefficients for M1S1 model variables, for species distribution models for the black vulture (*Coragyps atratus*) in the midwestern United States. Shown are average winter minimum temperatures (bio6), maximum precipitation amounts (bio13), precipitation seasonality (bio15), snow cover days (scd), the density of sheep, cows, chickens, and hogs, landcover type, net primary productivity (npp), elevation, and landcover interspersion and juxtaposition (iji). No correlation values ≥ 0.70(Dormann et al., 2013) are present in this model.

	bio6	bio13	bio15	scd	sheep	cows	chickens	hogs	landcover	npp	elevation	iji
bio6	1											
bio13	-0.44	1										
bio15	0.51	-0.51	1									
scd	-0.55	0.03	-0.10	1								
sheep	0.19	-0.38	0.39	-0.06	1							
cows	0.13	-0.03	-0.07	-0.25	0.26	1						
chickens	0.07	0.02	-0.01	-0.05	-0.01	0.29	1					
hogs	-0.38	0.09	-0.09	0.53	-0.02	-0.03	0.15	1				
landcover	0.04	0.02	-0.05	-0.07	-0.01	0.19	0.08	-0.01	1			
npp	0.04	-0.12	0.08	0.02	-0.04	-0.27	-0.08	-0.03	-0.33	1		
elevation	-0.39	-0.11	0.28	0.22	0.39	0.06	-0.03	0.18	-0.10	-0.03	1	
iji	0.06	-0.09	0.12	0.11	0.05	-0.23	-0.10	0.10	-0.09	0.19	-0.11	1

Table A5.2 Correlation coefficients for M1S25 model variables, for species distribution models for the black vulture (*Coragyps atratus*) in the midwestern United States. Shown are average winter minimum temperatures (bio6), maximum precipitation amounts (bio13), precipitation seasonality (bio15), snow cover days (scd), the density of sheep, cows, chickens, and hogs, landcover type, net primary productivity (npp), elevation, and landcover interspersion and juxtaposition (iji). No correlation values ≥ 0.70 (Dormann et al., 2013) are present in this model.

	bio6	bio13	bio15	scd	sheep	cows	chickens	hogs	landcover	npp	elevation	iji
bio6	1											
bio13	-0.44	1										
bio15	0.52	-0.46	1									
scd	-0.55	0.04	-0.10	1								
sheep	0.20	-0.43	0.41	-0.06	1							
cows	0.11	-0.06	-0.05	-0.25	0.21	1						
chickens	0.04	0.03	-0.03	-0.03	0.00	0.29	1					
hogs	-0.37	0.08	-0.07	0.53	-0.02	-0.02	0.19	1				
landcover	0.03	-0.02	-0.04	-0.02	0.05	0.34	0.12	0.08	1			
npp	-0.11	-0.01	-0.03	0.08	-0.20	-0.33	-0.08	-0.07	-0.42	1		
elevation	-0.43	-0.07	0.27	0.24	0.40	0.07	0.00	0.21	-0.06	-0.08	1	
iji	0.11	-0.15	0.15	0.06	0.13	-0.16	-0.05	0.04	0.01	0.08	-0.06	1

Table A5.3 Correlation coefficients for M1S100 model variables, for species distribution models for the black vulture (*Coragyps atratus*) in the midwestern United States. Shown are average winter minimum temperatures (bio6), maximum precipitation amounts (bio13), precipitation seasonality (bio15), snow cover days (scd), the density of sheep, cows, chickens, and hogs, landcover type, net primary productivity (npp), elevation, and landcover interspersion and juxtaposition (iji). No correlation values ≥ 0.70 (Dormann et al., 2013) are present in this model.

	bio6	bio13	bio15	scd	sheep	cows	chickens	hogs	landcover	npp	elevation	iji
bio6	1											
bio13	-0.50	1										
bio15	0.40	-0.49	1									
scd	-0.50	0.08	-0.01	1								
sheep	0.23	-0.63	0.48	-0.03	1							
cows	0.20	-0.07	-0.04	-0.39	0.15	1						
chickens	0.06	0.07	-0.26	-0.13	-0.04	0.40	1					
hogs	-0.62	0.18	-0.18	0.66	-0.06	-0.34	-0.11	1				
landcover	0.08	-0.08	0.24	0.13	0.26	0.15	0.08	-0.14	1			
npp	0.25	0.09	-0.23	-0.20	-0.26	0.01	0.23	-0.14	-0.34	1		
elevation	-0.53	-0.04	0.27	0.29	0.33	-0.03	-0.18	0.17	0.12	-0.38	1	
iji	0.11	-0.10	0.03	0.01	-0.15	-0.24	-0.17	0.02	0.13	0.10	-0.31	1

Table A5.4 Correlation coefficients for M2S25 model variables, for species distribution models for the black vulture (*Coragyps atratus*) in the midwestern United States. Shown are average winter minimum temperatures (bio6), maximum precipitation amounts (bio13), precipitation seasonality (bio15), snow cover days (scd), the density of sheep, cows, chickens, and hogs, net primary productivity (npp), elevation, landcover interspersion and juxtaposition (iji), and landcover types (urban, range, pasture, forests). Correlation values ≥ 0.70 (Dormann et al., 2013) are written in red.

	bio6	bio13	bio15	scd	sheep	cows	chickens	hogs	npp	elevation	iji	urban	range	pasture	forests
bio6	1														
bio13	-0.44	1													
bio15	0.52	-0.46	1												
scd	-0.55	0.04	-0.10	1											
sheep	0.20	-0.43	0.41	-0.06	1										
cows	0.11	-0.06	-0.05	-0.25	0.21	1									
chickens	0.04	0.03	-0.03	-0.03	0.00	0.29	1								
hogs	-0.37	0.08	-0.07	0.53	-0.02	-0.02	0.19	1							
npp	-0.11	-0.01	-0.03	0.08	-0.20	-0.33	-0.08	-0.07	1						
elevation	-0.43	-0.07	0.27	0.24	0.40	0.07	0.00	0.21	-0.08	1					
iji	0.11	-0.15	0.15	0.06	0.13	-0.16	-0.05	0.04	0.08	-0.06	1				
urban	0.00	-0.11	0.22	0.08	-0.10	-0.53	-0.16	-0.10	0.55	0.04	0.16	1			
range	0.56	-0.54	0.62	-0.31	0.31	0.45	0.10	-0.19	-0.28	0.06	-0.02	-0.27	1		
pasture	-0.66	0.22	-0.37	0.46	0.01	0.32	0.12	0.49	-0.16	0.28	-0.08	-0.22	-0.23	1	
forests	-0.45	0.57	-0.68	0.12	-0.31	-0.23	-0.03	0.06	0.05	-0.12	-0.05	-0.20	-0.72	0.04	1

Table A5.5 Correlation coefficients for M2S100 model variables, for species distribution models for the black vulture (*Coragyps atratus*) in the midwestern United States. Shown are average winter minimum temperatures (bio6), maximum precipitation amounts (bio13), precipitation seasonality (bio15), snow cover days (scd), the density of sheep, cows, chickens, and hogs, net primary productivity (npp), elevation, landcover interspersion and juxtaposition (iji), and landcover types (urban, range, pasture, forests). Correlation values ≥ 0.70 (Dormann et al., 2013) are written in red.

	bio6	bio13	bio15	scd	sheep	cows	chickens	hogs	npp	elevation	iji	urban	range	pasture	forests
bio6	1														
bio13	-0.50	1													
bio15	0.40	-0.49	1												
scd	-0.50	0.08	-0.01	1											
sheep	0.23	-0.63	0.48	-0.03	1										
cows	0.20	-0.07	-0.04	-0.39	0.15	1									
chickens	0.06	0.07	-0.26	-0.13	-0.04	0.40	1								
hogs	-0.62	0.18	-0.18	0.66	-0.06	-0.34	-0.11	1							
npp	0.25	0.09	-0.23	-0.20	-0.26	0.01	0.23	-0.14	1						
elevation	-0.53	-0.04	0.27	0.29	0.33	-0.03	-0.18	0.17	-0.38	1					
iji	0.11	-0.10	0.03	0.01	-0.15	-0.24	-0.17	0.02	0.10	-0.31	1				
urban	-0.16	-0.05	-0.01	0.05	-0.08	-0.24	-0.05	0.20	-0.20	-0.04	0.34	1			
range	0.59	-0.55	0.78	-0.31	0.53	0.27	-0.11	-0.40	-0.24	0.03	-0.10	-0.05	1		
pasture	-0.71	0.32	-0.28	0.60	-0.13	0.06	0.23	0.56	-0.29	0.29	-0.21	0.17	-0.39	1	
forests	-0.47	0.59	-0.69	0.06	-0.42	-0.31	0.07	0.20	0.32	-0.02	-0.02	-0.09	-0.79	0.07	1

Table A5.6 Variance inflation factor values for all models, for species distribution models for the black vulture (*Coragyps atratus*) in the midwestern United States. Shown are average winter minimum temperatures (bio6), maximum precipitation amounts (bio13), precipitation seasonality (bio15), snow cover days (scd), the density of sheep, cows, chickens, and hogs, net primary productivity (npp), elevation, landcover interspersion and juxtaposition (iji), and landcover types (urban, pasture, crops, forests). Values ≥ 10 (Dormann et al., 2013) are written in red.

	M1S1	M1S25	M1S100	M2S25	M2S100
bio6	4.19	4.86	7.94	7.14	12.66
bio13	1.64	1.66	2.64	2.37	2.97
bio15	2.59	2.71	2.75	5.03	6.33
scd	2.11	2.08	2.39	2.31	3.18
sheep	1.64	1.70	2.38	1.86	2.79
cows	1.51	1.57	1.57	2.94	2.45
chickens	1.14	1.17	1.44	1.33	1.78
hogs	1.49	1.42	3.43	2.02	3.26
landcover	1.16	1.36	1.70		
npp	1.21	1.39	1.60	1.61	1.75
elevation	2.52	2.91	4.30	2.94	5.69
iji	1.17	1.10	1.47	1.13	1.97
urban				3.20	1.56
range				6.74	8.77
pasture				4.56	6.77
forests				5.65	6.95

Table A5.7 Range expansion and contraction amounts (%) from the present-day predicted black vulture (*Coragyps atratus*) range to the projected range from 2071-2100 under climate scenario SSP3 RCP7.0. Projections were created for five different models, each with five different global climate models, and an ensemble of the five global climate models. See Table 5.1 and Table 5.2 for more information on the variables and models.

Model	**Range Change (%)**
M1S1 Ensemble	**-2.7**
GFDL-ESM4	+20.2
IPSL-CM6A-LR	-16.6
MPI-ESM1-2-HR	+6.4
MRI-ESM2-0	-13.2
UKESM1-0-LL	+2.3
M1S25 Ensemble	**+27.3**
GFDL-ESM4	+30.3
IPSL-CM6A-LR	+32.8
MPI-ESM1-2-HR	+23.2
MRI-ESM2-0	+10.1
UKESM1-0-LL	+32.8
M1S100 Ensemble	**+18.9**
GFDL-ESM4	+11.2
IPSL-CM6A-LR	+21.2
MPI-ESM1-2-HR	+11.2
MRI-ESM2-0	+12.7
UKESM1-0-LL	+28.1
M2S25 Ensemble	**+25.5**
GFDL-ESM4	+30.3
IPSL-CM6A-LR	+32.6
MPI-ESM1-2-HR	+24.6
MRI-ESM2-0	+13.2
UKESM1-0-LL	+32.5
M2S100 Ensemble	**+14.5**
GFDL-ESM4	+11.2
IPSL-CM6A-LR	+16.9
MPI-ESM1-2-HR	+11.2
MRI-ESM2-0	+10.4
UKESM1-0-LL	+19.4

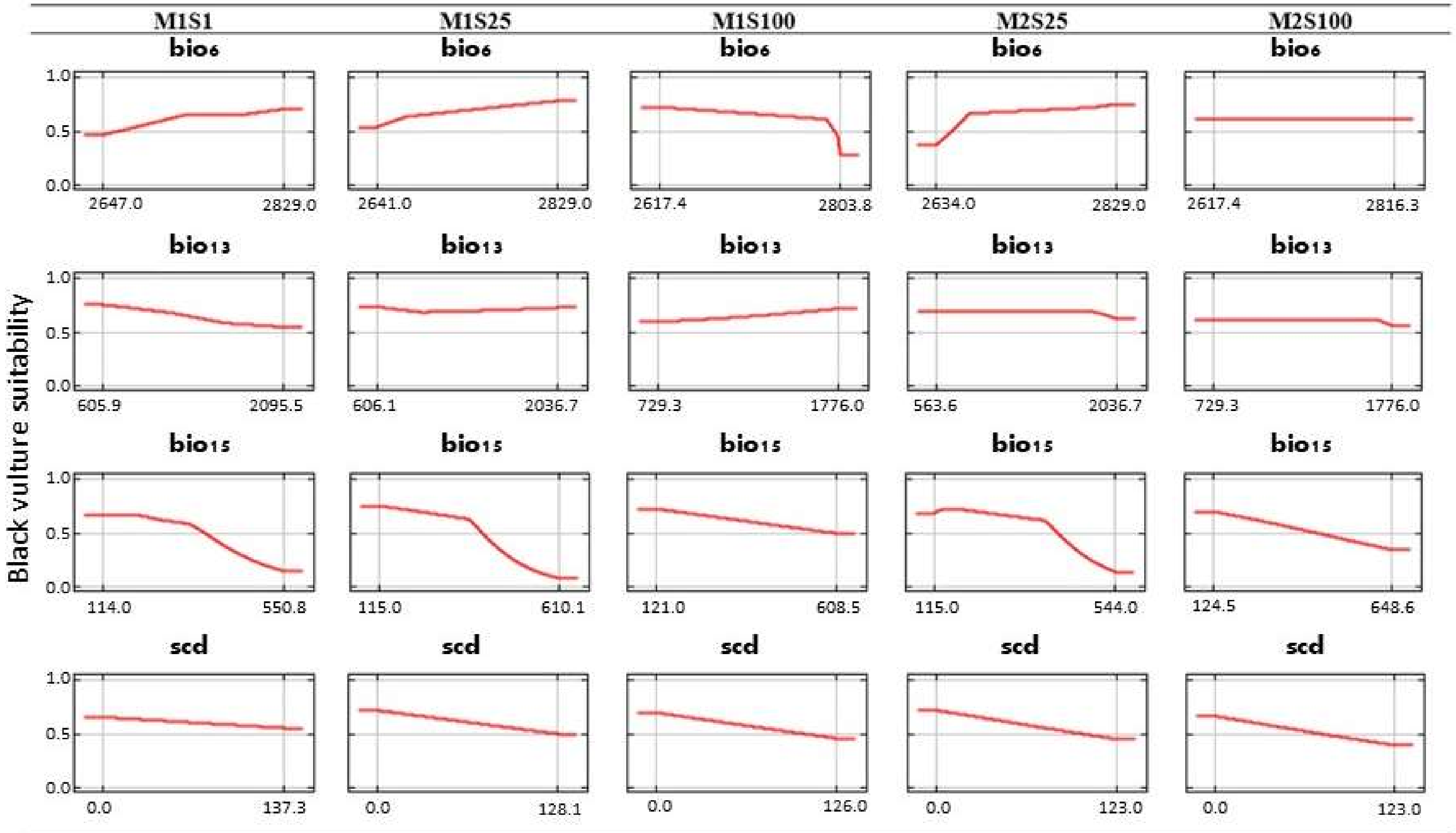

Figure A5.1 (continued on next page) Variable response curves for species distribution models (M1S1, M1S25, M1S100, M2S25, M2S100) for the black vulture (*Coragyps atratus*) in the midwestern United States. Shown are average winter minimum temperatures (bio6), maximum precipitation amounts (bio13), precipitation seasonality (bio15), and snow cover days (scd). The y-axis shows black vulture suitability, and the x-axis shows variable values. See Table 5.1 and Table 5.2 in the main text for more information on variables and models.

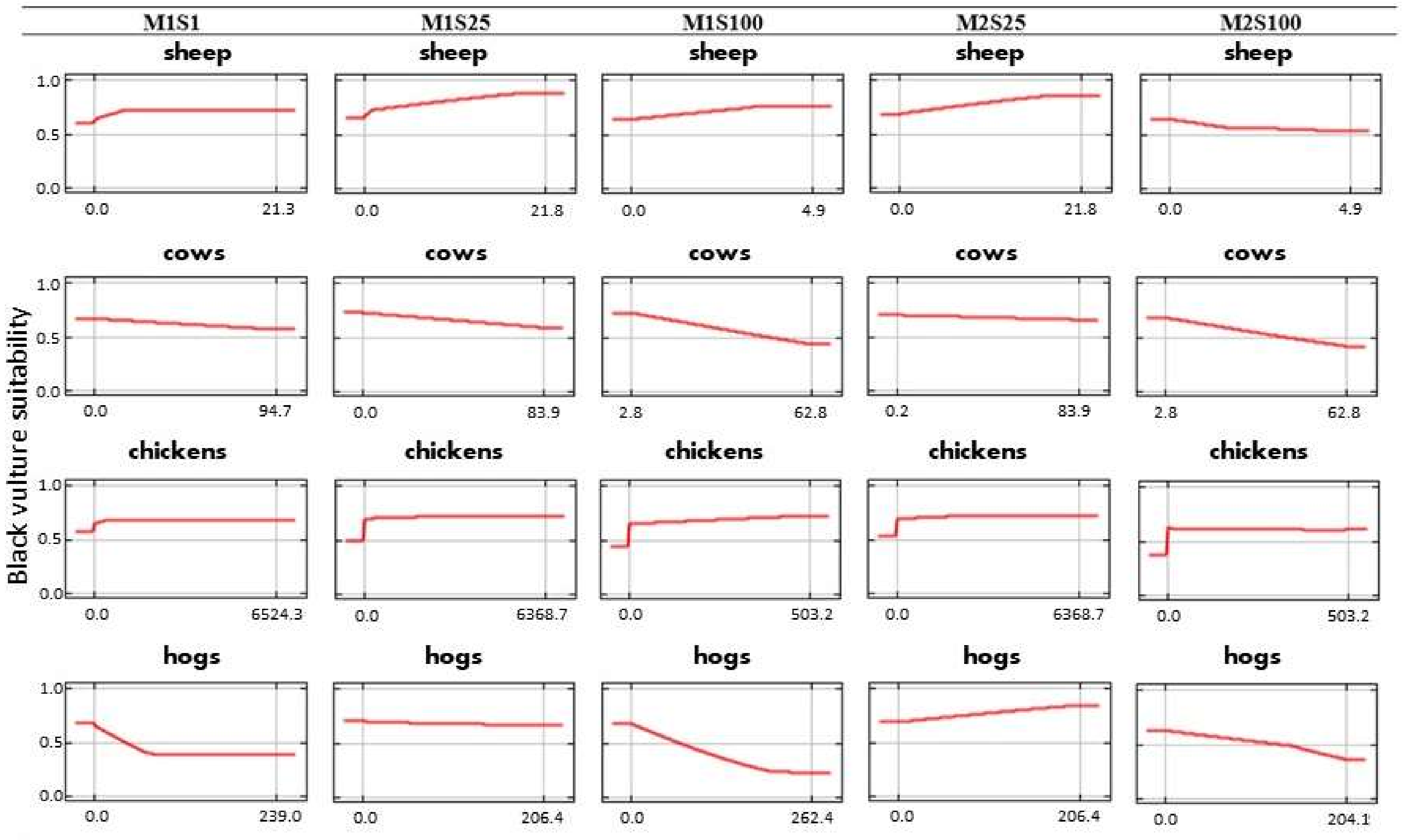

Figure A5.1 (continued) Variable response curves within five models, for species distribution models (M1S1, M1S25, M1S100, M2S25, M2S100) for the black vulture (*Coragyps atratus*) in the midwestern United States. Shown are the density of sheep, cows, chickens, and hogs. The y-axis shows black vulture suitability, and the x-axis shows variable values. See Table 5.1 and Table 5.2 for more information on variables and models.

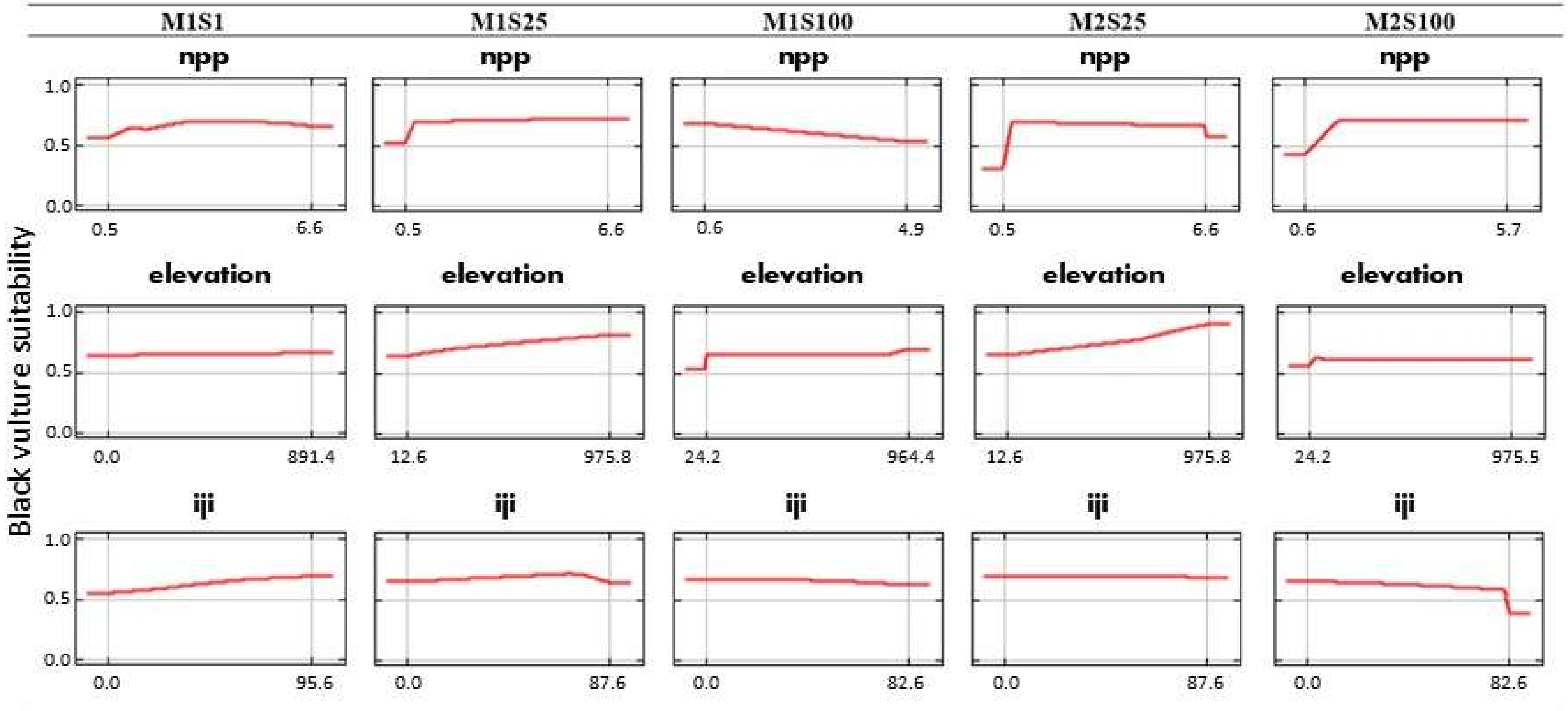

Figure A5.1 (continued) Variable response curves within five models, for species distribution models (M1S1, M1S25, M1S100, M2S25, M2S100) for the black vulture (*Coragyps atratus*) in the midwestern United States. Shown are net primary productivity (npp), elevation, and landcover interspersion and juxtaposition (iji). The y-axis shows black vulture suitability, and the x-axis shows variable values. See Table 5.1 and Table 5.2 for more information on variables and models.

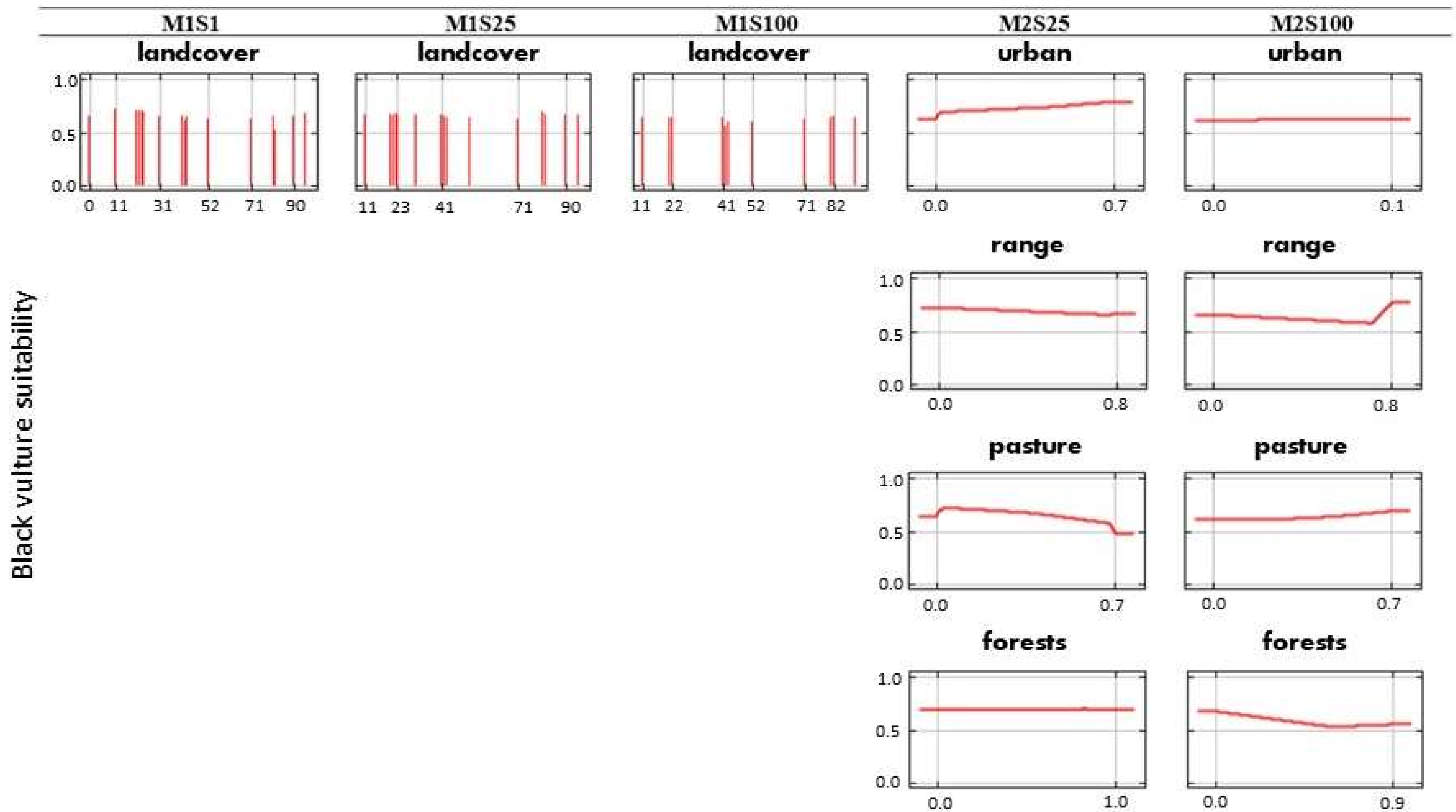

Figure A5.1 (continued) Variable response curves within five models, for species distribution models (M1S1, M1S25, M1S100, M2S25, M2S100) for the black vulture (*Coragyps atratus*) in the midwestern United States. Shown are categorical landcover (for M1S1, M1S25, and M1S100 models) and continuous landcover (for M2S25 and M2S100 models) including urban, range, pasture, and forests. The y-axis shows black vulture suitability, and the x-axis shows variable values. See Table 5.1 and Table 5.2 for more information on variables and models.

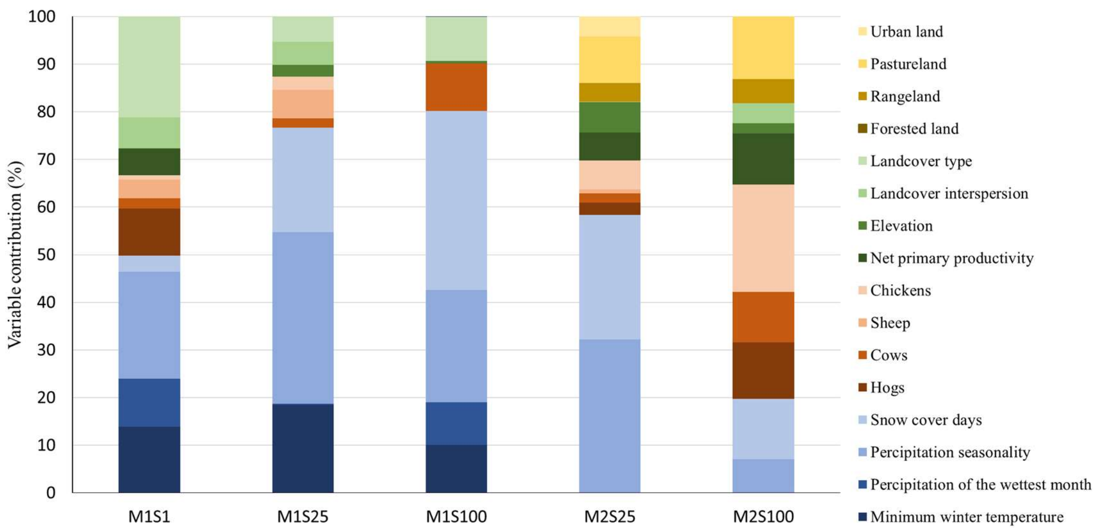

Figure A5.2 Variable contributions as permutation importance normalized to percentages, for species distribution models (M1S1, M1S25, M1S100, M2S25, and M2S100 (see Table 5.1 for variable descriptions and Table 5.2 for model descriptions)) for the black vulture (*Coragyps atratus*) in the midwestern United States. Shades of blue denote bioclimatic variables, oranges denote livestock density variables, greens denote landscape variables, and yellows denote landcover types (yellows only used in M2 models).

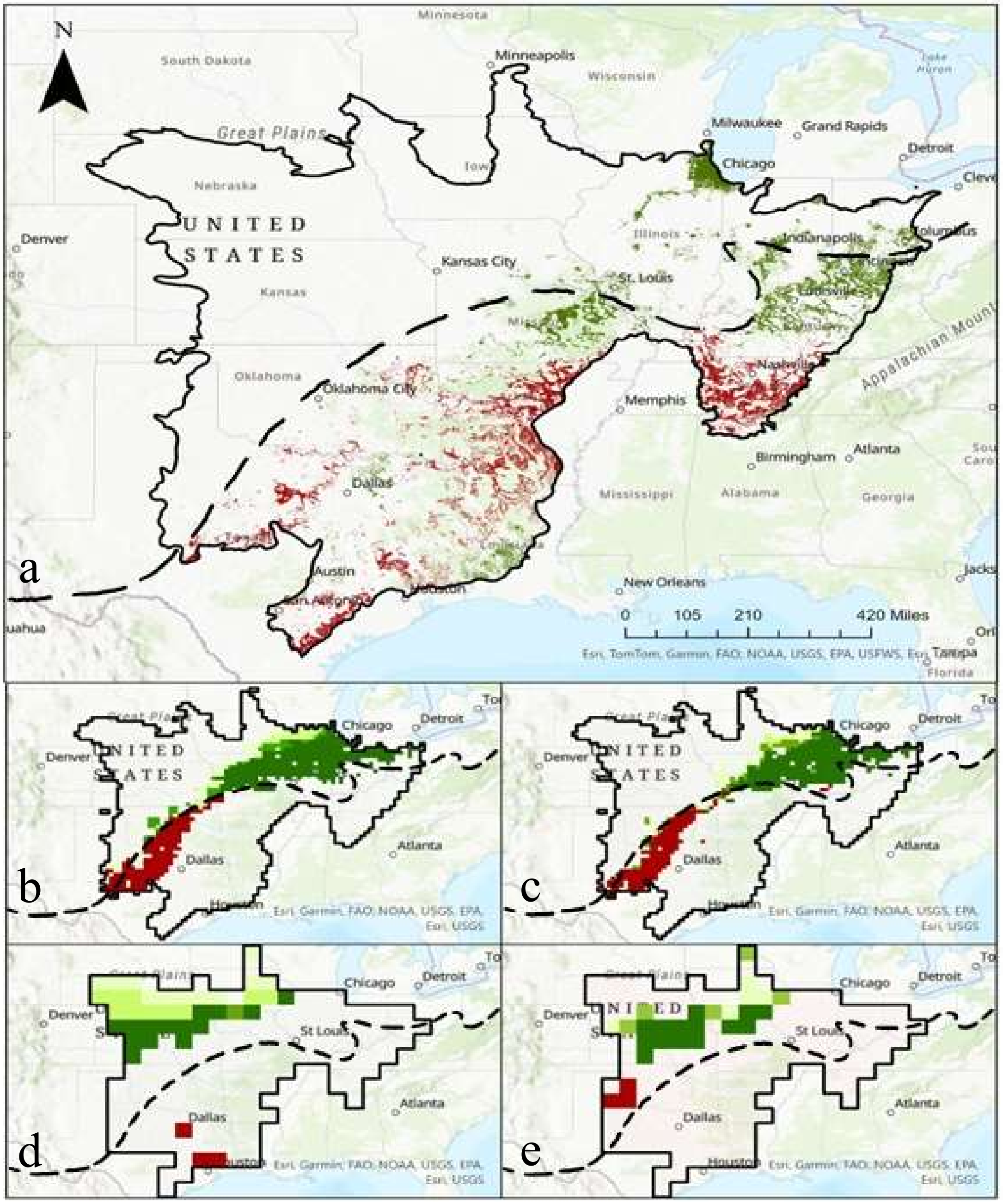

Figure A5.3 The black vulture (*Coragyps atratus*) presence change projected to the period 2071-2100 SSP3 RCP7.0 as an ensemble of five global climate models. Green areas indicate new presence, red areas indicate lost presence, and no color indicates no change. The presence changes for the following model ensembles: (a) M1S1, (b) M1S25, (c) M2S25, (d) M1S100, and (e) M2S100 models. Presence is seen to increase in the northern portion and slightly decrease in the southern portion. See Table 5.1 and Table 5.2 for more information on variables and models. The black vulture range edge is shown by the black dashed line, with the black vulture range including the southeastern and eastern United States (underneath the dashed line).

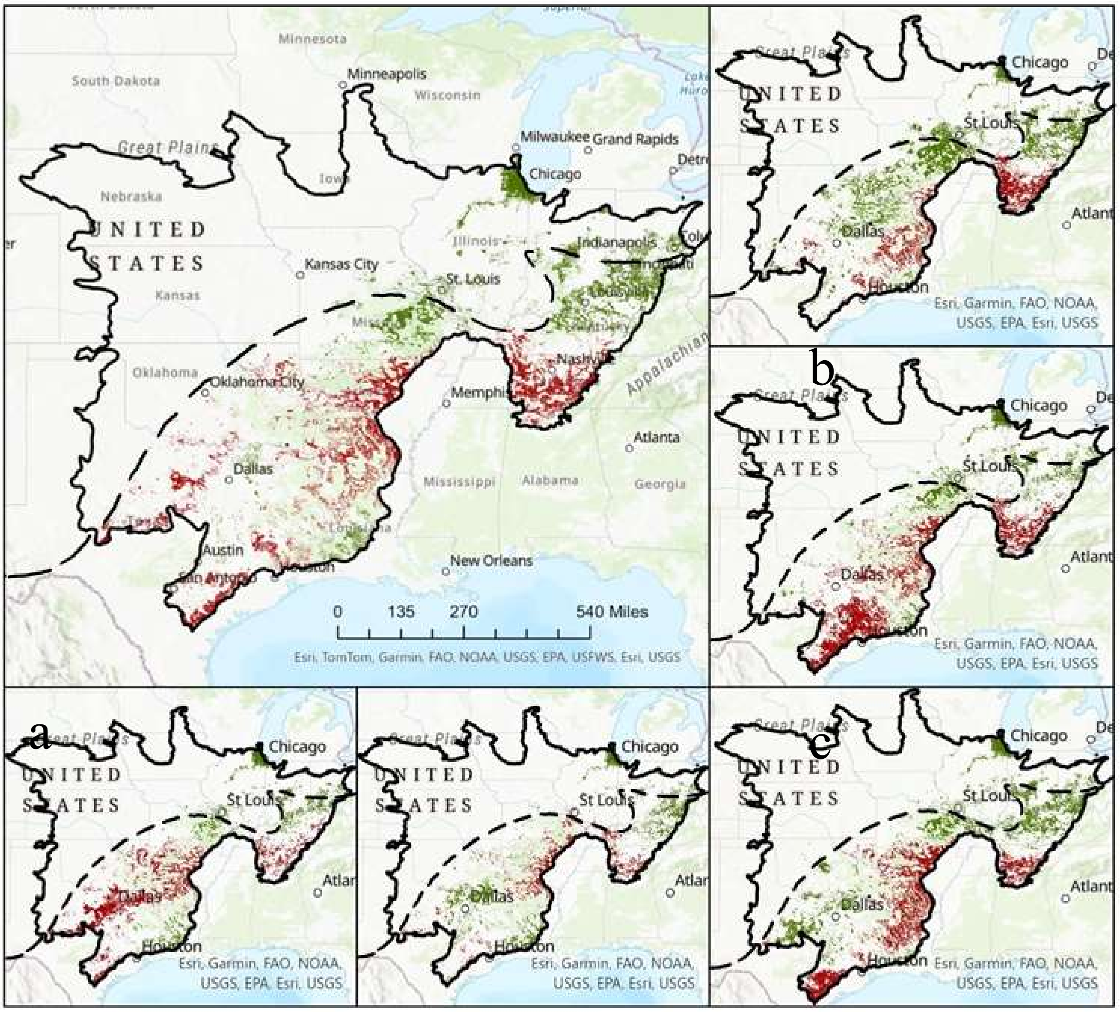

Figure A5.4 Projected presence changes for species distribution models for the black vulture (*Coragyps atratus*) in the midwestern United States. Shown are changes for the M1S1 model (see Table 5.2 for model descriptions) as (a) an ensemble of the five global climate model projections, (b) GFDL-ESM4 model projections only, (c) IPSL-CM6A-LR model projections only, (d) MRI-ESM2-0 model projections only, (e) MPI-ESM1-2-HR model projections only, and (f) UKESM1-0-LL model projections only. Red indicates lost presence, green indicates new presence, and no color indicates no change. The black vulture range edge is shown by the black dashed line, with the black vulture range including the southeastern and eastern United States (underneath the dashed line).

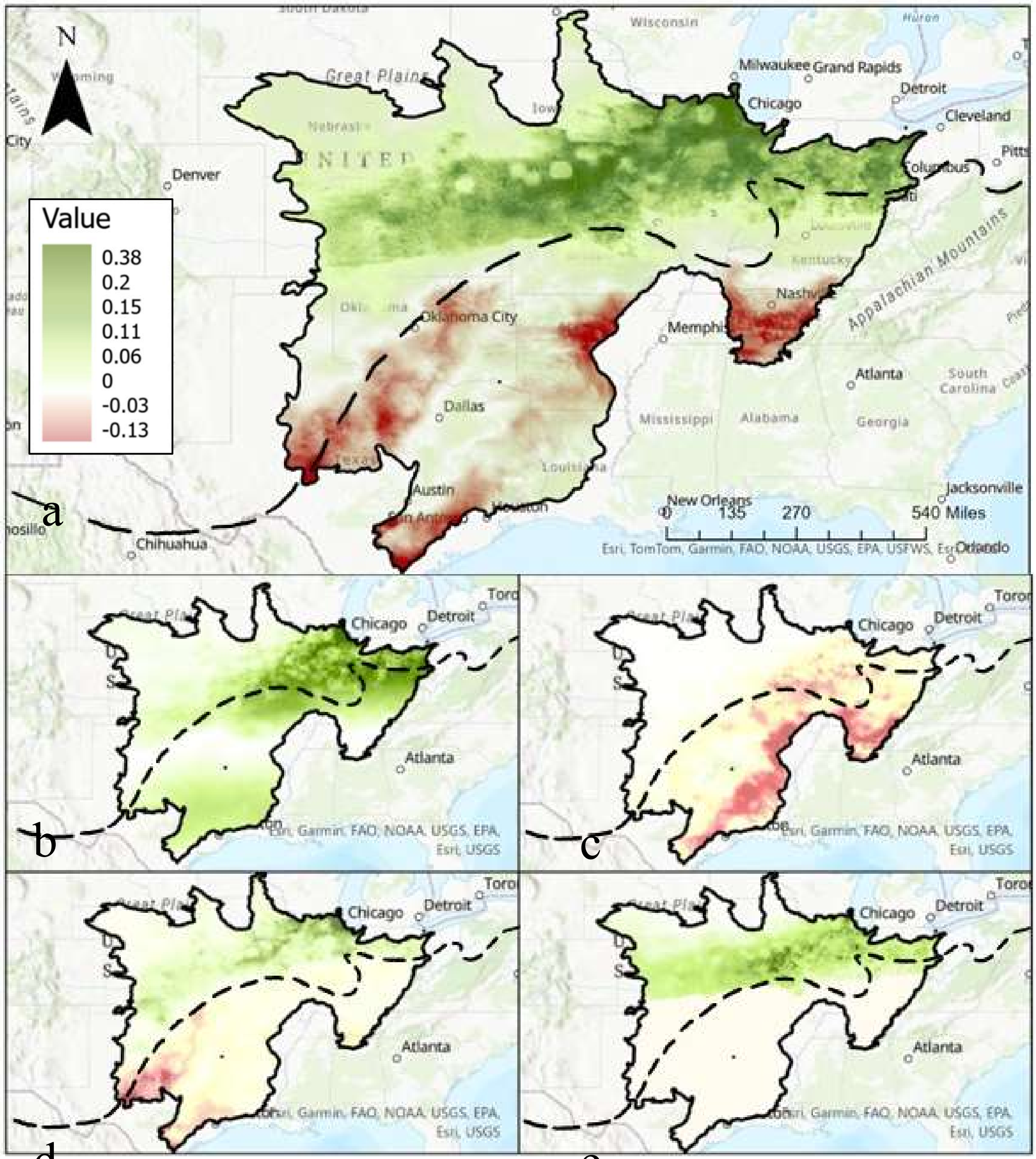

Figure A5.5 The black vulture (*Coragyps atratus*) suitability change projected to the period 2071-2100 SSP3 RCP7.0. Green areas indicate increasing suitability, while yellow and red areas indicate decreasing suitability. The range changes for (a) the M1S1 model ensemble, and when removing all bioclimatic variables except (b) average minimum winter temperatures, (c) maximum precipitation amounts, (d) precipitation seasonality, and (e) snow cover days. See Table 5.1 and Table 5.2 for more information on variables and models. The black vulture range edge is shown by the black dashed line, with the black vulture range including the southeastern and eastern United States (underneath the dashed line).

CHAPTER 6: DISCUSSION

6.1 Dissertation overview

Throughout this dissertation, we have explored a variety of interactions between human and raptor populations, all focused on the overarching question of how to improve human-raptor interactions and promote long-term coexistence. In Chapter Two, I discussed black vulture (*Coragyps atratus*) and turkey vulture (*Cathartes aura*) plastic ingestion, finding that vultures are ingesting more plastic materials within large landscapes with more developed landcover and food providers. Further, the plastic materials most often ingested were found to be silicone rubber (used in tires and automobile seals) and polyethylene (used in plastic bags and food packaging).

In Chapter Three, I discussed the RaPTR tool, with which we can select release sites for rehabilitated raptors in the Charlotte Metropolitan Area that maximize long-term chances of survival while minimizing the risk of conflicts. This tool provides an important service to the raptor rehabilitators in this region, allowing them to focus on rehabilitating the birds rather than selecting ideal release sites.

In Chapter Four, I returned to vulture populations, exploring the conflicts that occur between humans and black vultures. This largely focused on conflicts regarding livestock depredation given the relevance of this issue, and I found that these conflicts are primarily caused by resource availability (generally a food source) and are ultimately solved with human adaptation to the black vultures, rather than various lethal and nonlethal methods.

Finally, in Chapter Five, I explored the range expansion of black vultures across the midwestern United States. I found that black vulture suitability is higher in areas with less precipitation seasonality, warmer winters, more urban landcover and open water, less agricultural and cropland area, and more heterogeneous landscapes. Overall, the models project a slight contraction in the black vulture range by 2100, with expansions in the northern midwestern region and contractions in the southern midwestern region.

6.2 Contributions to human-raptor interactions and coexistence

So, how do all of these results add to the human-raptor interaction literature and work to promote long-term coexistence? Revisiting the framework from the introduction, I argue that we must first be analyzing these interactions from the view of a coupled human and natural system and with that view, we can then promote long-term coexistence by (1) understanding the species needs, threats, and interactions (*Understand*), (2) appropriately managing negative interactions and conflicts (*Manage*), and (3) implementing conservation measures to protect species and the resources they rely on (*Conserve*). Each of these chapters contributes to at least two of these dimensions, together combining to better inform human-raptor coexistence (Figure 1.2).

First, each of these chapters added to the knowledge base regarding human-raptor interactions. We now have a better understanding of what landscape features are associated with black vulture and turkey vulture plastic ingestion, as well as the types of plastic most commonly ingested. We understand where we should be releasing rehabilitated raptors within the Charlotte Metropolitan Area. We understand the drivers of black vulture conflicts involving livestock depredation and the efficacy of short-term and long-term solutions for these conflicts. Finally, we understand many of the landscape and bioclimatic features associated with black vulture presence in the midwestern United States.

These understandings allow us to better manage negative human-raptor interactions and conserve habitat and populations when necessary. We can better manage plastic pollution to protect vulture populations, especially in areas predicted to experience range contractions. We can release rehabilitated raptors into specific areas to reduce or avoid conflicts and target high quality landscapes to promote healthy populations. We can better manage existing conflicts between humans and black vultures by limiting food resources and adapting our lifestyles to the black vulture presence. We can also predict where conflicts will occur in the future and work with these identified areas to prevent and manage conflicts. Finally, we can predict where black vultures will decline and conserve habitat and resources to promote the presence of this important species.

Let's look at one specific example of this research contributing to long-term coexistence between human and raptor populations. Looking at the projected black vulture range for 2100, we see range expansions in the northern portion of the midwestern United States and range contractions in the southern portion of the midwestern United States (Figure 6.1). We see especially large increases in suitability near Chicago, IL and the Central Corn Belt Plains ecoregion (Commission for Environmental Cooperation, 1997) and especially large decreases in suitability surrounding Nashville, TN, in the Interior Plateau ecoregion (Commission for Environmental Cooperation, 1997) (Figure 6.1).

Focusing first on the range expansions, we can expect that if black vultures become a common occurrence across Chicago, IL and the surrounding areas, conflicts will arise as most people in the area will not have previously dealt with the species. Based on our understanding of human-black vulture conflicts, we can expect more conflicts involving property destruction and nuisances within more urban areas and more conflicts involving livestock depredation in the surrounding suburban and rural areas (Kluever et al., 2020). Looking at Chicago, IL, we can begin preparing for these conflicts now by limiting the availability of food sources and adapting human behaviors accordingly. This may include the following:

- Managing food waste more effectively by covering compost piles, securing dumpsters, and reducing the availability of organic matter from sources such as fishing sites
- Protecting vehicles and property at sites where food waste cannot be properly secured
- Protecting boats and recreational vehicles with durable covers that do not attract black vultures
- Properly disposing of carcasses near livestock areas
- Providing protection for livestock, especially during the birthing season, by using human guardians, guard dogs, or secure barns
- Releasing individuals in strategically selected areas that maximize habitat suitability while minimizing the chance of negative human-vulture interactions

Let's now look at one area with projected range contractions – the Interior Plateau ecoregion within Tennessee. Black vultures have been present in Tennessee since at least 1900 (National Audubon Society, 2023) and are an important part of the ecosystem. A decline in black vulture populations across this area may alleviate some conflicts, especially those involving livestock depredation across the region, but it may also alter ecosystem functioning at large scales, including scavenger distribution, nutrient cycling, and disease control patterns. This could lead to significant impacts on wildlife and humans alike. With the measures below, we may be able to promote the presence of some black vultures across the Interior Plateau to maintain the ecosystem services that have been provided for well over 100 years.

- Target heterogeneous landscapes with more urban landcover and open water for land conservation measures
- Provide supplemental feeding stations in urban and suburban landscapes near water sources and roosting habitat, as is frequently done for vultures with declining populations (Arkumarev et al., 2021)
- Maintain more heterogeneous urban and agricultural landscapes, with a variety of landcovers that provide resources, such as forested areas, open greenspace, developed area, and open water
- Work with local communities to better manage conflicts that arise, by providing education and support to change behaviors to accommodate black vultures
- Better manage plastic pollution to reduce the threats presented to individuals living in the area
- Again, releasing individuals in strategically selected areas that maximize habitat suitability while minimizing the chance of negative human-vulture interactions

While we can make these statements based on the research here, coexistence broadly and that between humans and vultures will take on different appearances across landscapes and time periods. The human perception of vultures significantly impacts the existence of conflicts, as do many other socioeconomic features such as income and culture, and environmental features including landcover and the presence of other scavenging species (Dickman, 2010). One example of this changing relationship throughout time can be seen in the history of Charleston, SC. Here, black vultures experienced periods of decline, fame, and revulsion fueled by changes in public opinion, rabies concerns, business patterns, resource availability, and sanitation practices (Butler, 2017a, 2017b). Human-vulture conflict and coexistence will always shift in space and time with altered socioeconomic conditions and natural resources and thus, there is no one state of human-vulture coexistence. Coexistence for one place may look like Charleston, SC in the early 1800s, where vultures were welcomed in large numbers to clean up waste and were protected from harm by fines (Butler, 2017a). In other places, coexistence may be a small group of vultures that feeds only on carrion and does not regularly interact with humans. And in other places, coexistence may be having no vultures around other than the occasional roaming individual. While we can propose general actions to promote coexistence between human and vulture populations, we must critically consider what coexistence actually means for the community involved, reflecting on the causes of conflict and the important socioecological features that may be impacted by changes to the relationship.

As black vultures are not a threatened species, and rather, they are expanding in range and increasing in population – why should we bother with conservation to begin with? Vultures as a whole are a threatened group, with approximately 70% of species threatened or near-threatened (Buechley & Şekercioğlu, 2016; Carucci et al., 2022). Vultures provide significant provisioning, regulation, and cultural ecosystem services, namely by breaking down waste materials, controlling disease, contributing to local economies, and holding spiritual importance for people (Buechley & Şekercioğlu, 2016; Carucci et al., 2022; Moleón et al., 2014). Where vulture populations have dramatically declined across India, feral dog populations have increased and contributed to the increase in rabies transmission, with all impacts estimated to cost the country billions over a 15 year period (Frank & Sudarshan, 2023; Markandya et al., 2008; Ogada et al., 2012). In addition to increases in feral dogs and the subsequent increases in rabies, a loss of vulture scavengers could lead to an increase in other diseases from feral dogs and rats, including increases in human anthrax which has found to be associated with vulture declines (Ogada et al., 2012). Additionally, some people, such as the Parsi community in India, practice sky burials through which they place their dead on pillars to be disposed of by vultures – a practice which has quickly come to an end with the loss of vultures in these areas (Ogada et al., 2012).

Vulture species in Europe, Asia, and Africa have received a great deal of research attention and have experienced very successful conservation efforts, but generally only after significant population declines, with some species seeing declines of more than 99% (Ogada et al., 2012; Santangeli et al., 2022). The reasons for decline in many of these vulture species are poisoning and human persecution, neither of which are unique to these species and could certainly contribute to future declines in other vulture species (Buechley & Şekercioğlu, 2016; Markandya et al., 2008; Ogada et al., 2012). Other researchers see the threat of a "New World vulture crisis" with declines in North and South American species similar to those seen in species in Europe, Asia, and Africa, and are calling for action now to prevent or better manage declines if they occur (Santangeli et al., 2022). To prepare for declines in North and South American vulture species, researchers are calling for research addressing significant knowledge gaps that exist for many vulture species, and especially for research focusing on species lacking attention regardless of IUCN status (i.e., nonthreatened species in addition to threatened species). This includes research on the species life history and spatial ecology as well as important socio-ecological research that evaluates threats, drivers, and mechanisms that may contribute to declines (Santangeli et al., 2022). While black vultures and turkey vultures are not currently threatened species, they may face population declines in the future and it is important to fill knowledge gaps now and understand how to adequately protect and conserve populations.

Changing climates will impact habitats and landscapes globally, presenting new challenges for conservation efforts globally (Nyhus, 2016). Many future conservation actions may be geared towards adaptive habitat management rather than specific species management (Tompkins & Adger, 2004), and nonthreatened species such as black vultures and turkey vultures may not be a priority for conservation. While these species can certainly be negatively impacted by various threats and landscape conditions, they are also inherently adaptable and may have a high adaptive capacity that will allow them to evolve and adjust their behavior to survive in new conditions (Beever et al., 2016). Regardless, ecosystems are in a constant state of flux, changing with new environmental and climatic conditions, and the species assemblage changes with these conditions. As stated by Warren (2023) – "there is no 'correct' species assemblage for a place because a region's current complement of species is a matter of historical accident and biogeographical happenstance" (p. 290). While there may be social and ecological impacts caused by declines in vulture populations, ecosystems will adjust, and adaptive management will promote the provisioning of services in the event of vulture declines.

6.3 Future research directions

This dissertation has focused largely on raptor populations, yet there exist many knowledge gaps regarding human-wildlife conflict and coexistence broadly that would benefit research on more specific human-wildlife interactions. To begin, there are many unique definitions of human-wildlife conflict and of human-wildlife coexistence, with no clearly understood definition across the field (Glikman et al., 2021). This can lead to individuals globally interpreting studies on human-wildlife conflict and coexistence in different ways that make progress difficult. Second, when researching human-wildlife conflicts, we are often searching for similarities between situations that can reveal insights that will improve all conflicts with that species and others. For example, in Chapter Four, I state that human-black vulture conflicts are broadly caused by resource availability and solved with human adaptation – aiming to share a finding that I believe will help other researchers, practitioners, and individuals when managing human-black vulture conflicts. Yet, whether or not we can generalize insights regarding human-wildlife conflicts has been called into question, with some scientists arguing that case studies on conflicts are “valid only for informing action at a local scale” (p. 1) and that even multiple case studies showing similar results does not make the finding universally true (Zimmermann et al., 2021). Further research evaluating a large number of case studies on human-wildlife conflict and evaluating the generalizability of findings would greatly benefit this field. In addition to this point, the International Union for Conservation of Nature (IUCN) has identified other considerations that can better guide human-wildlife coexistence efforts going forward, including the idea that management strategies should be designed and maintained in a collaborative fashion with a diversity of stakeholders (Zimmermann & Stevens, 2021). This idea is seen often, but whether or not such collaborative discussions are providing the best methods to overcome challenges to human-wildlife conflicts and coexistence has been called into question, requiring more research (Treves & Santiago-Ávila, 2020). Finally, there exist other broad questions regarding human-wildlife conflict and coexistence including the extent to which conflicts are increasing and worsening, the neutrality of scientists studying conflicts, and the true rate of wildlife damage that exists across landscapes with a consideration of how the perceptions of humans may be skewing this data (Treves & Santiago-Ávila, 2020). Each of these questions would provide important information to each of these research chapters and to other human-wildlife conflict and coexistence research globally.

Within the realm of human-raptor interactions, this research has answered several questions and raised many others. While we know that black vultures and turkey vultures are ingesting plastic across North and South America (Ballejo et al., 2021; Borges-Ramírez et al., 2021; Cunha et al., 2022; Partridge et al., 2023; Torres-Mura et al., 2015), there are many existing unknowns regarding this topic. It is unclear whether vultures are intentionally ingesting plastic materials or if they are mistaking the materials for food items (Houston et al., 2007). Observations of vulture foraging behavior focused on plastic ingestion would provide a better understanding of this behavior. Additionally, research identifying the actual sources of plastic ingestion would be beneficial for future conservation efforts. While we found that vulture pellets contained more plastic materials in large landscapes with more urban landcover and food providers, it is unclear where within these landscapes the vultures are ingesting the plastic. Further, the true impacts of plastic ingestion are unclear and require a great deal of future research. Plastic ingestion can certainly lead to gut blockages and impactions (Houston et al., 2007), and research has found that black vultures that ingested more plastic had worse health and more stress (Cunha et al., 2022). Additionally, research on Eurasian griffon vultures (*Gyps fulvus*) found shorter telomeres in individuals foraging in more urban environments, indicating a shorter lifespan that can be genetically passed to young (Gangoso et al., 2021). These studies highlight some impacts, but we need further research on the individual-level impacts of plastic ingestion in black vultures and turkey vultures, looking at the behavioral and physiological effects. Additionally, the impacts of plastic ingestion on nestling health and survival is an important understudied component. The ingestion of anthropogenic junk has been found to significantly decrease the nesting success of California condors (*Gymnogyps californianus*) (Mee et al., 2007), this may be true for other vulture species and present another major threat of living in urban areas that could have significant implications for vulture populations nationwide, as vultures are a long-lived species with low levels of reproductive capacity. Finally, the ecosystem-level impacts of vulture plastic ingestion deserve more attention. Previous research has shown that vulture plastic ingestion has created plastic islands in otherwise natural environments, as the vultures ingest the plastic in one area and regurgitate it at their natural roosting location (Ballejo et al., 2021). This behavior could be spreading plastic pollution into many natural environments across their range and altering the local ecosystems in important ways.

Moving onto the release of rehabilitated raptors using RaPTR, we are still lacking a great deal of knowledge that would strengthen this tool and other future tools. First and foremost, the spatial ecology of many raptor species is critically lacking, leaving us to make educated guesses on specifics. For example, we know that red-tailed hawks prefer edge habitat between open and forested landcover, which provides roosting and nesting habitat as well as many foraging opportunities (Preston & Beane, 2020). However, we lack information on their landscape ecology, including how much edge within landscapes of what size is ideal. These knowledge gaps exist for each of the six study species included in the RaPTR tool and while each may seem minor, they combine to create uncertainty in the tool. Moving on, future research should work to investigate the individual, population, and human impacts of raptor release and release tools. First, a validation of the release suitability results would provide great strength to the RaPTR tool, studied by tracking birds released into different areas to measure survival across suitability scores. Next, the population-level impacts of this practice could have significant effects to the ecosystem and the focal species. Higher post-release survival rates could lead to more concentrated populations of raptors in landscapes, leading to impacts of prey populations, altered conspecific and interspecific interactions, and ultimately lower survival rates long term due to increased competition. Finally, the human dimensions of this tool and other similar tools are worthy of investigation, evaluating how individuals use these tools, the time that is saved, and the value that they believe is contributed.

Black vulture conflicts involving livestock depredation have received more attention in recent years, but we are still critically lacking research focusing on the actual rate and context of black vulture depredation incidents (Buckley et al., 2022). There are trustworthy historical reports of this behavior occurring (Hagopian, 1947; McIlhenny, 1939; Mrosovsky, 1971), but many of the current research relies on ranchers observations of black vultures on carcasses or on post-mortem autopsies (Milleson et al., 2006; Wahl et al., 2023), which does not necessarily indicate fault and may be highly biased (Duriez et al., 2019). The few research studies that have actually made field observations have found that black vulture livestock depredation is rare and that the perceptions of farmers and the story shared by the media does not match the true situation (Ballejo et al., 2020; Duriez et al., 2019). Paired with more field observations of vulture-livestock interactions, future research would greatly benefit from a better understanding of the nationwide perceptions of black vultures from various stakeholders, focusing on finding the drivers of negative perceptions in an attempt to identify the social and environmental drivers of tolerance and coexistence.

Finally, several future research opportunities exist regarding the black vulture distribution and range changes. First of all, this dissertation chapter evaluated the black vulture landscape and bioclimatic associations across the midwestern United States. While this is already only a portion of the full black vulture range, future research should conduct similar studies looking at smaller, more localized study areas. While the study area is comprised of several similar ecoregions, it is very possible that black vultures are relying on different landscape and bioclimatic variables across their range. As such, studies investigating a series of small study areas, ideally spread across the full black vulture range, would allow us to identify what features specific black vulture populations are using and find commonalities across the range. To further understand the potential range changes, future research could project the black vulture distribution to past climates to understand historical presences and use abundance models to understand not only where we can expect black vultures to be present, but in what numbers. Finally, the black vulture range change will certainly impact interspecific interactions, especially with turkey vultures. As turkey vultures begin experiencing competition with black vultures in landscapes where there has previously been none, we may see population declines or altered ranges and landscape use in turkey vultures and other avian scavengers such as ravens.

6.4 Conclusion

The field of human-wildlife interactions is rapidly growing and changing with new research insights and with environmental and social changes to the world in which we live. My research has contributed a deeper understanding of several interactions that take place between human and raptor populations. Specifically, this includes (1) information on vulture plastic ingestion, further uncovering one of the potential consequences of living and foraging in urban areas (Chapter Two), (2) one way that researchers can better support conservation efforts such as wildlife rehabilitation to ensure practices are supported by scientific evidence (Chapter Three), (3) an understanding of the causes and solutions for human-black vulture conflicts that may help prevent and manage conflicts globally (Chapter Four), and (4) a projection of where the black vulture range may shift in future decades that could promote better management of conflicts and conservation efforts. In areas with declining black vulture and turkey vulture populations, researchers, practitioners, and other stakeholders should prioritize the management of necessary habitat and resources, the prevention of plastic ingestion and conflicts, and the selection of ideal release locations when translocation is used. In areas with stable or increasing populations, researchers, practitioners, and other stakeholders should continue to prioritize the management of habitat and resources, but in an effort to eliminate resources that may lead to conflict situations, rather than aiming to protect resources for populations for use. In areas with stable or increasing populations, there should also be more focus on the effective prevention and management of conflicts – aiming for long-term conflict mitigation that considers the social and environmental features contributing to the conflict and the actions that can best limit those contributing features. Each of these projects uncovered additional research questions that should be addressed to further develop the fields of human-raptor interactions and human-wildlife conflict and coexistence more broadly. With existing knowledge gaps filled regarding human-wildlife conflict and coexistence and human-raptor interactions, we can continue working towards a state of long-term coexistence between human and wildlife populations globally.

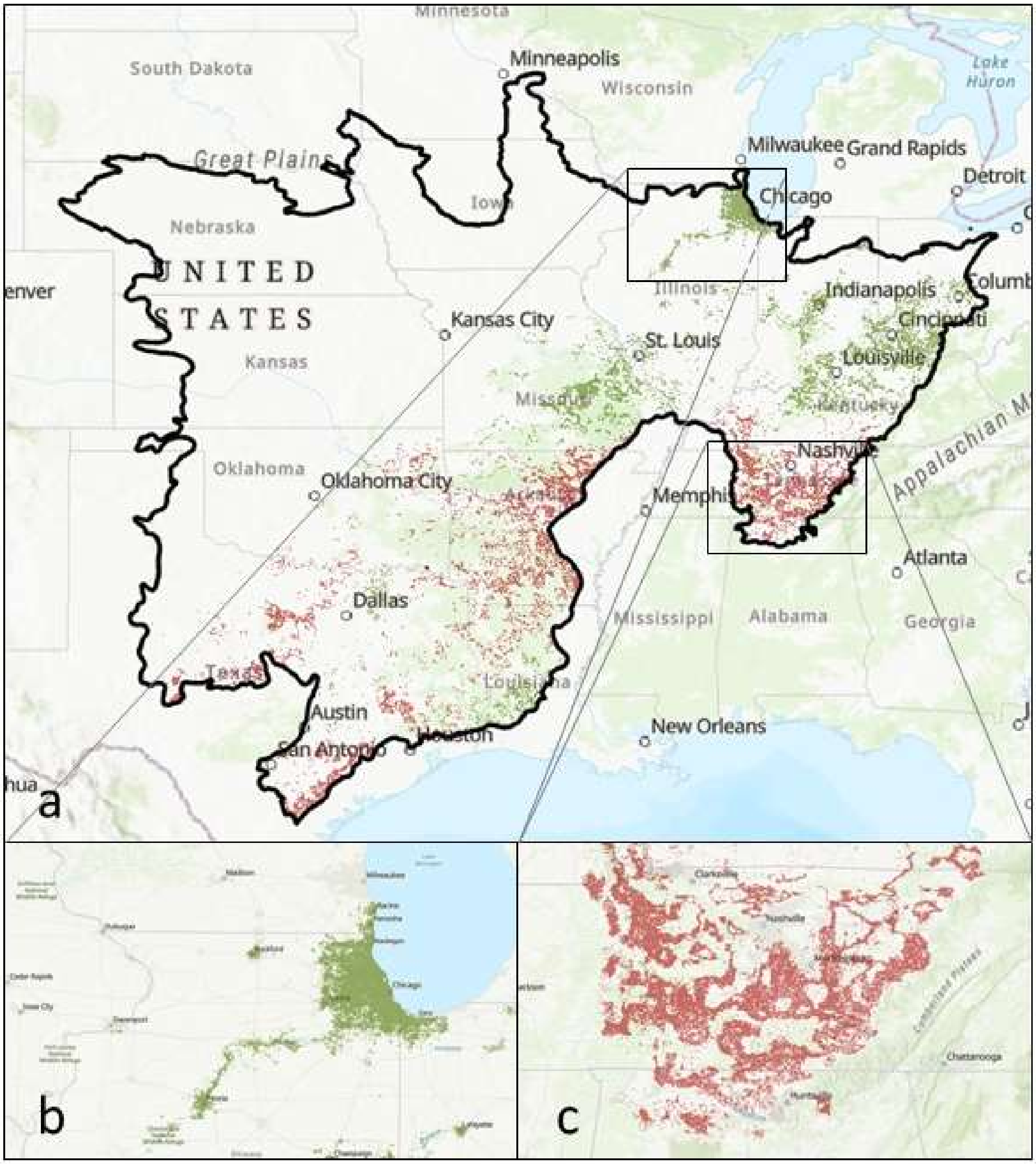

Figure 6.1 Changes in black vulture (*Coragyps atratus*) presence when the black vulture range is projected to the time period 2071-2100 under SSP3 RCP7.0. Changes in presence are shown (a) across the midwestern United States with (b) areas of new presence around Chicago, Illinois highlighted and (c) areas of lost presence in the Interior Plateau ecoregion of Tennessee highlighted. Green areas indicate a new black vulture presence, red areas indicate a lost black vulture presence (i.e., they were present and are no longer projected to be), and areas with no color indicate no change in presence.

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