THE INFLUENCE OF ROAD, ROAD VERGE AND LANDSCAPE CHARACTERISTICS ON THE OCCURRENCE OF RAPTOR-VEHICLE COLLISIONS

by

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ABSTRACT

JENNIFER L. BATES. The Influence of Road, Road Verge and Landscape Characteristics on the Occurrence of Raptor-Vehicle Collisions. (Under the direction of DR. SARA GAGNÉ)

The increasing prevalence of roads has had a corresponding impact on the risk of road mortality for wildlife, particularly for avian species such as birds of prey that commonly make use of foraging opportunities along roadside verges. Birds of prey, or raptors, are considered apex predators, which suggests that the impact of road mortality has far-reaching ecological consequences. The purpose of my research was to analyze the effect of traffic, habitat, and road verge variables on collision risk for raptors. I accomplished this in three ways: first, I assessed the impact of road and habitat variables on vehicle collision risk for Barred Owls (*Strix varia*) in the Charlotte, North Carolina region. I then applied this same analysis to both nocturnal and diurnal raptors in the Orlando, Florida region. Finally, I assessed the relative impact of species and individual traits on collision risk at locations with varying characteristics.

Although I did not observe a difference in collision risk for raptors based on time of activity, I found that traffic volume and the suitability of surrounding habitat were significant predictors of collision risk in both Florida and North Carolina. In many cases, I found that increased prey cover in the form of brush, shrubs and tall grass along road verges served to predict collision risk in both locations. Complex vegetation provides habitat for small vertebrates, which in turn attracts raptors to roadsides, thus increasing the risk of being struck by a passing vehicle.

My analysis of species traits showed that body size and reproductive output were the most important predictors of collision risk. Larger species and those with smaller clutch sizes were most likely to be hit, regardless of road conditions or habitat characteristics.

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DEDICATION

This work is dedicated to my partner in crime, my enemy, my best friend, Byzantyne. Thank you for teaching me the most important lesson of all. I can only hope I do it justice.

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Chapter 1: Introduction: Road Effects and Raptors

1.1 Introduction

There is a vast trend of acceptance among ornithologists that the most significant causes of mortality among all avian species in North America are from anthropogenic sources (Ress and Guyer 2004; Hager 2009). Along with predation, pesticides and electrocution, collisions with vehicles and other man-made structures pose the greatest cumulative threat to birds in the United States (Erikson et al. 2005). The increasing prevalence of roads and vehicle traffic, most particularly in urban areas, has a corresponding impact on road mortality, especially in avian species that make use of foraging opportunities along roadside verges (Meunier et al. 2000). The ever-expanding global network of roads currently includes more than 14 million km of paved surface and is projected to increase with an additional 25 million km before 2050 (Strano et al. 2017). Unlike in predation, where selection of prey is influenced by condition or fitness, road mortality results from the random selection of often healthy individuals (Bujoczek, et al. 2011). Raptors, or birds of prey, allow us to gauge environmental quality both as a result of their sensitivity to human activity and habitat disturbance, and because they are top-level predators (Rodríguez-Estrella et al. 1998; Molina-Lopez and Darwich 2011). Birds of prey hunt primarily via flight by using acute senses, including vision, to locate prey. Although many bird species are considered predatory, a standard designation of “raptor” has not been developed. In ornithology, the term generally refers to birds of three orders: Falconiformes and Accipitriformes (falcons, hawks and eagles), or diurnal raptors, and their nocturnal counterparts of the order Strigiformes (owls); however, the term has been applied to other taxa including Cathartiformes (New-world vultures) and Cariamiformes (including the extant Seriema) (McClure et al. 2019). In many cases, raptors are vulnerable to vehicle collisions because they forage along roads, and as a result, roadkilled/injured raptors are often the focus of rehabilitation centers across North America (Hager 2009). For the purpose of my research, I will focus on Accipitriformes and Strigiformes, primarily because of the preponderance of available data for species that fall within these taxa. In addition, an increased vehicle risk for nocturnal raptors, or Strigiformes, has been documented (Hager 2009, Hernandez et al. 2018).

The impact of human activity has been documented across a variety of birds of prey. Deem et al. (1998) found that 87% of raptors admitted to the University of Florida teaching hospital between 1988-1994 suffered injuries from anthropogenic causes. Trauma resulting from collisions with both vehicles and buildings has been described in many studies as a common cause of injury across both diurnal and nocturnal species (Wendell et al. 2002; Ress and Guyer 2004; Hernandez et al. 2018). A review of raptor mortality in the US and Canada by Hager (2009) noted that the most significant cause of mortality across all species was from vehicles; however, where car strikes posed the greatest threat for all Strigiformes, there was considerable variance in etiology for Accipitriformes ranging from vehicles to gunshot and window strikes. More recently, an attempt was made to identify trends in age and species across raptors admitted to an Alabama, USA rehabilitation facility. Again, owls were most often involved in vehicle collisions, where a variety of causes were observed for diurnal species (Hernandez, et al. 2018). Ultimately, vehicle collisions remain a notable cause of death or injury across both diurnal and nocturnal raptor species.

In many cases, roads and road verges are attractive sites for foraging raptors due to perch availability and the accessibility of prey and roadkilled animals (Dean and Milton 2003). A regrettable byproduct of crossing and foraging along roads by raptors is a prevalence of injury and mortality caused by collisions with motor vehicles (Planillo et al. 2015). The most fortunate of injured raptors are found by the public and admitted to rehabilitation centers for treatment and release when possible. Raptor centers exist across the United States and are committed to rehabilitating birds of prey. Vehicle collisions represent the most common cause of injury across all raptors admitted to two centers included in this dissertation (the Audubon Center for Birds of Prey in Maitland, FL, USA and the Carolina Raptor Center in Huntersville, NC, USA) in the year range included in my research (1996-2019 and 2000-2019, respectively). At both locations, vehicle collisions represent more than 25% of all patients of known etiology. Other common causes of admission are gunshot, electrocution, collision with other non-vehicle objects, entanglement, and animal attack. Nearly a quarter of all birds admitted are dead upon arrival or within 24 hours of admission; however, both centers release approximately 40% of patients treated. Although rehabilitation data reflect the inclination of an individual to intervene on behalf of wildlife as well as knowledge of possible responses to finding an injured animal, raptor center data represent the best opportunity to characterize species injury/mortality with an anthropocentric cause.

Using intake records from raptor centers in Florida and North Carolina, USA, I conducted a comprehensive investigation into the factors that influence collision risk for a variety of raptor species. Most research on road effects and raptors has focused on nocturnal species such as the Barn Owl (*Tito alba*), which has suffered population decline across parts of its range (Massemin and Zorn 1998; Boves and Belthoff 2012; de Jong et al. 2018). Suggestions regarding the mitigation of road effects for the Barn Owl have focused on modifying road verge vegetation to cause birds to fly higher when crossing roads, thus avoiding collision with motor vehicles (Massemin and Zorn 1998). The inclusion of road verge vegetation and its potential impact on collision/road mortality risk has not been repeated for other species. In Chapter 2, I developed an improvement to a previous study on Barred Owl-vehicle collisions (Gagné et al. 2015) by including a set of variables to evaluate the impact of road verge vegetation on collision likelihood in the Charlotte Metropolitan Area. In addition to the lack of focus on road verge vegetation, no previous research related to raptors and road mortality has conducted a comparison of road effects and collision/mortality risk between diurnal and nocturnal birds of prey. To address this gap, in Chapter 3, I repeated the Charlotte analysis in Florida, USA using data for four species, the nocturnal Barred Owl (*Strix varia*) and Eastern Screech Owl (*Megascops asio*) and the diurnal Bald Eagle (*Haliaeetus leucocephalus*) and Red-Shouldered Hawk (*Buteo lineatus*). In Chapter 4 I investigated the impact of species and individual traits including foraging strategy, reproductive output, body size, migration and age on the location of raptor-vehicle collisions using the same species listed above. The effect of species traits on road mortality has been documented for both mammals and birds, but this is the first time that the impact of species traits on the nature of vehicle collisions has been investigated specifically for raptors (Jaeger et al. 2005; Bujoczek et al. 2011). Finally, this dissertation ends with a discussion of syncretized results for each of the three analyses and the implication of these results for future research and mitigation.

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Chapter 2: The Likelihood of Vehicle Collisions involving Barred Owls (Strix varia) in Charlotte, NC is Influenced by Road Characteristics, Surrounding Habitat and Road Verge Vegetation

2.1 Introduction

As road networks continue to expand, corresponding negative effects for wildlife, including raptors, abound. For example, habitat fragmentation and the risk of vehicle collisions have been widely documented and in some cases are damaging enough to cause measurable impacts on local raptor populations (Silva et al. 2012). In many cases, traffic noise in major roads creates a barrier effect, ultimately causing a change in home range use and behavior for both diurnal and nocturnal birds-of-prey (Bautista et al. 2004; Silva et al. 2012; van der Horst et al. 2019). Negative effects, including road mortality, habitat fragmentation and disturbance from traffic noise have been documented in the Tawny Owl (*Strix aluco*) and Little Owl (*Athene noctua*) in Southern Portugal (Silva et al. 2012). While major roads certainly provide the greatest noise impact and risk imposed by high-speed vehicles, a study examining effects of different road types on the Tawny Owl indicated that the greatest collision risk occurred along secondary roads where less disturbance led owls to use proximal habitat and forage along road verges (van der Horst 2019). In fact, it appears that in some cases, road verges attract owls, regardless of the disturbance imposed by traffic (Harding 1986).

The Barred Owl (*Strix varia*) is an opportunistic, nocturnal raptor species indigenous to eastern North America. Historically, this species was thought to exist in isolation from human activity, yet we currently know that the Barred Owl can thrive amongst people, even in densely populated urban areas (Bierregaard 2018). Urban owls enjoy prey availability and the open understory provided by the city's residential design; however, reproductive success is offset considerably by car strike mortality both in and outside of the city (Bryner 2007). Prey availability along roadside verges can attract owls to high-traffic and higher speed limit areas (Dean and Milton 2003; Grilo et al. 2018), where car strike risks are higher. In addition, narrow roads in urban residential areas allow a bird to forage across roads where prey is available (Planillo et al. 2015). For this reason, traffic volume, speed limit and road width are included in the analysis described below.

Road verge vegetation appears to affect the use of roadsides by raptors (Meunier et al. 2000; Dean and Milton 2003), but the impact of road verges on collision risk is unclear. In some cases, recommended mitigation strategies require the removal of shrubs and hedges (Orlowski 2008), but in other cases, vegetation appears to reduce risk (Arnold et al. 2019). The lack of consistency in recommendations involving roadside vegetation are likely related to differences among the species in question: most notably, in foraging behavior. The Barred Owl, for example, forages in and around woodland and prefers to look for prey while perched, a strategy that does not fit open land (Harrold 2003). Conversely, Barn Owls (*Tyto alba*) primarily forage in open landscapes and have experienced significant mortality due to vehicle collisions (Boves and Belthoff 2012). The risk of vehicle collisions for this species is highest where roads intersect open fields without shrubs or hedges (Massemin and Zorn 1998; Gomes et al. 2008; Arnold et al. 2019). Collision risk mitigation strategies for the open landscape Barn Owl are likely to be vastly different than for its sit-and-wait foraging counterparts. Ultimately, road risk mitigation will need to be tailored to the most at-risk species present in a certain landscape.

For a forest forager like the Barred Owl, the presence of perches is a primary factor in habitat suitability (Andersson 2009). Perches facilitate the sit-and-wait foraging strategy used by this species and ultimately provide accessibility to prey, where open land is less well-suited, even when prey exist in higher densities (Widén 1994). Perch height has a measurable effect on the visibility of prey, as well as hunting success, for owls (Andersson et al. 2009). A study that explored habitat requirements for raptors, especially in urban environments, indicated the importance of tree height as a primary estimator for the presence of owls, even above impervious surface (Clement et al. 2019). Mature deciduous trees provide an open understory where flight is unobstructed, and prey is exposed.

Another component of habitat quality for Barred Owls is prey density (Widén 1994). Barred Owls utilize a variety of prey items, from insects, amphibians and reptiles, to small birds and mammals. In more urban areas, owls feed more exclusively on birds and rodents than their rural counterparts (Hindmarch and Elliott 2015; Cauble 2008). In some cases, road verges provide adequate habitat for both songbirds and small rodents, especially where complex vegetation exists in close proximity to roads (Meunier et al. 1998; Orlowski 2008; Silva et al. 2012). Complex vegetation provides good cover for prey animals such as small mammals and Passerine songbirds (Meunier et al. 1998; Cauble 2008; Santos et al. 2016). However, dense vegetation can conceal prey and make successful foraging difficult for owls regardless of perch height (Andersson et al. 2019). It is unclear what degree of visibility is necessary for owls, or whether complex vegetation provides the best accessibility to prey along roadsides.

Gagné, et al. (2015) investigated the comparative effects of road characteristics and surrounding habitat on the occurrence of collisions involving Barred Owls in Charlotte, NC (USA). Using intake records from the Carolina Raptor Center (CRC), this study examined both roadway and habitat variables surrounding each collision. The results of this study suggest that collision risk is influenced positively by speed limit and the habitat suitability at a home range scale (using a radius of 825m from the collision site) and negatively by road width. Notably, this project did not examine road verge habitat specifically as a separate set of variables.

An improvement upon the model described by Gagné, et al. (2015) would identify the effect of road verge vegetation and perch availability on the likelihood of owl-vehicle collisions. This study aims to use collision data in combination with land cover and traffic data to evaluate the effect of roadway characteristics, surrounding habitat suitability, and road verge habitat on collision risk for Barred Owls. Roadside verge habitat is described by 1) prey accessibility in the form of *perch availability*, and 2) the presence of habitat for songbirds and small mammals in the form of *prey cover,* which consists of complex road verge vegetation such as shrubs, brush and tall grass. I hypothesize that road verge habitat will significantly influence collision risk for Barred Owls because the presence of suitable perches and prey cover attracts owls to roadsides. Given existing knowledge of the foraging behavior and diet of Barred Owls, areas of highest risk may occur along verges where prey density exists in proximity to perch availability. To this aim, I used intake records collected from the Carolina Raptor Center in Huntersville, NC for Barred Owls in conjunction with aerial imagery and traffic data. I included all ten counties named in the Charlotte–Concord–Gastonia Metropolitan Statistical Area (MSA).

2.2 Methods

Study Area

Charlotte is the largest city in North Carolina and is of interest because of its rapid growth and exponential increase in developed land cover since 1980 (Meentemeyer et al. 2013). Even in more recent years, growth has continued in surrounding communities, exceeding 40% in some places (Bell 2017). The Charlotte-Concord-Gastonia Metropolitan Statistical Area (MSA) includes seven counties in North Carolina and three in South Carolina. The 2019 population of the Charlotte-Concord-Gastonia MSA exceeded 2.6 million, with a current density of 181.9 people/km^2 (US Census Bureau 2020).

Barred Owl-vehicle collisions

Collision data consist of archives gathered from the Carolina Raptor Center (CRC). The CRC has been dedicated to both public education and the rehabilitation of injured raptors since its beginning in 1975. The center currently treats close to 1000 birds each year. Close to 70% of birds admitted to the center are rehabilitated and returned to the wild. Although car collisions are the most common cause of injury, poisoning, gunshot, and electrocution are also common sources of injury for raptors brought to the center. I included records from a total of 271 injured Barred Owls brought to the center between 1995 and 2019 (Fig. 2.1). This year range reflects years where the total intake of Barred Owls exceeded 100 individuals annually. I selected from available records to include only collisions for which spatial locations were available. I used Google Earth (Google Inc. 2019) to assign spatial coordinates to each collision using addresses available in CRC records. I then randomly designated an equal number of non-collision locations for use as pseudo absences using ArcGIS 10.8.2 (ESRI 2022).

Explanatory variables

I applied similar methods and data sources used in Gagné, et al. (2015) for traffic volume and road width. Traffic volume was obtained from the North Carolina Department of Transportation Annual Average Daily Traffic (AADT) archives. Data for roads in North Carolina is collected in every even numbered year beginning in 2002. I assigned traffic volume to each collision and non-collision location based on values in the closest of three years: 2002, 2008, or 2014. These years were chosen because they had the largest number of road segments with available data. For road segments where no traffic volume data is available, I assigned a value based on the closest road segment in Charlotte with similar characteristics and a known traffic volume value. Traffic volume was expressed in this study by dividing by road width, which was included as a separate predictor. The decision to standardize traffic volume was based on the results of pairwise comparisons, which indicated a high level of correlation with other predictors. Road width, i.e. the paved surface (excluding verges), was measured using Google Earth. Medians were included in road width measurements where the median width did not exceed the width of a paved section on either side.

Speed limit was obtained from NC OneMap (nconemap.org), and the shapefile containing speed limits was joined to geocoded collision/non-collision locations in ArcGIS. Most road segments lacking a speed limit via NC OneMap were residential or dead-end roadways, which were assigned a speed limit of 25mph.

To account for annual and seasonal variation in the data, I included year and month for all collision sites and assigned months and years at random to non-collision sites. Barred Owls typically breed in mid-winter in the Southeastern USA, and road mortality tends to increase in the non-breeding season, when inexperienced juveniles are leaving the nest and females are more mobile. Annual variation could be a function of breeding success of urban pairs, a factor that could be affected by climactic changes (Boves and Belthoff 2012).

Habitat suitability scores for land cover surrounding each collision/non-collision location were derived from the National Land Cover Database (NLCD) (https://www.usgs.gov/centers/eros/science/national-land-cover-database). For each location, the closest year for NLCD surveys was used from the years 2001, 2008, 2013, and 2016. Given common knowledge of Barred Owl habitat use (Harrold 2003), the Wetland, Forest, Shrub/Scrub classes were given a score of 2; the Developed Open Space, Low-Intensity Residential, Grassland/Herbaceous, Pasture/Hay, Cultivated or Row Crops, Barren or Bare Rock/Sand/Clay and Open Water classes were assigned a score of 1, and the Developed High-Intensity, High-

Intensity Residential, and Commercial/Industrial/Transportation classes was assigned a score of 0. The score of each land cover class in an 825m radius circular landscape centered on collision/non-collision locations was weighted by the proportion of the landscape represented by the class. This radius reflects a maximum home range size of Barred Owls tracked in Charlotte, NC using radio transmitters (Harrold 2003). Habitat suitability for each landscape equals the sum of all weighted scores.

I included road verge habitat along each side of the collision/non-collision location and in close proximity to the road edge on each side. Roadside verge vegetation was based on perch availability and prey cover. Perch availability was evaluated on the presence of perches in the form of tree canopy. Reinhert (1984) found a preference of a variety of raptor species for perches with a minimum height of 3.7m and a branch diameter of 2. In this study, I defined suitable perches as trees rather than shrubs and brush given these minimum height and branch diameter requirements. To evaluate the presence of suitable trees (perch availability), I measured the percent of the road segment at a distance of 100m on each side of the collision/non-collision that intersected canopy cover. Canopy cover was represented by the Forest land cover class derived from National Land Cover Database (NLCD) data using the closest year to 2001, 2008, 2011, 2013 and 2016.

Based on my knowledge of the diet of Barred Owls, along with habitat preferences for small mammals and birds (Meunier et al. 1998; Orlowski 2008), I expect that ideal prey habitat consists of complex vegetation in the form of dense shrubs, tall grass, and brush. This type of vegetation provides better cover for prey species and was thus termed “high” prey cover. In the interest of gauging the relative effect of prey cover on the likelihood of a collision, I estimated the amount of ground and shrub cover along roadsides near each site. Using Google Earth Street

View, I classified road verges based on the proportion of prey cover in the form of brush, shrubs or tall grass as low (33% or less), medium (33-66%) or high (greater than 66%). The prey cover designation was determined using a distance of 15m outward from the paved surface (or gravel surface if the location was along a gravel drive) on both sides of the road and at a distance of 50m along the road on each side of the collision. I chose these distances because they produced substantial variation in road verge cover across all collision and non-collision locations. For older collisions (>5years prior to current street view data), I compared current data to historical aerial photos available at timemachine.mcmap.org. These photos were used to determine whether a major change had occurred (such as the addition of a subdivision or an industrial park) that would drastically alter roadside vegetation.

Analysis

I used logistic regression to model the effects of the following variables on the likelihood of a collision involving a Barred-Owl: road width, speed limit, traffic volume, habitat suitability, month, year, perch availability, and prey cover. Pairwise comparisons among all variables were conducted and correlation was found to be low or moderate ($|r|\leq0.65$) in all cases except with traffic volume. I standardized traffic volume by dividing that variable by road width, in effect creating a rate of traffic volume per meter road width. I tested model fit using the Hosmer and Lemeshow goodness of fit test (Hosmer and Lemeshow 2000).Model fit was tested using the Hosmer and Lemeshow goodness of fit test (Hosmer and Lemeshow 2000). The analysis was completed using R 4.2.2 (R Core Team 2022).

2.3 Results

I observed a marginal difference in sex with females being slightly more numerous than males (268 and 222, respectively) (Fig. 2.2b). Records included in this study's analysis yielded results sufficient to indicate a higher intake of first and second-year birds when compared to adults (95, 71 and 63, respectively) (Fig. 2.2a). The number of recorded collisions at the CRC were most numerous between October and March and peaked in December (46), with the lowest value occurring in July (8) (Fig. 2.3a). By year, Barred Owl-vehicle collisions show a general increasing trend in numbers between 1992 and 2019 (Fig. 2.3b).

Traffic volume, year, habitat suitability and prey cover all had a significant positive effect on the likelihood of a Barred Owl-vehicle collision. A significant negative effect was observed for both speed limit and perch availability (Hosmer and Lemeshow $X^2 = 6.85$, $p = 0.55$; pseudo $R^2 = 0.27$) (Table 2.1). Based on these results, owl-vehicle collisions are most likely on roads with an annual average daily traffic volume per meter width at or exceeding 1500 (Fig. 2.4a). Collisions are more likely at higher speed limits (Fig. 2.4b), and were most likely where habitat is at least moderately suited to owl foraging and nesting behavior (Fig. 2.4c). Collisions are also most likely where road verges have a moderate to high percentage of forest cover (Fig. 2.4d), and where prey cover is provided by the presence of hedges and coarse, unaltered/mowed vegetation (Fig. 2.5).

Summary statistics coincide with statistical results. For continuous variables, an apparent difference can be observed between the median, mean, and third quarter values between collision and non-collision data for all significant variables (Table 2.2). For prey cover, the total value for each classification is markedly different between collision and non-collision data (Table 2.3).

2.4 Discussion

The results of this analysis indicate that the likelihood of Barred Owl-vehicle collisions is influenced by year, traffic volume/road width, speed limit, habitat suitability, perch availability and prey cover. I predicted a positive effect of both perch availability and prey cover on collision risk. Although my results for prey cover show a positive effect as predicted, I found a negative effect of perch availability, which does not align with my hypothesis.

The results of my logistic regression model included a negative effect of perch availability on owl collision risk. This result suggests that Barred Owls are at greater risk of collision with a passing vehicle where roadside canopy cover is lower. It is possible that owls are able to utilize immature trees, less dense forest, and possibly man-made objects including buildings, power lines and other stationary structures that were not accounted for in my data. It may also be that understory vegetation may be of higher value as an attractant, at least in the case of roadsides. The preference of Barred Owls for forest cover, including old growth forest habitat, is well-reported and has long been documented in the literature, even for urban owls, where urban design adequately “mimics” old growth forest cover (Nicholls and Warner 1972; Mazur and James 2000; Harrold 2003). However, more recent research suggests that an urban landscape facilitates plasticity in habitat selection and behavior (Clement et al. 2021). Although the impact of road verge landscape features has not been examined for the Barred Owl prior to this paper, I suggest that further research focus on urban habitat preferences for this species, particularly along roadsides, instead of assuming that preferred habitat use in urban landscapes will mimic those for rural counterparts. Instead, it would be interesting to repeat this study and account for man-made perches along road verges, especially in places where forest cover is low. I expect such a study might reveal that urban Barred Owls are adept at utilizing non-natural perches while foraging near roadways.

I found a strong significant effect of prey cover on Barred Owl collision risk. To my knowledge, this is the first statistical evidence supporting an effect of road verge vegetation on collision risk for this species. In urban areas, a higher density of brush and deciduous shrubs is correlated with species richness for Passerine birds and for small mammals (Erritzoe et al. 2003; Loss et al. 2014). Low visibility vegetation affords protection for prey species; however, this same complex vegetation also attracts predators, and in the case of the Barred Owl, the presence of an increased percentage of prey cover on road verges also increases vehicle collision risk.

Similar to Gagné et al. (2015), I found habitat suitability had a significant effect on the likelihood of owl-vehicle collisions. Barred Owls are known to prefer old growth forest habitat (Harrold 2003), and my results support a preference for forest cover which is well-documented for this species. Suitable land cover likely supports a larger populations of owls, and at this scale, we can assume that owls crossing habitat are more likely to encounter roads, especially in urban and suburban areas (Baudvin 2004; Gomes et al. 2008).

In addition to landscape and road verge vegetation, the likelihood of owl-vehicle collisions was influenced by road characteristics including traffic volume and speed limit. Although Gagné et al. (2015) did not find traffic volume to be a significant predictor of collision risk, my data indicated that owl-vehicle collisions were more likely along roads with a higher daily traffic count per meter road width. This variable differs from previous studies using traffic volume as an annual daily traffic count (AADT) not measured as a factor of road width. In this case, the significant positive effect of traffic count per meter road width suggests a possible parallel between road width and traffic, where collisions are more likely where the concentration of passing vehicles is higher, not necessarily where the overall traffic count is higher. Roads with a higher concentration of traffic could be smaller, busier roads instead of interstates or divided highways with multiple lanes. To my knowledge, the effect of traffic volume standardized by road width has not been investigated as a predictor of wildlife-vehicle collisions; however, it would be interesting to further analyze the effect of vehicle concentration instead of volume on its own.

In general, my results suggest that owl-vehicle collisions are more likely on roads with lower speed limits. Other studies have found a positive effect of vehicle speed on road mortality in owls which contradicts the negative effect shown here, citing turbulence and diminished driver reaction time as possible explanations for this effect (Baudvin 1997; Massemin and Zorn 1998, Gagné et al. 2015). In my analysis, speed limit does not represent the greatest effect when compared to other predictors included in my model. In addition, a graph of predicted probability indicates that the range of speed limits where collisions are most likely occurs around 45mph, which is similar to previous results (53mph) (Gagné et al. 2015).

Consistent with previously published literature (Loos and Kerlinger 1993), most collisions in my dataset involved either first or second year birds, and slightly more females than males (Boves and Belthoff 2012). A spike in monthly intake values, though not significant in my analysis, occurs in late fall/early winter and in the spring which is consistent with a dispersal period for first-year owls, along with increased foraging for a pair with young in the nest (Loos and Kerlinger 1993). This trend has been observed in a variety of raptors, both diurnal and nocturnal, where inexperienced first and second-year birds are at higher risk of road mortality simply because their increased distance traveled while dispersing to new territories causes them to cross more roadways (Loos and Kerlinger 1993; Massemin and Zorn 1998). The effect of year, though significant in this analysis, is likely a factor of increased annual intake at the Carolina Raptor Center, not an effect of year on collision risk. The CRC started in the mid 1970s in the basement of then University of North Carolina at Charlotte Biology building. Its location, size, staff and the scope of its outreach and ability to treat and release injured raptors, as well as programs focusing on education and outreach, have gradually increased over time. Annual intake numbers have also gradually increased over time, presumably at least in part due to an increase in public awareness of the facility in addition to the ever-increasing road network. For example, the CRC admitted 88 birds in 1981, rising to over 1000 in 2012 (carolinaraptorcenter.org).

This study is the first of its kind to investigate the effect of road verge vegetation on the occurrence of vehicle collisions involving the Barred Owl. It is clear that road verge vegetation is an important predictor of collision risk. Although my data did not adequately capture the use of roadside perches by foraging owls, it did show a clear positive effect of complex vegetation. I suggest that mitigation efforts focus on the elimination of complex road verge vegetation in the form of shrubs, brush and tall grass that would attract small birds and mammals to roadsides. Other research has noted similar trends in wildlife-vehicle collisions and have called for similar strategies to mitigate road mortality (Orlowski 2008; Silva et al. 2012). The management of road verges represents a practical solution to mitigating the occurrence of owl-vehicle collisions.

Although I found a positive effect of habitat suitability, which is similar to the results found by Gagné et al. (2015), I found no effect of road width, and a negative effect of speed limit, both of which contradict results found in previous research. One thing to note is that the results of the previous study were based on collision data from an older year range; namely from 1982-2009, where this study used data in the range 1996-2019. Given that the road network and population density in and around Charlotte, NC is constantly increasing, it seems likely to suspect that the relative effect of road features on collision risk for owls will change in time. Therefore, it is difficult to explain the difference in results between these two analyses. It is likely that changes in the landscape over time are responsible.

A limitation of this study should be noted. First, the intake records provided by the Carolina Raptor Center (CRC) are publicly sourced, meaning that with very few exceptions, all birds are found and are brought to the center by the public. This means that a passerby or driver must possess the ability to capture, restrain and transport an injured bird, knowledge of the CRCs mission and location, and finally (and possibly most importantly), the willingness to intervene on behalf of the injured bird. This study does not examine the percentage of the general population in and around Charlotte, NC that would care to or be able to rescue and transport an injured owl; nor does it account for the number of birds not included in this sample because they were obviously deceased, escaped capture and resulting rescue, or were injured either along roadways where stopping to assist proved too risky given traffic or location, or where the driver or passerby lacked the ability or willingness to intervene.

Conclusion

Barred owl-vehicle collisions in the Charlotte Metropolitan Region are more likely on roads with a higher concentration of traffic that have more prey cover along their verges, and are surrounded by good owl habitat. Collisions were also more likely along roads with low or moderate speed limits and with a lower percentage of road verge forest cover.

My results suggest that future research on this topic should focus on gaining a better understanding of the effect of traffic concentration and road verge perch availability on collision risk for Barred Owls. My data analyzed the impact of roadside forest cover on collisions without accounting for man-made perches used by foraging owls or identifying a minimum number of mature trees required to attract an owl. I suggest that future research investigate the use of perches along roadsides by Barred Owls in an urban landscape with the ultimate goal of determining a preference of perches by owls and a possible impact of man-made structures on road mortality. In addition, separating traffic volume data to account for hourly rates that would reflect the true impact of traffic volume on a nocturnal species.

As the global network of roads continues to expand, our understanding of the effect of traffic on wildlife, and particularly on apex predators like birds of prey, serves to decrease the negative impact of human activity on our natural world by informing road verge management and transportation planning.

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TABLES

Table 2.1: Results of a logistic regression model of the risk of a Barred Owl (Strix varia)-vehicle collision in the Charlotte, North Carolina Metropolitan Region from 1996 to 2019.

Variable	**Estimate**	**Standard error**	**p-value**	
Road width	-0.00655	0.0122	0.591	
Speed limit	-0.0428	0.0114	1.63E-04	***
Traffic volume/ road width	9.93E-04	2.23E-04	8.74E-06	***
Year	0.0797	0.0177	7.00E-06	***
Month	0.0072	0.0263	0.784	
Habitat suitability	3.48	0.408	<2E-16	***
Perch availability	-4.26	0.733	6.32E-09	***
Prey cover (high)	2.15	0.401	8.28E-08	***
Prey cover (medium)	1.62	0.258	3.30E-10	***

Table 2.2: Summary statistics for continuous collision and non-collision (used as pseudo absences) variables used in logistic regression analysis of factors influencing Barred Owl (*Strix varia*)-vehicle collision risk in the Charlotte, North Carolina Metropolitan Region. Collision data derived from intake records taken from the Carolina Raptor Center, Huntersville, North Carolina, USA. Non-collision data from random points

Variable	**Source**	**Obs.**	**Min.**	**1st Qtr.**	**Median**	**Mean**	**3nd Qtr.**	**Max.**
Road Width:	Collision	271	3.3	6.5	8.2	12.8	14.5	64.6
	Non-collision	271	4	6.7	8.2	12.94	12.3	115.1
Traffic Vol./Road Width:	Collision	271	10.2	92.6	565.22	762.1	1221.9	6385.5
	Non-collision	271	11.94	120.48	169.49	481.37	619.12	4622.36
Speed Limit:	Collision	271	25	35	35	40	45	70
	Non-collision	271	20	25	36	37.55	45	65
Month:	Collision	271	1	3	7	6.838	11	12
	Non-collision	271	1	3	6	6.52	11	12
Year:	Collision	271	1996	2010	2013	2012	2016	2019
	Non-collision	271	1996	2004	2011	2010	2015	2019
Habitat Suitability:	Collision	271	0.17	1.04	1.69	1.63	2.19	3
	Non-collision	271	0	0.39	0.75	0.82	1.29	1.92
Perch Availability:	Collision	271	0	0	0.053	0.15	0.25	1
	Non-collision	271	0	0	0.013	0.12	0.19	0.82

Table 2.3: Total values for collision and non-collision prey cover categories used in logistic regression analysis of factors influencing Barred Owl (*Strix varia*)-vehicle collision risk in the Charlotte, North Carolina Metropolitan Region. Data derived from intake records taken from the Carolina Raptor Center, Huntersville, North Carolina, USA. Non-collision data from random points

Prey Cover	Collision	Non-collision
Low	50	197
Medium	117	14
High	104	60

FIGURES

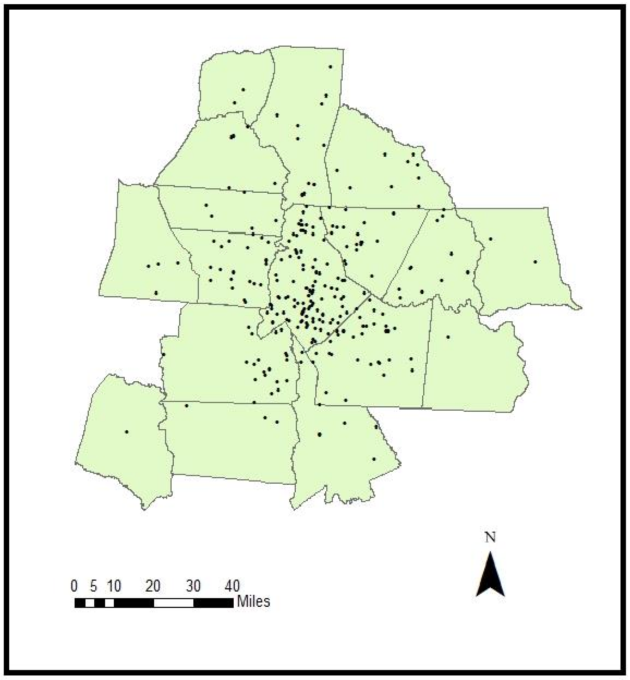

Figure 2.1: Barred Owl (*Strix* varia)-vehicle collisions in the Charlotte Metropolitan Region (1996-2019) in North Carolina, USA

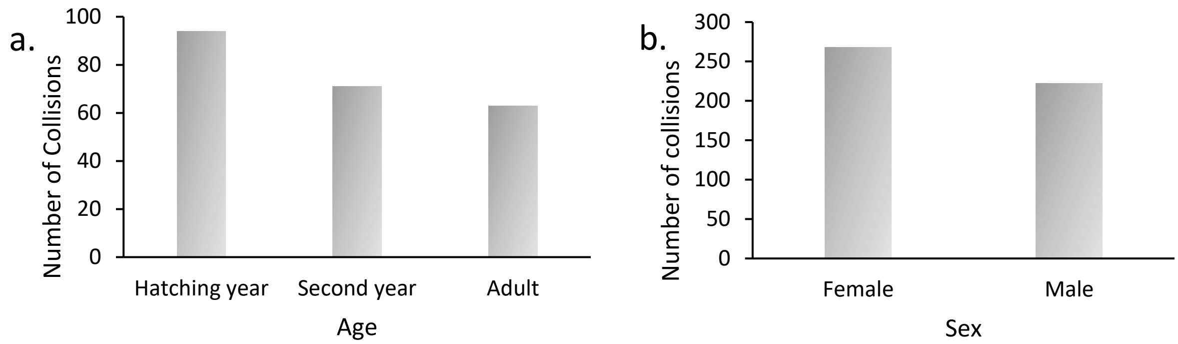

Figure 2.2: The total number of Barred Owl (*Strix varia*)-vehicle collisions of varying age (a) and sex (b) admitted to the Carolina Raptor Center in Huntersville, North Carolina, USA between 1996 and 2019. Panel a represents geo-coded collision locations used in the analysis. Panel b represents all Barred Owl collisions in the study area with or without locational information due to insufficient reported sex in geocoded points for review.

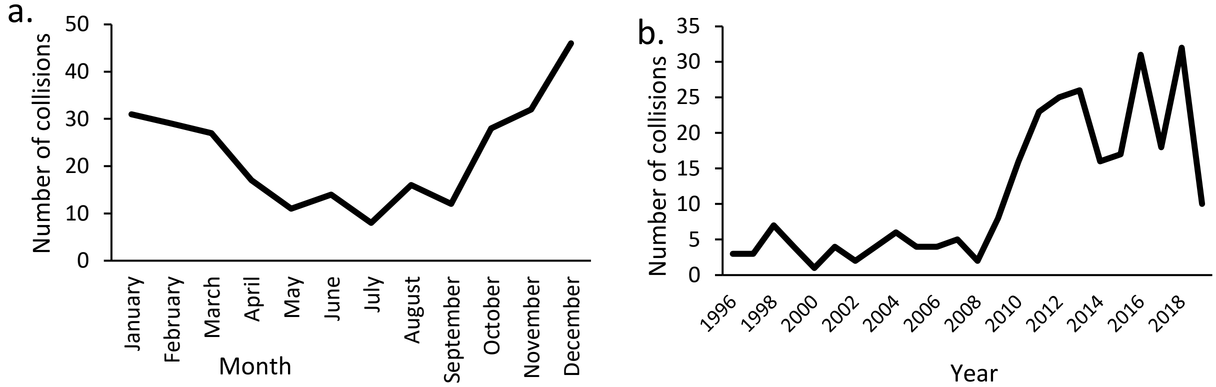

Figure 2.3: The total number of Barred Owl (*Strix varia*)-vehicle collisions for each month (a) and year (b) admitted to the Carolina Raptor Center in Huntersville, North Carolina, USA between 1996 and 2019.

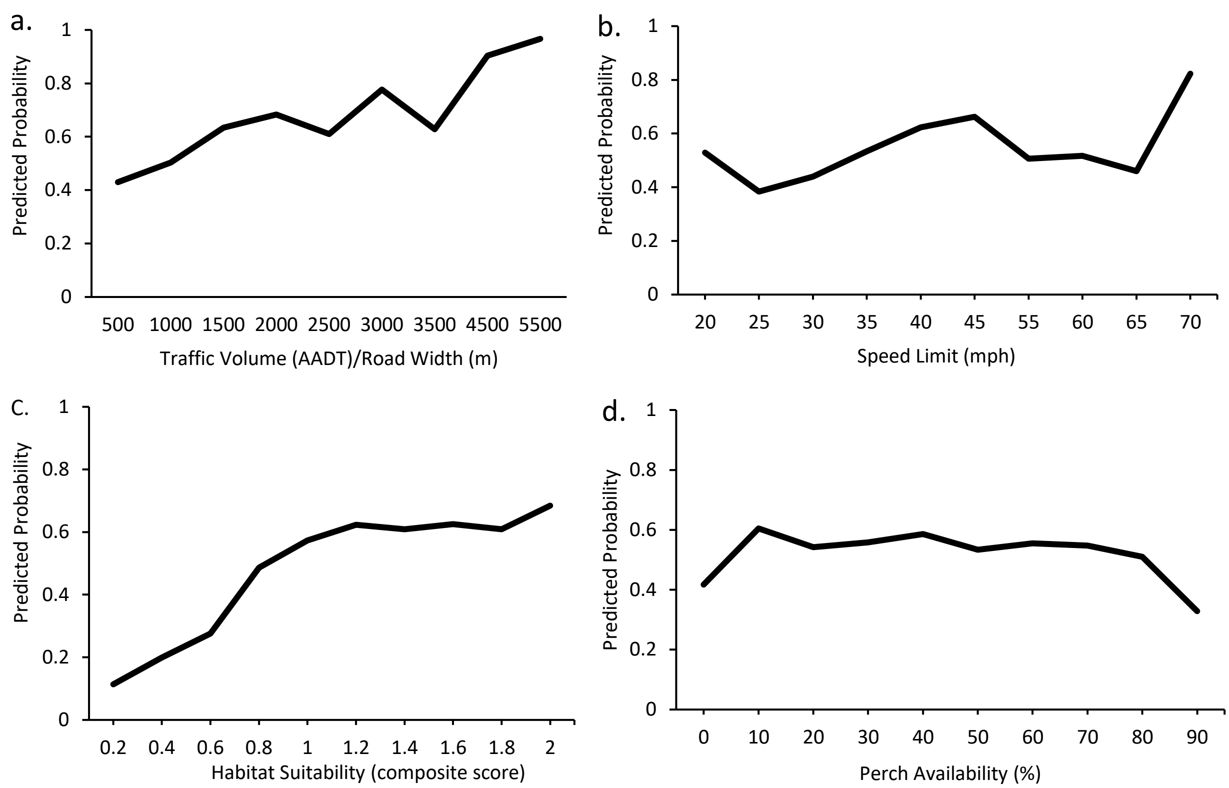

Figure 2.4: Predicted probability for traffic volume/road width (a), speed limit (b), habitat suitability (c) and perch availability (d) based on results of a logistic regression analysis of Barred Owl-vehicle collision data taken from intake records at the Carolina Raptor Center in Huntersville, North Carolina, USA

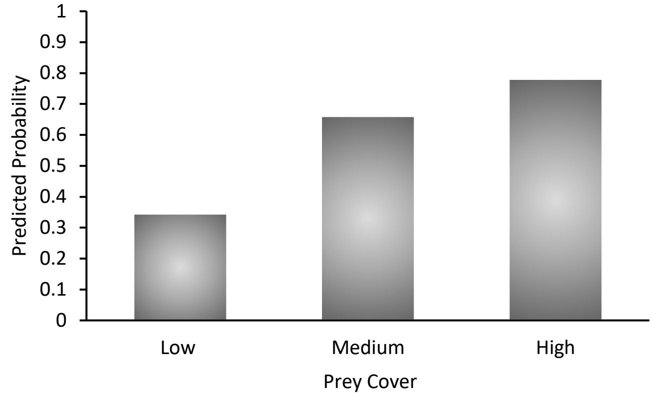

Figure 2.5: Predicted probability for prey cover based on results of a logistic regression analysis of Barred Owl-vehicle collision data taken from intake records at the Carolina Raptor Center in Huntersville, North Carolina, USA

Chapter 3: The Likelihood of Raptor-Vehicle Collisions in Central Florida, USA is Influenced by Roadway, Land Use and Road Verge Characteristics

3.1 Introduction

Although vehicle collisions are not always a primary source of anthropogenic mortality for diurnal raptors (Hager 2009), road mortality is still noted as a significant threat for Falconiformes (Thompson et al. 2013). Roads exist as distinct ecological systems, fragmenting habitats and creating distinct barriers. In many cases, roadways attract both predator and prey, where attractants (e.g. spilled grain or trash/wrappers discarded from passing vehicles) bring smaller animals that become prey for larger birds, such as raptors (Erritzoe et al. 2003). Vehicle collisions have been noted as an important factor in mortality for birds of prey, especially in urban areas: a review of raptor mortality from anthropogenic sources indicated that while electrocution was more prevalent than vehicle collisions across diurnal species of the order Falconiformes, road mortality remained a leading factor for nocturnal raptors, or Strigiformes (Hager 2009).

The increased prevalence of road mortality in Strigiformes has led to a corresponding focus in research on road effects for nocturnal raptor species. Several studies dedicated to Barn Owl (*Tyyo alba*) road effects in both North America and Europe have investigated the impact of road verge characteristics and surrounding habitat and roadway features on the prevalence of mortality (Boves and Belthoff 2012; de Jong et al. 2018; Arnold et al. 2019). Mitigation of road effects for Barn Owls has focused on modifying road verge vegetation to cause birds to fly higher when crossing roads, thus avoiding collision with motor vehicles (Massemin and Zorn 1998). For other raptors with differing species traits, mitigation may take an entirely different form. In fact, literature examining road effects and vehicle collisions for raptors has spanned a variety of nocturnal species (Loos and Kerlinger 1993; Gomes et al. 2008; Grilo et al. 2014; van der Horst et al. 2019). Unfortunately, similar research for diurnal raptors is less prevalent and typically focuses on foraging behavior associated with road-killed animals (Dean and Milton 2003; Lambertucci et al. 2009; Vidal- Vallés et al. 2018), not the related risk of vehicle collisions or the mitigation of collision risk.

To date, no study has investigated the comparative effects of road characteristics on vehicle collisions using both nocturnal and diurnal raptors. My objective is to analyze vehicle collision records for four raptor species and compare the magnitude of effect of important predictors on collision likelihood based on my hypotheses, described below. Using rehabilitation intake records from the Audubon Center for Birds of Prey (ACBP) in Maitland, FL, I conducted this comparison using two diurnal raptors, the Bald Eagle (*Haliaeetus leucocephalus*) and Red-Shouldered Hawk (*Buteo lineatus*), and two nocturnal species, the Barred Owl (*Strix varia*) and Eastern Screech Owl (*Megascops asio*). The ACBP treats more than 800 sick or injured raptors each year, especially in the spring when displaced nestlings frequent the center. Although the Audubon Center admits a variety of raptors due to injury and illness, these four species represent the most commonly admitted diurnal and nocturnal raptors and the only species with sufficient data for analysis. Each of these raptors is also known to employ a foraging style that utilizes forest cover and perches instead of solely open areas (Dykstra et al. 2012; Rullman and Marzluff 2014). With the exception of the Bald Eagle, each species included in this study prefers woodland cover with suitable perches for foraging (Dykstra et al. 2012) and consume small vertebrates as a primary prey source (Strobel and Boal 2010; Rullman and Marzluff 2014). The Bald Eagle is a more opportunistic predator that obtains food either by taking live prey or scavenging, foraging either on the wing or from perches. In many parts of its range, the Bald Eagle hunts over water for fish and aquatic birds (Mersmann 1989). The general similarity in habitat preference makes this group a suitable mix to facilitate a comparison between diurnal and nocturnal raptor vehicle collision risk.

All four raptors used in this study are common species found in North America, and in many cases have been observed nesting and foraging in proximity to human activity (Stout et al. 2006; Dykstra et al. 2012). In some cases, the Red-Tailed Hawk even appears to prefer nesting on man-made structures (Stout et al. 2006). In spite of a recognized negative impact of roads on diurnal raptors (Thompson et al. 2013), road effects and collision risk have not been examined in detail for either diurnal species. Morrison et al. (2016) suggests a negative impact of vehicle collisions on reproductive success for Red-Tailed Hawks in Hartford, CT; however, this statement has not been further investigated. Road effects and vehicle collision mitigation have been studied to a greater extent for nocturnal raptors, including the two species used in this study. Gagné, et al. (2015) found an effect of vehicle speed, road width and surrounding habitat suitability on the likelihood of a Barred Owl-vehicle collisions in Charlotte, NC. A higher number of Eastern Screech Owls were killed on roads in Southern NJ in the winter months, suggesting that dispersal may influence collision risk (Loos and Kerlinger 1993).

I hypothesize two mechanisms responsible for a variation in road effects. First, it appears that diurnality/nocturnality is the most important explanation of divergence in the diets of hawks and owls (Marti and Kochert 1995). Although a distinction has been observed at a species level, I argue that the behavior of small vertebrates may further contribute to observed differences in raptors, especially along roadways. Prey selection for the raptor species included in this study includes small vertebrates consisting mostly of small mammals and/or passerine songbirds in urban/suburban areas (Roth and Lima 2003; Hindmarch and Elliott 2015). Selection of avian prey has been shown to be high in urban/suburban areas (Roth and Lima 2003), and in some cases has been found to be significantly higher when compared to surrounding rural habitat (Zalewski 1994; Cauble 2008; Mrykalo et al. 2009). As a result, the relative accessibility of songbirds between night and day is likely to create an effect. Small avian species are attracted to shrubs, brush, or other suitable prey cover (Orlowski 2008), especially at night, when most birds seek cover in dense vegetation. During the daytime, the same species may be found in a more varied habitat, including both high and low visibility cover. As a result, I expect to find a greater effect of prey accessibility along road verges for nocturnal species, where collision risk is higher in road verge segments with a high percentage of adequate prey cover consisting of shrubs, hedges or tall grasses.

To my knowledge, this is also the first investigation into road and habitat characteristics that influence vehicle collision risk for both the Bald Eagle and Red-Shouldered Hawk. I hypothesize that temporal variation in traffic volume is a second mechanism explaining the differential effects of factors underlying collision risk for nocturnal and diurnal raptor species. Traffic volume is at its highest during the day in most locations, especially along major roads in and around urban areas where commuters and transporters are traveling into and out of the city. Although traffic load is thought to have an overall negative ecological impact on wildlife. (Donazar et al. 2018, Arnold et al. 2019), the avoidance of higher-traffic roads that I expect to see here may actually have a positive impact on diurnal raptors by reducing the risk of road mortality (Bautista et al. 2004). While I expect that traffic volume will be insignificant for nocturnal species as shown previously (Gagné, et al. 2015), the same variable will have a greater inverse effect for diurnal species.

3.2 Methods

Study Area

This study is focused on Florida, USA, with most data points surrounding the Orlando metropolitan area. The city of Orlando is the county seat of Orange County in Florida, and along with the surrounding metropolitan area hosts a population of more than 2.5 million, making it the third most populous area in the state. The city has experienced an increase in growth since 2010 and ranked in the top 20 in the US for growth based on Census Bureau data for 2014 and 2015 (Brinkmann 2016).

Data: Raptors in Central Florida

Data include archived intake files from the ACBP, located in Maitland, FL, just outside of Orlando. For the purpose of this study, I used all available vehicle collision records, which spanned from 2000-2019, with a focus on the two most common diurnal and nocturnal species that also share a preference for forest cover: Red-Tailed Hawk (*Buteo jamaicensis*), Red-Shouldered Hawk (*Buteo lineatus*), and Barred Owl (*Strix varia*), Eastern Screech owl (*Megascops asio*). There were a total of 1063 collisions across these four species with sufficient data for analysis (Table 3.1). I used Google Earth (Google Inc. 2019) to assign spatial coordinates for each collision location (Fig. 3.1). An equal number of pseudo absences for all collision sites for each species were assigned using ArcGIS 10.8.2 (ESRI 2022). Non-collision sites were assigned at random and were based on the total number of collisions per county for each species.

Explanatory Variables

I included traffic volume, speed limit, and road width in this analysis. Traffic volume and speed limit were obtained from the Florida Department of Transportation (DOT) Traffic Data &

Analytics Office (TDA) (https://tdaappsprod.dot.state.fl.us/fto/).The TDA is updated annually, so traffic volume and speed limit both reflect data for the corresponding year of each collision/non-collision. For roads without traffic volume or speed limit data, I assigned a value based on the closest road segment with similar characteristics and a known value. Nearly all roadways lacking speed limit data were residential roads and were assigned a speed limit of 25mph.

Due to the number of collisions and non-collisions included in this study, road width is represented here as *lane count*, a value that is available as "number of lanes," which is available through the Florida Department of Transportation (DOT) Open Data Hub (https://gis-fdot.opendata.arcgis.com/). The number of through lanes, or *lane count*, is defined as the number of through lanes on one side of a given roadway. For example, a local residential street would typically have a lane count of 1.

To account for annual and seasonal variation in the data, I included year and month for all collision locations and assigned months and years at random to non-collision sites. All species typically raise young during the spring or early summer months, so seasonal variation in collision likelihood due to dispersal and foraging is likely to be observed (Tapia and Zuberogoitia 2018).

Habitat suitability was included at an estimated nesting territory range using the Cornell Ornithology Lab's Birds of the World data for each species (https://birdsoftheworld.org). This website includes comprehensive information focusing on the biology of the world's birds and includes references to the literature on nesting and nesting territories. I used average nesting territory sizes for each species reported on the Birds of the World website and calculated a radius then used to determine habitat suitability for each species: Bald Eagle (950m), Barred Owl (850m), Eastern Screech Owl (500m) and Red-Shouldered Hawk (600m). Habitat suitability values were determined using the National Land Cover Database (NLCD). Using NLCD land use classes, I assigned Wetland, Forest, Shrub/Scrub a score of 2; Developed Open Space, Low-Intensity Residential, Grassland/Herbaceous, Pasture/Hay, Cultivated or Row Crops, Barren or Bare Rock/Sand/Clay and Open Water a score of 1, and the Developed High-Intensity, High-Intensity Residential, and Commercial/Industrial/Transportation classes a score of 0. The score for each collision was determined within a circular landscape using the radius reflecting average nesting territory size for each species and was weighted by the proportion each NCLD class. I used NCLD year closest to each collision/non-collision from the years 2001, 2008, 2013, and 2016.

Road verge habitat was included in my analysis to estimate both perch availability and the visibility of road verge vegetation, or prey cover. Perch availability was determined using the percent of a 100m road segment on each side of the collision/non-collision passing through canopy cover using forest cover classes included in National Land Cover Database (NCLD) data for the closest year to 2001, 2008, 2011, 2013 and 2016. Forest cover classes were used to represent mature trees used as preferred perches (Reinhert 1984).

I evaluated road verge prey cover by estimating the presence of complex vegetation in the form of brush, shrubs and tall grasses. I used a detailed land cover/land use file available from the Florida Department of Environmental Protection's Geospatial Open Data site (https://geodata.dep.state.fl.us/datasets/2f0e5f9a180a412fbd77dc5628f28de3_3/about). The land use shapefile available at this website provides more detailed information, especially with regard to vegetation type and is of a higher resolution than the National Land Cover Database (NCLD) file. Using a distance of 50m along the road on each side of the collision and including a distance of 15m from the roadway edge, I calculated the percentage of area represented by land cover types associated with prey cover including mixed shrubs, shrub and brushland, and upland shrub and brushland. Prey cover was termed either low, medium, or high based on the overall percentage of shrubs, brush and other complex vegetation.

Analysis

I identified the factors underlying collision risk for each species using logistic regression in R 4.2.2 (R Core Team 2022). I modeled the effect of road width, speed limit, traffic volume, habitat suitability, month, year, perch availability and prey cover on the likelihood of a raptor-vehicle collision for each of four species included in this study: Barred Owl, Bald Eagle, Eastern Screech Owl, and Red-Shouldered Hawk. Pairwise comparisons among variables for all models were tested and correlation was found to be low or moderate ($|r| \leq 0.65$). I tested model fit using the Hosmer and Lemeshow goodness of fit test (Hosmer and Lemeshow 2000). Support or lack thereof for my hypotheses concerning roadside prey availability and traffic volume was determined by comparing the relative importance and effects sizes of predictors in nocturnal and diurnal species models.

3.4 Results

For the Bald Eagle, Barred Owl and Red-Shouldered Hawk, more males were admitted to the center than females in the year range represented here (Fig. 3.2). For the Eastern Screech Owl, slightly more females were admitted (Fig. 3.2). For all species, more adults were brought to the ACBP than juveniles (Fig. 3.3). With the exception of the Bald Eagle, the majority of collisions occur in late spring, summer and early fall for all species (Fig. 3.4). The majority of Bald Eagle-vehicle collisions occurred between October and March (Fig. 3.4). There is an overall increasing trend in the number of vehicle collisions per year for all species with the exception of the Eastern Screech Owl, for which the number of collisions decreased (Fig. 3.5).

I observed a significant negative effect of habitat suitability and significant positive effects of road width, speed limit traffic volume, prey cover and year for the Bald Eagle (Hosmer and Lemeshow $X^2 = 3.57$, $p = 0.89$; pseudo $R^2 = 0.37$) (Table 3.2). Collision risk was greater for roads with at least two lanes (Fig. 3.6a). Roads with an Average Annual Daily Traffic count (AADT) above 10000 posed the greatest risk (Fig. 3.6b). Roadways with a speed limit at or above 45mph were of greater risk (Fig. 3.6c). Habitat suitability had a negative effect on vehicle collision risk for Bald Eagles: roads surrounded by more developed land use posed a greater hazard (Fig. 3.6d). Finally, collision risk was higher along roads where verges had a greater amount of prey cover (Fig. 3.7).

Habitat suitability, traffic volume and year each had a significant positive effect on vehicle-collision risk for the Barred Owl (Hosmer and Lemeshow $X^2 = 23.68$, $p = 0.0026$; pseudo $R^2 = 0.16$) (Table 3.3). Collisions were most likely along roads with Average Annual Daily Traffic counts (AADT) of at least 15000 (Fig. 3.8a). Owl-vehicle collisions were also most likely along roads surrounded by suitable habitat (Fig. 3.8b).

My results show a significant positive effect of traffic volume habitat suitability and prey cover on collision risk for the Eastern Screech Owl, and a negative effect of year, month and speed limit (Hosmer and Lemeshow $X^2 = 10.23$, $p = 0.25$; pseudo $R^2 = 0.15$) (Table 3.4). The greatest effect of traffic volume is present along roads with a very high Average Annual Daily Traffic count (AADT) averaging 100,000 (Fig. 3.9a). The greatest risk for the Eastern Screech Owl is present along roads with lower speed limits (15-20mph) (Fig. 3.9b). Similar to the Barred Owl, Screech Owl-vehicle collisions were more likely along roads surrounded by suitable habitat (Fig. 3.9c). Finally, collision risk was also higher along roads where verges contained a medium or high percentage of prey cover (Fig. 3.1).

A significant positive effect of year, habitat suitability, and traffic volume on vehicle collision risk was observed for the Red-Shouldered Hawk (Hosmer and Lemeshow $X^2 = 16.25$, $p = 0.039$; pseudo $R^2 = 0.19$) (Table 3.5). Similar to the Barred Owl and Eastern Screech Owl, Red-Shouldered Hawk-vehicle collisions are more likely along roads with a high Average Annual Daily Traffic count (AADT) totaling 15,000 or higher (Fig. 3.11a). Collisions are also more likely where surrounding habitat is highly suitable (Fig. 3.11b).

A summary table of results (Table 3.6) and summary statistics are included in the appendix. A comparison of values between collision and non-collision data coincide with statistical results for all significant continuous variables (Tables 3.7, 3.8, 3.9, 3.10, 3.11, 3.12, 3.13, 3.14). Although a marked difference in collision and non-collision prey cover totals can be observed for Both the Barred Owl and Red-Shouldered Hawk (Tables 3.10 and 3.14, respectively, this difference was not found to be significant.

3.4 Discussion

My data show significant effects for both road and habitat predictors for each of the four raptor species included in this study. Traffic volume and habitat suitability had a significant effect on collision risk for all four species. An effect of speed limit and road verge prey cover was observed for the Bald Eagle and Eastern Screech Owl, and a significant effect of road width was observed for the Bald Eagle (Table 3.6). I expected to find a greater effect of road verge vegetation on collision risk for nocturnal raptors and a greater effect of traffic volume for diurnal raptors. My results are not consistent with my hypotheses in that no observable trends can be determined between nocturnal and diurnal species. I suggest that this study repeated with more diurnal and nocturnal species represented would potentially reveal a notable trend between the two.

Although for all species, more males were admitted to the Audubon center than females, more female Eastern Screech Owls were admitted. It is unclear why vehicle collisions affected more female screech owls. Although the species is considered a resident within its range, an increase in dispersal distance by females has been observed (Gelbach 1994). It is possible that dispersing females may encounter a greater number of roads simply by way of an increase in distance traveled.

Surprisingly, for each species, more adults were brought to the ACBP than juveniles. This conflicts with data for Chapter 2, as well as the commonly accepted trend in road mortality for raptors. Historically, more juvenile raptors were hit by cars than adults, as dispersal and inexperience both lent themselves to an increase in risk for younger birds (Loos and Kerlinger 1993). More recent research, however, has suggested a different trend in age and collision/road mortality risk, where more adults are hit by vehicles than juveniles (Mariacher et al. 2016, Hernandez et al. 2018). It is likely that additional variables are at play, at least in some cases to create this shift in trends.

With the exception of the Bald Eagle, the majority of collisions occurred in late spring and early summer. Most Bald Eagle-vehicle collisions occurred in the winter months in Florida. The Bald Eagle is the only true migrant among the species described in this study. Although much of the Southern population does not migrate (Broley 1947), those that do, mostly including immature birds traveling north in the spring, will spend the winter months in Florida (Mojica et al. 2008). An increase in the winter population of Bald Eagles could explain the increase in vehicle collisions in the winter months.

For the Bald Eagle, Barred Owl, and Red-Shouldered Hawk, there is a general increasing trend in the number of vehicle collisions resulting in birds admitted to the Audubon Center for

Birds of Prey (ACBP) per year (Fig. 3.5). This trend is likely a result of an increase in outreach and education on the part of the ACBP and is likely not due to an actual effect of year on collision risk. For the Eastern Screech Owl, the opposite trend is evident in this same figure. What is interesting is that the decreasing trend in intake has continued over time, and the percentage of Screech Owls brought to the ACBP annually was at its lowest in 2019. The most likely explanation for the decline in Screech Owl-vehicle collision numbers lies in its biology, habitat preference, and the availability of suitable habitat as Florida's population density continues to increase at a notable rate (Brinkman 2016). The Eastern Screech Owl prefers to forage using subcanopy perches and often preys on invertebrates, including crayfish and insects (Gehlbach 1994). It is possible that continued urbanization in Florida has affected the availability of suitable foraging habitat and/or prey for the Screech Owl.

My results show a positive effect of traffic volume, speed limit, road width, year and prey cover, and a negative effect of habitat suitability on collision risk for the Bald Eagle. Bald Eagle-vehicle collisions were most likely along roadways with verges containing a high percentage of prey cover and on roads with higher daily traffic counts; however, several of my results differ from those for the other three species included here, including a strong positive effect of speed limit and a significant positive effect of road width that is not observed for any other species. Bald Eagles are the only true migrants included here, as well as being the only species of the four that regularly feeds on fish or carrion (Todd et al. 1982). Unlike the other raptors I discuss here, collision risk for Bald Eagles is higher in areas where land-use scores are lower. This species is a noted scavenger (Todd et al. 1982) and will make use of carrion along roadways and landfill trash. Although I did not analyze this trend, I observed a higher number of Bald Eagle-vehicle collisions along roadways near landfills when compared to other species used in this study.

Landfills are typically open areas without significant tree cover. A strong positive effect of speed limit and road width is unique to the Bald Eagle. It is possible that scavenging behavior leads this species to forage along wider roads or roads with higher speed limits. DeVault et al. (2014) found that flight initiation in Turkey Vultures (*Cathartes aura*) was diminished as vehicle speeds exceeded 55mph. Scavenging behavior is vastly different than the sit-and-wait foraging method almost exclusively employed by the remaining species in this study in that it requires the forager to remain on the ground in or beside the road. It is possible that the nature of this behavior leads to an increase in collision risk along roads with higher speed limits.

For the Barred Owl, a notable positive effect of habitat suitability score is evident, indicating that collision risk is higher where roads pass through forested areas. The Barred Owl is almost exclusively a "sit-and-wait" predator, meaning he makes less use of open areas while foraging and tends to select a perch from which to scan for prey below. In addition, a positive effect of traffic volume is observed here, suggesting overall that the highest risk for the Barred Owl in Florida is along busy roadways passing through wooded areas.

For the Eastern Screech Owl, I found a negative effect of speed limit, year, month and perch availability, and a positive effect of traffic volume, habitat suitability and prey cover. A negative effect of speed limit suggests that most Screech Owl- vehicle collisions occur along residential and side roads, where speed limits are typically 25mph or below. The Screech Owl is known to forage in suburban landscapes, including on lawns and patios or along lighted streets (Gehlbach 1994). Its preference for residential foraging grounds could explain the increase in vehicle collisions in low speed limit areas. I observed a negative effect of perch availability and a positive effect of habitat suitability, which suggests that although roads surrounded by suitable habitat create a higher risk for this species, the presence of tree cover along verges does not. This species hunts in a sit-and-wait fashion similar to the Barred Owl, which could explain their preference for forested habitat; however, they are known to prefer lower perches when compared to other raptor species, which may make tree cover as defined in this study not preferable (Gelbach 1994).

As with the Barred Owl, I observed a positive effect of year, traffic volume and habitat suitability for the Red-Shouldered Hawk. The Barred Owl and Red-Shouldered Hawk have long been considered to share the same ecological niche of prey preference and foraging tactics, separated by nocturnal and diurnal activity, respectively (Dykstra et al. 2020). My results support a preference for forested habitat, along with an increasing risk of vehicle collision along roadways with higher traffic volume. It is unclear which species traits could more definitively explain the similarities in my results between these two species.

Conclusion

This is the first study to characterize road effects for both nocturnal and diurnal birds of prey. I predicted that my results would reveal a differential effect of road verge vegetation and traffic volume between nocturnal and diurnal raptors. My results did not support my hypotheses; however, I did observe similar results for the Barred Owl and Red-Shouldered Hawk. Like the Great-Horned Owl (*Bubo virginianus*) and Red-Tailed Hawk (*Buteo jamaicensis*), the Barred Owl and Red-Shouldered Hawk have long been considered to be ecological counterparts (Temple and Temple 1976, Springer and Kirkley 1978, Dykstra et al. 2012). Historically, it has been assumed that Falconiformes and Strigiformes can exist as nocturnal/diurnal counterparts in a similar ecological niche that differs primarily by time of activity (Springer and Kirkley 1978). Although in the case of raptors, time of day has historically been considered to be the least influential dimension separating the two groups (Jaksić 1982), my results suggest that species sharing a similar ecological niche may be subject to the same drivers affecting vehicle collision risk. It suggest that this study should be repeated both in another location and with the Red-Tailed Hawk and Great Horned Owl to examine a potential similarity in vehicle collision risk between species where time of activity is the most obvious ecological difference.

This study is also the first investigate the effects of road verge vegetation on collision risk for raptors. My results show a significant positive effect of road verge prey cover on collision risk for both the Bald Eagle and Eastern Screech Owl. I did not observe an effect of prey cover for the Barred Owl or Red-Shouldered Hawk. I did not observe an effect of perch availability for any of the species included in the study, my analysis did not account for power lines, rooftops, fencing, road signs and other potential man-made structures that could be used by raptors. I recommend that further research focus on the use of man-made perches by foraging raptors and their possible effect on vehicle collision.

Although my results do not fully support a strong effect of available perches and prey cover on collision risk, further research into the impact of road verge vegetation may prove useful in the mitigation of road mortality for raptors. Mitigation in the form of removing tall grass and shrubs proves far more feasible than redesigning landscapes or modifying structures already in place. Other studies have recognized the risk posed by roadside vegetation and have called for its removal as a means to mitigate wildlife road mortality (Orlowski 2008; Silva et al. 2012). Although these studies do not focus specifically on raptors, the modification of surrounding habitat may prove impossible.

3.5 References

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TABLES

Table 3.1: Total number of collisions used in this study for each of four raptor species: Bald Eagle (*Haliaeetus leucocephalus*) (BAEA), Barred Owl (*Strix varia*) (BDOW), Eastern Screech Owl (*Megascops asio*) (EASO), and Red-Shouldered Hawk (*Buteo lineatus*) (RSHA). Collision number based on available intake data from 2000-2019 taken from the Audubon Center for Birds of Prey in Maitland, FL, USA.

Species	Collision Number
BAEA	201
BDOW	394
EASO	214
RSHA	254

Table 3.2: Results of logistic regression analysis indicating the risk of a Bald Eagle (*Haliaeetus leucocephalus*)-vehicle collision in the Orlando, FL metropolitan area between 2000 and 2019. Data based on intake files from injured or deceased birds admitted to the Audubon Center for Birds of Prey in Maitland, FL.

Variable	**Estimate**	**Standard error**	**p-value**	
Road width	-1.14	0.288	7.56E-05	***
Speed limit	0.101	0.0143	1.95E-12	***
Traffic volume	2.84E-05	1.18E-05	0.0159	*
Year	0.0628	0.0248	0.0114	*
Month	-0.0482	0.0362	0.183	
Habitat suitability	-2.17	0.462	2.61E-06	***
Perch availability	8.99E-04	0.00826	0.913	
Prey cover (high)	2.64	0.542	1.07E-06	***
Prey cover (medium)	1.23	0.312	8.02E-05	***

Table 3.3: Results of logistic regression analysis indicating the risk of a Barred Owl (*Strix varia*)-vehicle collision in the Orlando, FL metropolitan area between 2000 and 2019. Data based on intake files from injured or deceased birds admitted to the Audubon Center for Birds of Prey in Maitland, FL.

Variable	**Estimate**	**Standard error**	**p-value**	
Road width	0.160	0.153	0.296	
Speed limit	-0.00755	0.0105	0.473	
Traffic volume	2.59E-05	8.49E-06	0.00227	**
Year	0.0435	0.0138	0.00163	**
Month	-0.0347	0.0262	0.185	
Habitat suitability	2.11	0.221	< 2E-16	***
Perch availability	0.00525	0.00558	0.347	
Prey cover (high)	0.120	0.355	0.736	
Prey cover (medium)	-0.105	0.195	0.591	

Table 3.4: Results of logistic regression analysis indicating the risk of an Eastern Screech Owl (*Megascops asio*)-vehicle collision in the Orlando, FL and surrounding area between 2000 and 2019. Data based on intake files from injured or deceased birds admitted to the Audubon Center for Birds of Prey in Maitland, FL.

Variable	**Estimate**	**Standard error**	**p-value**	
Road width	0.0502	0.230	0.827	
Speed limit	-0.0477	0.0167	0.00432	**
Traffic volume	4.55E-05	1.36E-05	8.15E-04	***
Year	-0.0809	0.0195	3.31E-05	***
Month	-0.0707	0.0320	0.0271	*
Habitat suitability	1.64	0.338	1.31E-06	***
Perch availability	-0.00980	0.00976	0.315	
Prey cover (high)	1.06	0.629	0.0918	
Prey cover (medium)	0.914	0.258	4.03E-04	***

Table 3.5: Results of logistic regression analysis indicating the risk of a Red-Shouldered Hawk (*Buteo lineatus*)-vehicle collision in the Orlando, FL metropolitan area between 2000 and 2019. Data based on intake files from injured or deceased birds admitted to the Audubon Center for Birds of Prey in Maitland, FL.

Variable	**Estimate**	**Standard error**	**p-value**	
Road width	-0.284	0.226	-0.208	
Speed limit	0.0106	0.0140	0.446	
Traffic volume	4.25E-05	1.04E-05	4.70E-05	***
Year	0.0924	0.0182	3.93E-07	***
Month	-0.0606	0.0311	0.0513	
Habitat suitability	1.97	0.339	6.64E-09	***
Perch availability	-0.0112	0.00834	0.180	
Prey cover (high)	0.635	0.520	0.222	
Prey cover (medium)	0.369	0.253	0.146	

Table 3.6: A compilation of results of a linear regression analysis of traffic, road verge and habitat characteristics on vehicle collision risk for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*) based on intake records from the Audubon Center for Birds of Prey in Maitland, FL, USA.

Species	**Road Width**	**Speed Limit**	**Traffic Volume**	**Habitat Suitability**	**Perch Availability**	**Prey Cover**
Bald Eagle	positive	positive	positive	negative	*no effect*	positive
Barred Owl	*no effect*	*no effect*	positive	positive	*no effect*	*no effect*
Eastern Screech Owl	*no effect*	negative	positive	positive	*no effect*	positive
Red-Shouldered Hawk	*no effect*	*no effect*	positive	positive	*no effect*	*no effect*

Table 3.7: Summary statistics for continuous collision and non-collision (used as pseudo absences) variables used in logistic regression analysis of factors influencing Bald Eagle (*Haliaeetus leucocephalus*)-vehicle collision risk in Florida, USA. Collision data derived from intake records taken from the Audubon Center for Birds of Prey, Maitland, FL, USA. Non-collisions appointed at random

Variable	Source	Obs.	Min.	1st Qtr.	Median	Mean	3rd Qtr.	Max.
Road Width:	Collision	201	1	1	2	1.78	2	6
	Non-collision	201	1	1	1	1.55	2	4
Traffic Volume:	Collision	201	50	2250	8900	22231	28000	143500
	Non-collision	201	50	250	850	6564	7800	80400
Speed Limit:	Collision	201	10	35	50	48.23	60	70
	Non-collision	201	15	25	25	31.39	35	70
Month:	Collision	201	1	2	5	6.21	10	12
	Non-collision	201	1	5	7	7	10	12
Year:	Collision	201	2000	2008	2012	2011	2015	2019
	Non-collision	201	2000	2004	2009	2009	2015	2019
Habitat Suitability:	Collision	201	0.011	0.41	0.7	0.66	0.94	1
	Non-collision	201	0.04	0.32	0.62	0.68	0.92	2
Perch Availability:	Collision	201	0	0.0015	0.009	0.027	0.03	0.2
	Non-collision	201	0	0.0027	0.014	0.042	0.047	0.52

Table 3.8: Total values for collision and non-collision prey cover categories used in logistic regression analysis of factors influencing Bald Eagle (*Haliaeetus leucocephalus*)-vehicle collision risk Florida, USA. Data derived from intake records taken from the Audubon Center for Birds of Prey, FL, USA. Non-collisions appointed at random

Prey Cover	**Collision**	**Non-collision**
Low	55	107
Medium	67	15
High	79	79

Table 3.9: Summary statistics for continuous collision and non-collision (used as pseudo absences) variables used in logistic regression analysis of factors influencing Barred Owl (*Strix varia*)-vehicle collision risk in Florida, USA. Collision data derived from intake records taken from the Audubon Center for Birds of Prey, Maitland, FL, USA. Non-collisions appointed at random

Variable	Source	Obs.	Min.	1st Qtr.	Median	Mean	3rd Qtr.	Max.
Road Width:	Collision	394	1	1	2	1.69	2	5
	Non-collision	394	1	1	1	1.59	2	4
Traffic Volume:	Collision	394	70	650	4150	11652	17925	160000
	Non-collision	394	50	250	1000	7528	8100	130000
Speed Limit:	Collision	394	5	25	35	35.93	45	70
	Non-collision	394	15	25	25	31.69	35	70
Month:	Collision	394	1	4	6	6.34	8	12
	Non-collision	394	1	4	7	6.83	10	12
Year:	Collision	394	2000	2006	2012	2011	2016	2019
	Non-collision	394	2000	2004	2010	2010	2015	2019
Habitat Suitability:	Collision	394	0.0013	0.72	1.01	0.98	1.27	1.96
	Non-collision	394	0	0.28	0.55	0.61	0.85	2
Perch Availability:	Collision	394	0	0.007	0.029	0.069	0.083	0.83
	Non-collision	394	0	0.0025	0.0012	0.042	0.04	0.53

Table 3.10: Total values for collision and non-collision prey cover categories used in logistic regression analysis of factors influencing Barred Owl (*Strix varia*)-vehicle collision risk Florida, USA. Data derived from intake records taken from the Audubon Center for Birds of Prey, FL, USA. Non-collisions appointed at random

Prey Cover	**Collision**	**Non-collision**
Low	98	127
Medium	87	30
High	209	237

Table 3.11 Summary statistics for continuous collision and non-collision (used as pseudo absences) variables used in logistic regression analysis of factors influencing Eastern Screech Owl (*Megascops asio*)-vehicle collision risk in Florida, USA. Collision data derived from intake records taken from the Audubon Center for Birds of Prey, Maitland, FL, USA. Non-collisions appointed at random.

Variable	Source	Obs.	Min.	1st Qtr.	Median	Mean	3rd Qtr.	Max.
Road Width:	Collision	214	1	1	1	1.51	2	4
	Non-collision	214	1	1	1	1.57	2	4
Traffic Volume:	Collision	214	100	250	1000	7849	8900	63000
	Non-collision	214	50	250	1000	6943	7800	80400
Speed Limit:	Collision	214	15	25	25	30.3	35	60
	Non-collision	214	15	25	25	31.19	35	70
Month:	Collision	214	1	4	6	6.11	9	12
	Non-collision	214	1	3.25	7	6.77	10	12
Year:	Collision	214	2000	2002	2005	2007	2011	2019
	Non-collision	214	2000	2004	2010	2010	2015	2019
Habitat Suitability:	Collision	214	0.0034	0.58	0.86	0.82	1	1.88
	Non-collision	214	0.034	0.3	0.51	0.59	0.79	2
Perch Availability:	Collision	214	0	0	0.0069	0.037	0.037	0.56
	Non-collision	214	0	0	0.0057	0.037	0.034	0.48

Table 3.12: Total values for collision and non-collision prey cover categories used in logistic regression analysis of factors influencing Eastern Screech Owl (*Megascops asio*)-vehicle collision risk Florida, USA. Data derived from intake records taken from the Audubon Center for Birds of Prey, FL, USA. Non-collisions appointed at random.

Prey Cover	Collision	Non-collision
Low	50	96
Medium	18	10
High	146	108

Table 3.13: Summary statistics for continuous collision and non-collision (used as pseudo absences) variables used in logistic regression analysis of factors influencing Red-Shouldered Hawk (*Buteo lineatus*)-vehicle collision risk in Florida, USA. Collision data derived from intake records taken from the Audubon Center for Birds of Prey, Maitland, FL, USA. Non-collisions appointed at random.

Variable	Source	Obs.	Min.	1st Qtr.	Median	Mean	3rd Qtr.	Max.
Road Width:	Collision	254	1	1	2	1.66	2	4
	Non-collision	254	1	1	2	1.61	2	4
Traffic Volume:	Collision	254	100	250	6050	14828	22875	131000
	Non-collision	254	50	250	1000	7837	7950	130000
Speed Limit:	Collision	254	20	25	35	37.13	45	70
	Non-collision	254	15	25	25	31.73	35	70
Month:	Collision	254	1	3	6	6.21	9	12
	Non-collision	254	1	4	7	6.85	10	12
Year:	Collision	254	2000	2008	2014	2012	2017	2019
	Non-collision	254	2000	2004	2010	2009	2015	2019
Habitat Suitability:	Collision	254	0.0016	0.66	0.97	0.95	1.17	1.87
	Non-collision	254	0.07	0.38	0.59	0.66	0.84	2
Perch Availability:	Collision	254	0	0.0018	0.015	0.06	0.064	0.79
	Non-collision	254	0	0.0008	0.012	0.045	0.045	0.53

Table 3.14: Total values for collision and non-collision prey cover categories used in logistic regression analysis of factors influencing Red-Shouldered Hawk (*Buteo lineatus*)-vehicle collision risk Florida, USA. Data derived from intake records taken from the Audubon Center for Birds of Prey, FL, USA. Non-collisions appointed at random

Prey Cover	Collision	Non-collision
Low	73	103
Medium	46	16
High	135	135

FIGURES

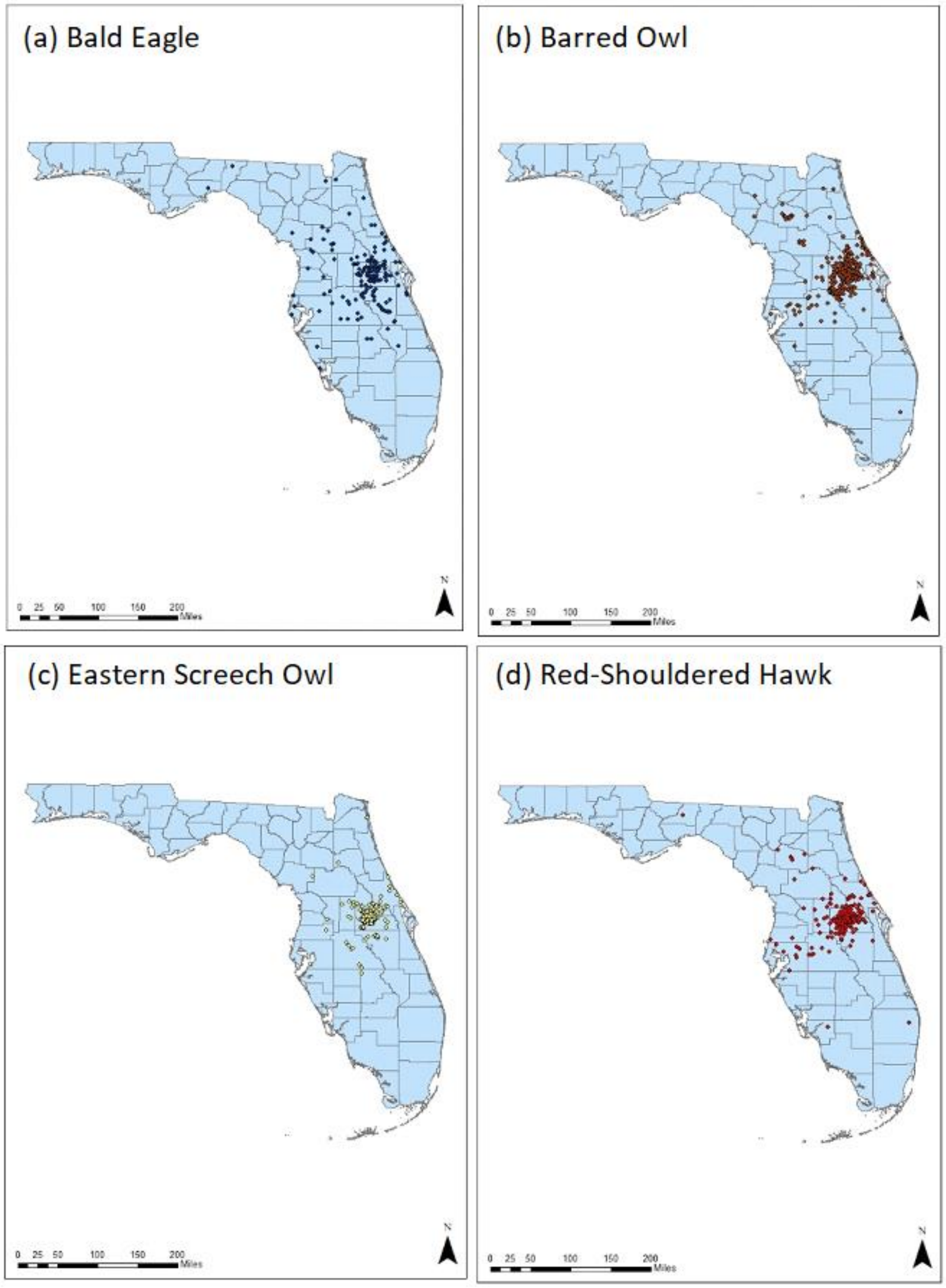

Figure 3.1: Collision locations for the Bald Eagle (*Haliaeetus leucocephalus*) (a), Barred Owl (*Strix varia*) (b), Eastern Screech Owl (*Megascops asio*) (c) and Red-Shouldered Hawk (*Buteo lineatus*) (d) in Florida based on data taken from the Audubon Center for Birds of Prey in Maitland, FL between 2000-2019.

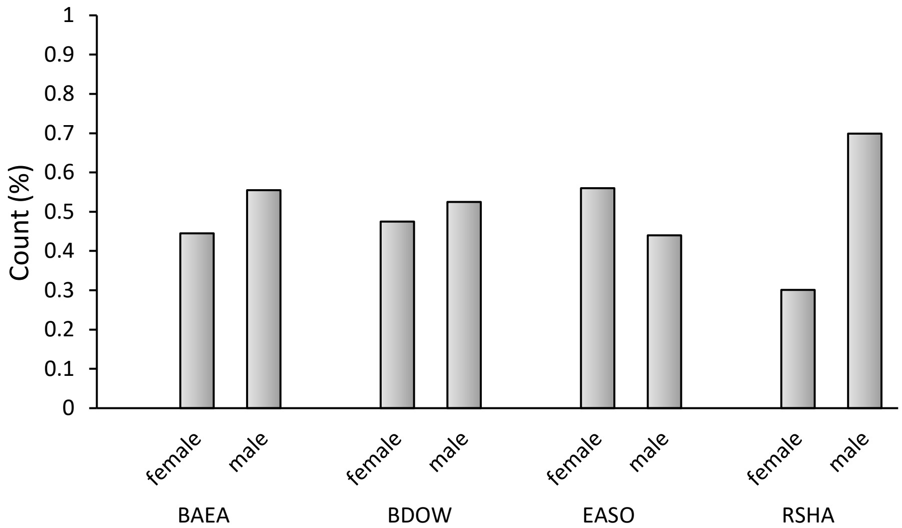

Figure 3.2: Vehicle collision count by sex for each of four species: Bald Eagle (BAEA); Barred Owl (BDOW), Eastern Screech Owl (EASO) and Red-Shouldered Hawk (RSHA) brought to the Audubon Center for Birds of Prey in Maitland, FL between 2000 and 2019. Count of sex represented as a percentage of the total number of collisions per species. Count (%)

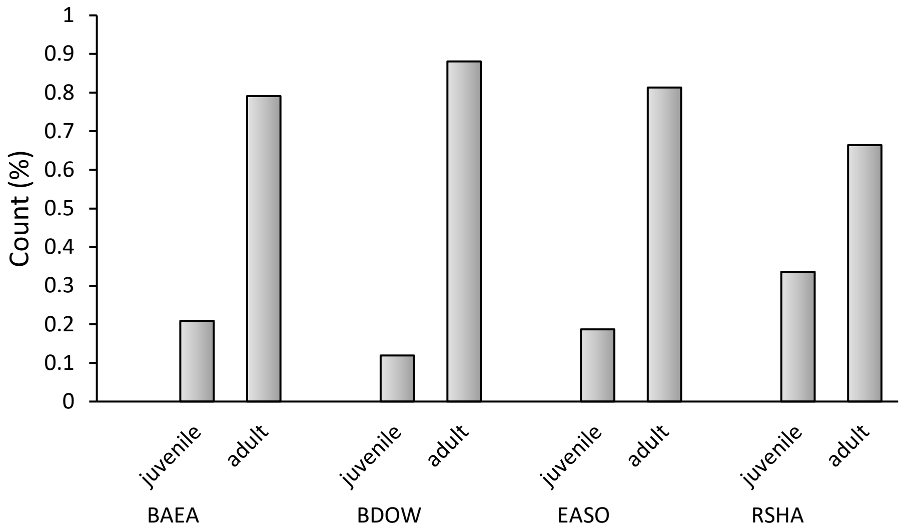

Figure 3.3: Vehicle collision count by age for each of four species: Bald Eagle (BAEA); Barred Owl (BDOW), Eastern Screech Owl (EASO) and Red-Shouldered Hawk (RSHA) brought to the Audubon Center for Birds of Prey in Maitland, FL between 2000 and 2019. Count of age represented as a percentage of the total number of collisions per species.

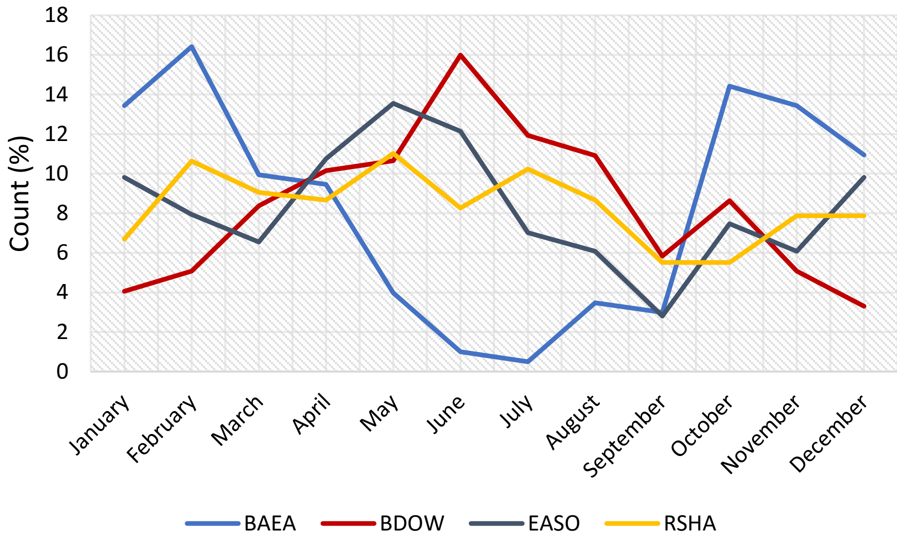

Figure 3.4: Vehicle collision count by month for each of four species: Bald Eagle (BAEA); Barred Owl (BDOW), Eastern Screech Owl (EASO) and Red-Shouldered Hawk (RSHA) brought to the Audubon Center for Birds of Prey in Maitland, FL between 2000 and 2019. Count per month represented as a percentage of the total number of collisions per species.

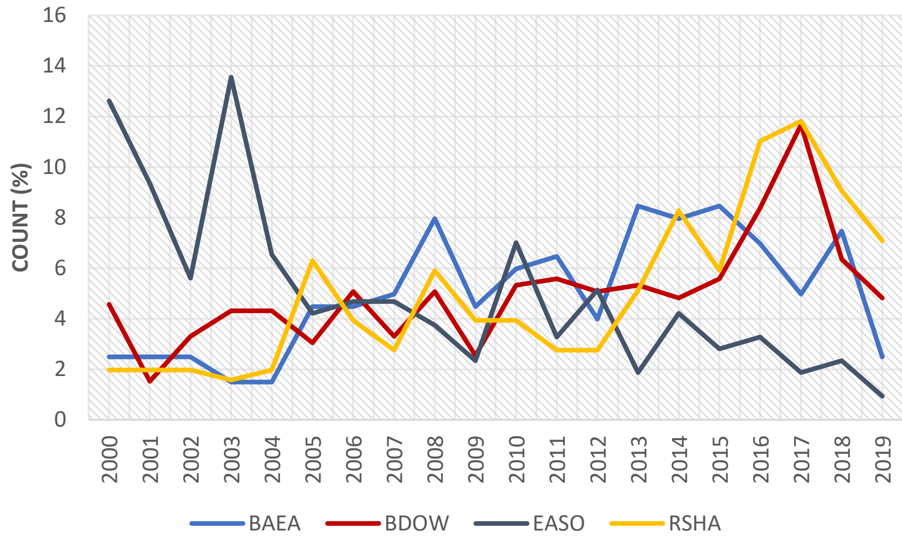

Figure 3.5: Vehicle collision count by year for each of four species: Bald Eagle (BAEA); Barred Owl (BDOW), Eastern Screech Owl (EASO) and Red-Shouldered Hawk (RSHA) brought to the Audubon Center for Birds of Prey (ACBP) in Maitland, FL between 2000 and 2019. Count per year is represented as a percentage of the total number of collisions per species.

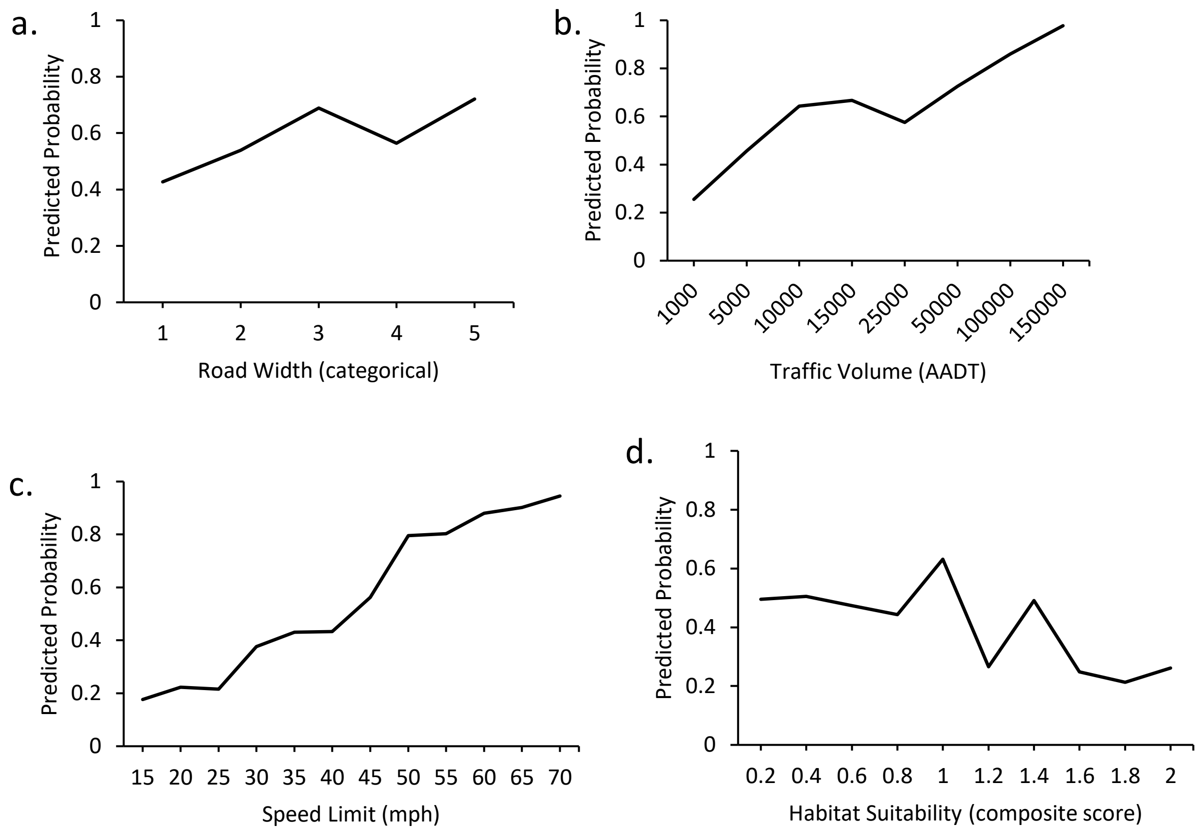

Figure 3.6: The effects of road width (a), traffic volume (b), speed limit (c) and habitat suitability (d) on the likelihood of a Bald Eagle (*Haliaeetus leucocephalus*)-vehicle collision based on intake records from the Audubon Center for Birds of Prey in Maitland, FL, USA. Predicted probabilities are fitted values at each collision or non-collision site.

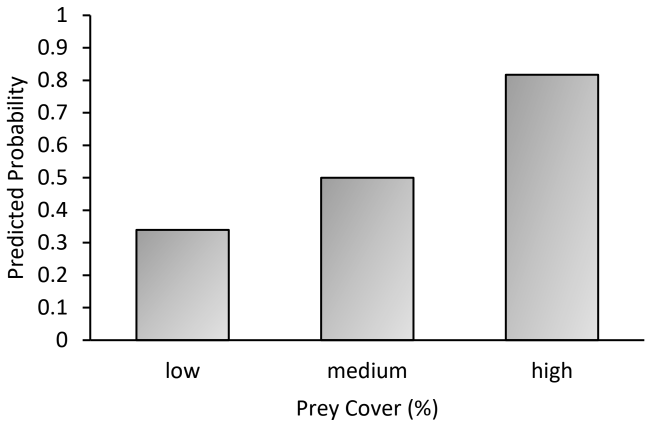

Figure 3.7: The effects of prey cover on the likelihood of a Bald Eagle (*Haliaeetus leucocephalus*)-vehicle collision based on intake records from the Audubon Center for Birds of Prey in Maitland, FL, USA. Predicted probabilities are fitted values at each collision or non-collision site.

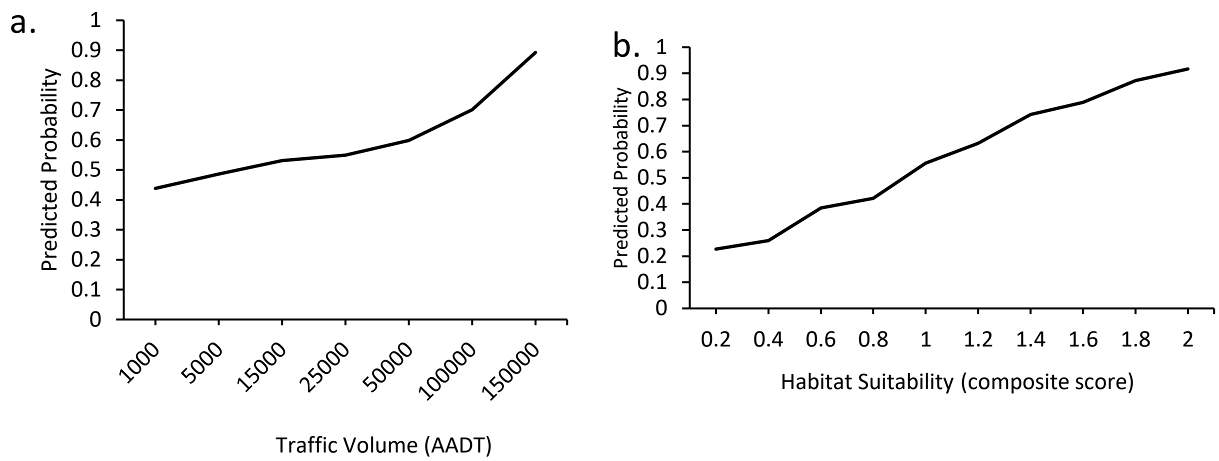

Figure 3.8: The effects of traffic volume (a) and habitat suitability (b) on the likelihood of a Barred Owl (*Strix varia*)-vehicle collision based on intake records from the Audubon Center for Birds of Prey in Maitland, FL, USA. Predicted probabilities are fitted values at each collision or non-collision site.

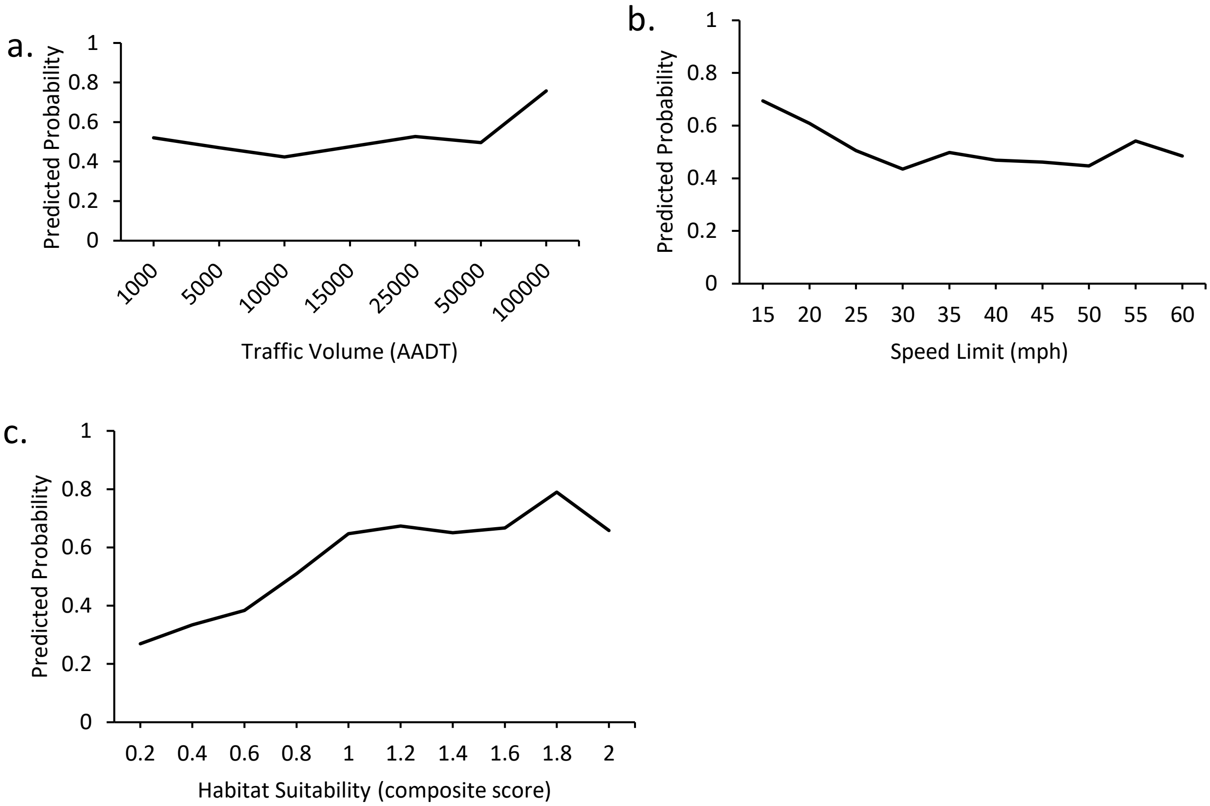

Figure 3.9: The effects of traffic volume (a), speed limit (b) and habitat suitability (c) on the likelihood of an Eastern Screech Owl (*Megascops asio*)-vehicle collision based on intake records from the Audubon Center for Birds of Prey in Maitland, FL, USA. Predicted probabilities are fitted values at each collision or non-collision site.

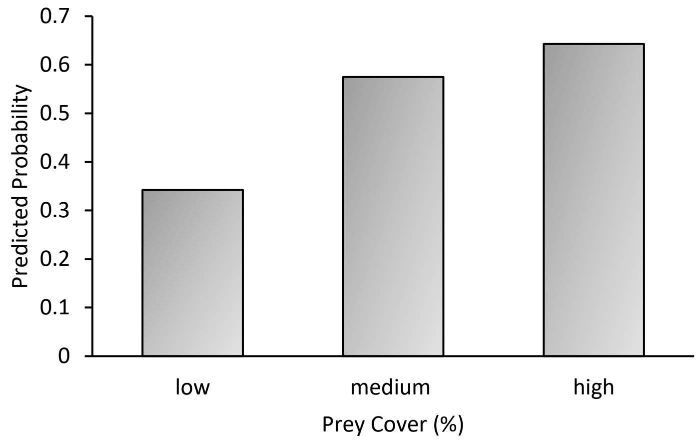

Figure 3.10: The effects of prey cover on the likelihood of an Eastern Screech Owl (*Megascops asio*)-vehicle collision based on intake records from the Audubon Center for Birds of Prey in Maitland, FL, USA. Predicted probabilities are fitted values at each collision or non-collision site.

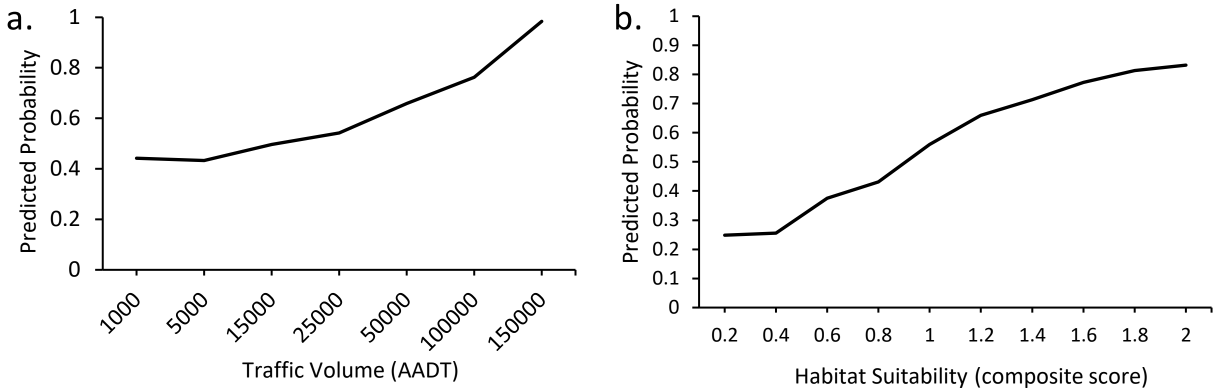

Figure 3.11: The effects of traffic volume (a) and habitat suitability (b) on the likelihood of a Red-Shouldered Hawk(*Buteo lineatus*)-vehicle collision based on intake records from the Audubon Center for Birds of Prey in Maitland, FL, USA. Predicted probabilities are fitted values at each collision or non-collision site.

Chapter 4: Species and Individual Traits Influence the Location of Raptor-Vehicle Collisions in Central Florida, USA

4.1 Introduction

The negative impacts of an increasingly prevalent global network of roads have been widely documented for a variety of wildlife species (Fahrig and Rytwinski 2009; Loss et al. 2014). Mortality resulting from collisions between wildlife and motor vehicles is perhaps the most recognizable effect of roadways: in some cases, road mortality poses a significant threat to species persistence (Boves and Belthoff 2012; Ceia-Hasse et al. 2017). However, collision risk is not the same across all wildlife, and species traits including body size, diet, and home range size appear to impact vulnerability to road effects (Grilo et al. 2020).

Species traits and the corresponding impact on road mortality has been considered for a variety of terrestrial vertebrates, including many avian species (Jaeger et al. 2005; Bujoczek et al. 2011). The interaction of road networks and birds is particularly interesting because of both the high level of mobility afforded by flight and variability in life history traits including foraging strategy, reproductive output, time of activity, dispersal and migration (Meunier et al. 1998; McClure et al. 2019). Previous research focusing on species traits for both birds and mammals suggest and effect of body size and reproductive output on road mortality (Santos et al. 2016; González- Suárez et al. 2018).

Foraging strategy is perhaps the most recognizable characteristic of birds of prey. While many raptors employ a "sit-and-wait" hunting strategy by scanning for prey from an elevated perch, other species use low quartering flight in open habitat, where prey is obtained by diving from a height several meters above the ground. Scavenging raptors, including vultures, commonly feed on wild and domestic carrion along road verges or on road surfaces (Lambertucci et al. 2009). By default, the foraging opportunities provided by roadkill suggest an increased risk of vehicle collisions involving scavengers. In fact, scavenging behavior has been shown to impose a higher risk for mammals (Gonzalez-Suarez et al. 2018), and although this has not been indicated in birds, I expect to find a notable increase in road effects for aerial, scavenging and opportunistic hunters over perch foragers because of the increased risk posed by scavenging and aerial hunting. Road mortality for the Barn Owl (*Tyto alba*), a well-known nocturnal aerial hunter, has been widely documented (Massemin and Zorn 1998; Boves and Belthoff 2012; de Jong et al. 2018). I expect that increased collision risk for aerial hunters is a factor of the larger distance covered and resulting roads crossed in flight while foraging. In addition, perch hunters are more likely to see and possibly respond to oncoming traffic while scanning roads and road verges for prey while foraging.

Body size has been identified as having a significant impact on road mortality for many birds (Santos et al. 2016, González- Suárez et al. 2018) but has not been examined specifically for raptors. In general, it appears that the frequency of road mortality increases with body size to a point (Ford and Fahrig 2007). It seems logical to assume greater road mortality for larger species, which are more mobile and are more likely to encounter roads. Ford and Fahrig (2007) speculate that the peak body size (1.06kg) represents a combination of population size and mobility, which together serve to increase the risk of road mortality. I expect to find a similar effect of body size for the four species included in my study, where collision rates are higher for medium sized birds.

Mortality is typically much higher for migratory species (Klaassen et al. 2014), but mortality specific to vehicle collisions is likely a factor of an increase in distance traveled (and associated increase in roads crossed), exhaustion, and lack of familiarity with the landscape. Hypotheses based on species traits and road effects suggest a positive correlation between mobility and road mortality, under the assumption that species with greater mobility and larger home ranges encounter roads more frequently (Rytwinski and Fahrig 2012). The association of mobility and road mortality suggests a corresponding association between migration and collision risk. I expect the same positive correlation between migratory behavior and collision risk for raptors in this study.

Strigiformes are typically more susceptible to vehicle collision than diurnal birds of prey, which suggests that time of activity affects road mortality in raptors (Hager 2009; Hernandez et al. 2018). In comparing the effect of diurnality/nocturnality on collision risk across the species represented in this study, I expect that traffic volume will be present as a mechanism underlying collision risk between nocturnal and diurnal raptors used in this study. Behavior patterns across a variety of raptor species have been shown to mirror cyclical changes in road traffic and associated noise and lights (Bautista et al. 2004; Silva et al. 2012). The noise generated by high traffic volume appears to contribute to a widespread pattern of avoidance in some raptors (Silva et al. 2012). Along most major roads, traffic volume is at its highest during daylight hours, which will impact which road segments are visited by foraging birds or by birds passing through. In some cases, increased traffic volume will discourage raptor presence near roads, which in effect will reduce the risk of a vehicle collision. Although diurnal raptors are more responsive to traffic volume, I expect that daytime traffic associated disturbance will lead to a decrease in collision risk. Nocturnal raptors are more likely utilize road verges when decreased traffic volume along many roads no longer serves to foster avoidance.

The biological drivers behind clutch size have been investigated for many avian species. Predation risk, fledgling mortality, and parental energy expenditure, along with environmental conditions have been shown to impact clutch size (Martin 2014). Although I am not aware of a study that has researched the relative parental energy expenditure per offspring for raptors, I assume that in general, larger clutches will require an increase in parental energy expenditure, and thus an increase in time spent foragin (Biebach 1981). If this is the case, I expect higher collision risk for larger clutch size. In addition, more fledglings implies more young birds dispersing in a given year, which will increase the number of individuals at higher risk for vehicle collisions.

Finally, I included age (adult or juvenile/first year) for each crash across all species included in the study. Although this is not a species trait, an effect of age on collision risk in nocturnal raptors has been suggested (Boves and Belthoff 2012; Šálek et al. 2019). In many cases, no significant increase exists in the overall numbers of first-year or juvenile birds admitted to raptor centers (Ress and Guyer 2004; Molina-Lopez et al. 2013.); however, Boves and Belthoff (2012) observed a differential impact of age on collision risk for Barn Owls (*Tyto alba*) in Idaho, USA, where juvenile individuals comprised more than 75% of deaths in a two-year span of data. I expect that the risk of road mortality in juvenile raptors is typically higher, presumably because of dispersal and an increase in the number of roads encountered. Birds can also learn to respond to approaching traffic by adapting flight initiation distance, suggesting that younger individuals may lack experience sufficient to avoid a vehicle (DeVault et al. 2017). Although I expect to find that juvenile raptors are at higher risk of collision, I am interested in the relative effect of age, migration and body size. I expect a nominal effect of age for smaller resident birds because of the incidental decrease in the number of roads encountered, and a very significant effect of age for migratory species. For example, juvenile Ospreys suffer a much higher rate of mortality when compared to adults (Ospreytrax.com). I expect that lack of experience combined with the increased number of roads encountered during migration will increase risk for juveniles.

The objective of this study is to examine the effects of species traits described above on factors underlying the location of vehicle collisions given road width, speed limit, traffic volume, habitat suitability, perch availability and prey cover. My aim is to investigate the possibility that these traits predispose a species to collision risk at particular locations. Across all traits included in my analyses, and given all of the individual predictions described, I expect that time of activity and age will be of highest relative importance across a variety of road and habitat conditions based on the trends noted in previous literature, which suggest an increase in road mortality for nocturnal raptors, along with juveniles (Hager 2009). My aim is to determine how vehicle collision risk is influenced by species traits given varied roadway and habitat characteristics in the hopes that my results may be used to inform mitigation efforts to reduce road mortality for raptors.

To examine the potential effect of species traits on vehicle collisions for birds of prey, I tested for the effects of migration, clutch size, body size, time of activity, and foraging strategy on the characteristics of collision locations for four raptor species using records from the Audubon Center for Birds of Prey in Maitland, FL: the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*). These four species exhibit a variety of behavioral and phenotypic traits relevant to vehicle collision rate (Table 4.1), and which may influence the characteristics of collision locations, including road width, speed limit, traffic volume, surrounding habitat suitability, road verge perch locations, and prey cover along road verges. In other words, species or individuals with certain traits may be more or less likely to be hit by a vehicle depending on speed limit, road verge perch availability, or surrounding habitat suitability, among measurable characteristics of collision locations. Ultimately, trait-based vulnerability to vehicle collisions will have a spatially based impact on ecosystem processes, which can have broader implications for ecosystem functioning.

4.2 Methods

Collision Data: Raptors in the North Carolina Piedmont and Central Florida

The following material is taken from Chapter 3. Records were obtained from archived intake files from the Audubon Center for Birds of Prey (ACBP) in Maitland, FL. For the purpose of this study, I used vehicle collision data between 2000-2019, with a focus on four species frequently admitted to the center (Table 4.1). Over a 19-year span, nearly 3,000 individuals across these four species were admitted to the ACBP, where more than 50% of admissions with known etiology were described as anthropogenic in nature. In accordance with previous research (Hager 2009), vehicle collisions are the most common cause of admission, followed distantly by gunshot and electrocution. I was able to include at least 200 collision points for each species, totaling 1,063 vehicle collisions in this year range for analysis (Table 4.2).

Species and Individual Traits

I included five species traits in my analysis: migration, clutch size, body size, time of activity and foraging strategy (Table 4.1). I derived trait values from biological and life history data available in the Cornell Lab of Ornithology, *Birds of the World* database (birdsoftheworld.org). Species were listed as either migrant or resident, where the resident classification excludes any species that is not entirely non-migratory. Clutch size was determined as a numerical mean of highest and lowest values estimated using studies reported for each species on the website. For body size, I used a simple classification (small, medium, large) based on available data using the average weight of females for each species, where birds with an average weight of less than 500g were classified as small. Medium birds were between 500 and 1200g, and large birds were greater than 1200g on average.

Time of activity is classified as either diurnal or nocturnal, based upon the time of day of foraging. Finally, foraging strategy takes three forms: aerial hunter, including species that primarily utilize low quartering flights in open habitats, perch hunter, which includes species known to employ a sit-and-wait tactic by scanning for prey while perched, and scavenger, which includes species known to feed on carrion as a primary food source. In the case of a species that employs multiple foraging strategies, foraging strategy is classified as opportunistic.

In addition to the five species traits described above, I included age as a variable on an individual basis for each collision. Age was classified as juvenile or adult, with juvenile including first- and second-year birds, and adults, including all birds in their third or later years. Age was taken directly from intake records.

Characteristics of Collision Locations

Traffic volume, speed limit and road width were included as roadway characteristics at collision locations. Data were acquired in the same manner described in Chapter 3. Traffic volume and speed limit were obtained from the Florida Department of Transportation (DOT) Traffic Data & Analytics Office (TDA) (https://tdaappsprod.dot.state.fl.us/fto/). The TDA is updated annually, so traffic volume and speed limit both reflect data for the corresponding year of each collision/non-collision. For roads without traffic volume or speed limit data, I assigned a value based on the closest road segment with similar characteristics and a known value. Nearly all roadways lacking speed limit data were residential roads and were assigned a speed limit of 25mph.

Due to the number of collisions and non-collisions included in this study, road width is represented here as *lane count*, a value that is available as "number of lanes," which is available through the Florida Department of Transportation (DOT) Open Data Hub (https://gis-fdot.opendata.arcgis.com/). The number of through lanes, or *lane count,* is defined as the number of through lanes on one side of a given roadway. For example, a local residential street would typically have a lane count of 1.

Habitat suitability was included at an estimated nesting territory range using the Cornell Ornithology Lab's Birds of the World data for each species (https://birdsoftheworld.org). This website includes comprehensive information focusing on the biology of the world's birds and includes references to the literature on nesting and nesting territories. I used average nesting territory sizes for each species reported on the Birds of the World website and calculated a radius then used to determine habitat suitability for each species: Bald Eagle (950m), Barred Owl (850m), Eastern Screech Owl (500m) and Red-Shouldered Hawk (600m). Habitat suitability values were determined using the National Land Cover Database (NLCD). Using NLCD land use classes, I assigned Wetland, Forest, Shrub/Scrub a score of 2; Developed Open Space, Low-Intensity Residential, Grassland/Herbaceous, Pasture/Hay, Cultivated or Row Crops, Barren or Bare Rock/Sand/Clay and Open Water a score of 1, and the Developed High-Intensity, High-Intensity Residential, and Commercial/Industrial/Transportation classes a score of 0. The score for each collision was determined within a circular landscape using the radius reflecting average nesting territory size for each species and was weighted by the proportion each NCLD class. I used NCLD year closest to each collision/non-collision from the years 2001, 2008, 2013, and 2016.

Road verge habitat was included in my analysis to estimate both perch availability and the visibility of road verge vegetation, or prey cover. Perch availability was determined using the percent of a 100m road segment on each side of the collision/non-collision passing through canopy cover using forest cover classes included in National Land Cover Database (NCLD) data for the closest year to 2001, 2008, 2011, 2013 and 2016. Forest cover classes were used to represent mature trees used as preferred perches (Reinhert 1984).

I evaluated road verge prey cover by estimating the presence of complex vegetation in the form of brush, shrubs and tall grasses. I used a detailed land cover/land use file available from the Florida Department of Environmental Protection's Geospatial Open Data site (https://geodata.dep.state.fl.us/datasets/2f0e5f9a180a412fbd77dc5628f28de3_3/about). The land use shapefile available at this website provides more detailed information, especially with regard to vegetation type and is of a higher resolution than the National Land Cover Database (NCLD) file. Using a distance of 50m along the road on each side of the collision and including a distance of 15m from the roadway edge, I calculated the percentage of area represented by land cover types associated with prey cover including mixed shrubs, shrub and brushland, and upland shrub and brushland. Prey cover was termed either low, medium, or high based on the overall percentage of shrubs, brush and other complex vegetation.

Analyses

I followed the methods used by González- Suárez et al. (2018) to generate random forest regression trees to model the effects of species and individual traits on collision location characteristics. Random forest regression trees define the importance of predictors (traits) using a machine learning technique that utilizes bootstrapped data samples (Breiman, 2001). Previous trait data studies using regression trees have included taxonomic order as a predictor (González-

Suárez et al. 2018; Grilo et al. 2020); however, the data used in this study represent relatively few species and an uneven representation of traits within families, so I did not include taxonomic relatedness as a predictor. For each collision location characteristic, a random forest model with 1000 trees using all traits was generated. Models were generated R version 3.4.1 (Lele et al. 2014) using the randomForest library (Liaw and Weiner 2002).

Overall model performance was evaluated using variance explained. I assessed the relative importance of traits by permuting values for each trait and estimating the resulting effect on total variance explained. More important traits will have a greater effect on model performance (variance explained).

4.3 Results

The results of my analysis revealed several general patterns. First, clutch size was the most or second most important predictor of collision risk for all road and habitat conditions with the exception of road width. Body size present as the first or second most important predictor in three analyses. For habitat suitability and perch availability, relative importance was highest for body size, followed by clutch size (Fig. 4.1 and 4.2). Age appeared as the second most important predictor for prey cover behind clutch size, and the most important predictor for road width (Fig. 4.3 and 4.4, respectively). Residency and Time of activity each appeared once as the most or second most important predictor across all results (Fig. 4.5 and 4.6).

Collisions at locations surrounded by high habitat suitability were more likely to be with adults of diurnal resident species with smaller clutch sizes (Red-Shouldered Hawk) or juveniles of nocturnal resident species with smaller clutch sizes (Barred Owl) (Fig. 4.7). Where perch availability was high, collisions typically involved adults of diurnal large-bodied species with smaller clutch sizes (Bald Eagle) or medium sized nocturnal species with smaller clutch sizes

(Barred Owl) (Fig. 4.8). Where a higher percentage of prey cover was present along roadsides, collisions occurred with adults of medium-sized, diurnal species with smaller clutch sizes (Red-Shouldered Hawk) or nocturnal species with smaller clutch sizes (Barred Owl) (Fig.4.9). Along wider roads, adults of large-bodied species (Bald Eagle) and juveniles of medium-bodied diurnal species (Red-Shouldered Hawk) were most at risk of collision (Fig. 4.10). Where speed limit was higher, opportunistic foragers (Bald Eagle) were most at risk of collision (Fig. 4.11). Adults of diurnal perch hunting species (Red-Shouldered Hawk) were also at risk. Finally, opportunistic foragers (Bald Eagle) and diurnal perch hunters (Red-Shouldered Hawk) were most at risk of collision with vehicles where traffic volume was high (Fig. 4.12).

4.4 Discussion

Although my results do not fully support my predictions, I observed clear trends in the relative importance of species and individual traits on the location of vehicle collisions. Several of these trends are supported by prior research; namely, clutch size and body size have both been documented as important predictors of road mortality (Ford and Fahrig 2007, Santos et al. 2016, González-Suárez et al. 2018, Grilo et al. 2020), and appear in my results as the most or second most important predictor of vehicle collision risk for most characteristics of collision locations. Although neither age nor time of activity were the most important predictors across all analyses as predicted, I found that each was a primary factor predicting collision risk based on road width and traffic volume, respectively.

Clutch size was the most or second most important variable for five of six roadway and habitat characteristics, including habitat suitability, perch availability, prey cover, speed limit, and traffic volume. Reproductive rate, or clutch size in birds, has been identified as an important predictor for wildlife road mortality (Grilo et al. 2020, Rytwinski and Fahrig 2012). For mammals and amphibians, a lower reproductive rate has been linked to an increase in vulnerability to negative road effects, including mortality (Rytwinksi and Fahrig 2012). Paton et al. (2019) suggest that increased clutch sizes in birds may offset losses due to parasitism and predation.

Body size was the most important predictor of collision risk for habitat suitability and perch availability and was the second most important predictor for road width. An association between larger body size and road mortality has been widely documented for birds and mammals (Ford and Fahrig 2007, Rytwinski and Fahrig 2012, Santos et al. 2016, González-Suárez et al. 2018). In some cases, a peaked relationship has been observed between body size and road mortality (Ford and Fahrig 2007). My results suggest that body size is an important factor in predicting raptor-vehicle collisions across a variety of traffic and habitat conditions.

Although clutch size and body size were the most important predictors for the majority of road and habitat characteristics, age and traffic volume appeared with the highest relative importance for road width and traffic volume, respectively. Age was most important predictor of collision risk for road width and second most important for prey cover. Age has been noted as a factor in road mortality risk for raptors (Hager 2009). Time of activity was identified as the most important predictor for traffic volume. In many cases, the visual and auditory disturbance created by a large number of cars is enough to deter raptors from crossing or foraging along roadways (Planillo et al. 2015).

Overall, my regression tree results support common trends identified in prior research for both clutch size and body size. Collision risk was higher for species with smaller clutch sizes for each of five road and habitat conditions for which reproductive output was identified as the most or second most important predictor: habitat suitability, perch availability, prey cover, speed limit and traffic volume. Based on my data, species with smaller clutch sizes were more vulnerable to vehicle collision, regardless of roadway and habitat conditions. It seems likely that larger clutch sizes in raptors serve to compensate for losses due to road mortality; however, it is unclear how clutch size directly affects vehicle collision risk (Paton et al. 2019).

Collision risk was higher for medium-bodied species along wider roads and where forest cover (perch availability) was higher along road verges. Medium and large species were more vulnerable along busy roads and where prey cover was higher along road verges. These results align with previous research, which suggests that the risk of road mortality is higher for larger species (González-Suárez et al. 2018, Santos et al. 2016, Rytwinski and Fahrig 2012).

Historically, research has indicated a higher risk of road mortality for juvenile raptors (Loos and Kerlinger 1993, Hager 2009). Across all regression tree results, adults of diurnal species are most vulnerable to collision, except in the case of road width, where the highest risk is found for juvenile Red-Shouldered Hawks. Given the records used in this study, the total number of adults overall was higher than juveniles in my dataset (848 and 215, respectively). Although it is unclear why collision risk was generally higher for adult birds, more recent research has revealed a similar trend, where more adults were admitted for vehicle collision than juveniles (Hernandez et al. 2012, Mariacher et al. 2016), suggesting that a possible shift in age and collision risk is occurring.

The regression tree for traffic volume indicated that nocturnal species are at higher risk of vehicle collisions along busy roads. Traffic volume is typically highest during daylight hours when commuters are traversing the distance to and from work. It is possible that a decline in traffic numbers at night is enough to attract foraging nocturnal birds to suitable roadside territories, where they may then be at risk of collision with the relatively few vehicles on the road at that time.

Overall, my results indicate that some combination of clutch size, body size, time of activity and age are most important in determining raptor-vehicle collision risk along roadways, regardless of surrounding habitat, road verge or roadway characteristics. The Bald Eagle, Red-Shouldered Hawk and Barred Owl were species of highest risk along roadways with varying characteristics. The Eastern Screech Owl, which is the smallest raptor with the highest clutch size of the four species included here, was not at highest risk in any analysis. These results are consistent with prior research, which suggests that large body size and a small clutch size are important predictors of road mortality risk for wildlife (Ford and Fahrig 2007, Santos et al. 2016, González-Suárez et al. 2018, Grilo et al. 2020).

Conclusion

This is the first study to investigate the impact of species traits on the location of vehicle collisions for raptors. My results identified clutch size, body size, time of activity and age as the primary predictors of collision risk across all included roadway and habitat conditions. This suggests that a combination of these species and individual traits predisposes raptors to road mortality. Each of my regression trees show that the species with the lowest risk across all roadway and habitat conditions is the Eastern Screech Owl, which, interestingly, is the species with the smallest body size and largest clutch size.

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TABLES

Table 4.1: Species traits for raptors used in this analysis.

Species	Migration	Clutch Size	Body Size	Time of Activity	Foraging Strategy
Bald Eagle (*Haliaeetus leucocephalus*)	Migrant	2	Large	Diurnal	Opportunistic hunter
Red-Shouldered Hawk (*Buteo lineatus*)	Resident	3	Medium	Diurnal	Perch hunter
Barred Owl (*Strix varia*)	Resident	3	Medium	Nocturnal	Perch hunter
Eastern Screech Owl (*Megascops asio*)	Resident	4	Small	Nocturnal	Perch hunter

Table 4.2: Total number of collisions used in this study for each of four raptor species: Bald Eagle (*Haliaeetus leucocephalus*) (BAEA), Barred Owl (*Strix varia*) (BDOW), Eastern Screech Owl (*Megascops asio*) (EASO), and Red-Shouldered Hawk (*Buteo lineatus*) (RSHA). Collision number based on available intake data from 2000-2019 taken from the Audubon Center for Birds of Prey in Maitland, FL, USA.

Species	**Collision Number**
BAEA	201
BDOW	394
EASO	214
RSHA	254

FIGURES

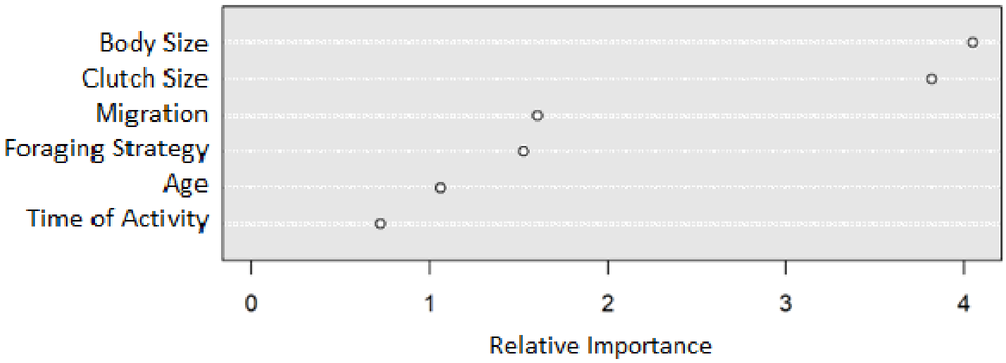

Figure 4.1: Relative importance of species and individual traits in a random forest regression model of habitat suitability surrounding collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*). Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, Florida, USA

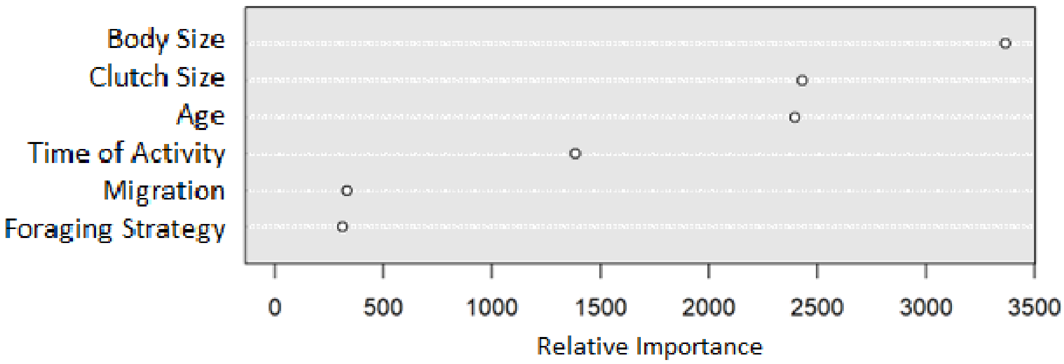

Figure 4.2: Relative importance of species and individual traits in a random forest regression model of perch availability along road verges surrounding collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*). Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, Florida, USA.

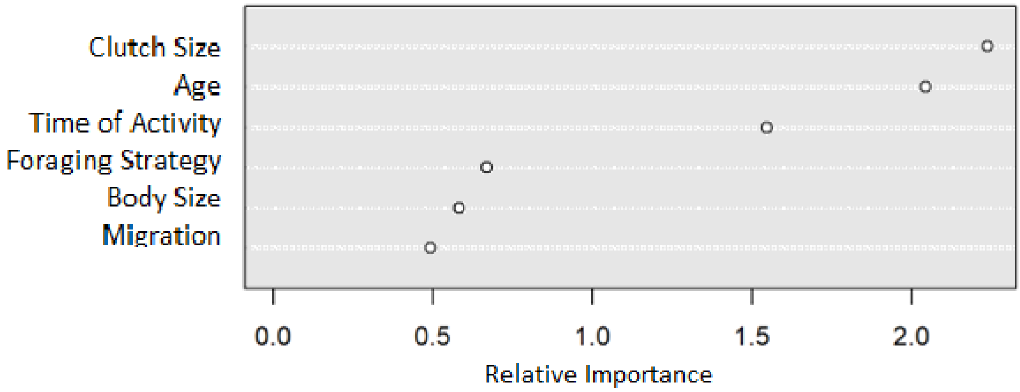

Figure 4.3: Relative importance of species and individual traits in a random forest regression model of prey cover along road verges surrounding collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*). Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, Florida, USA.

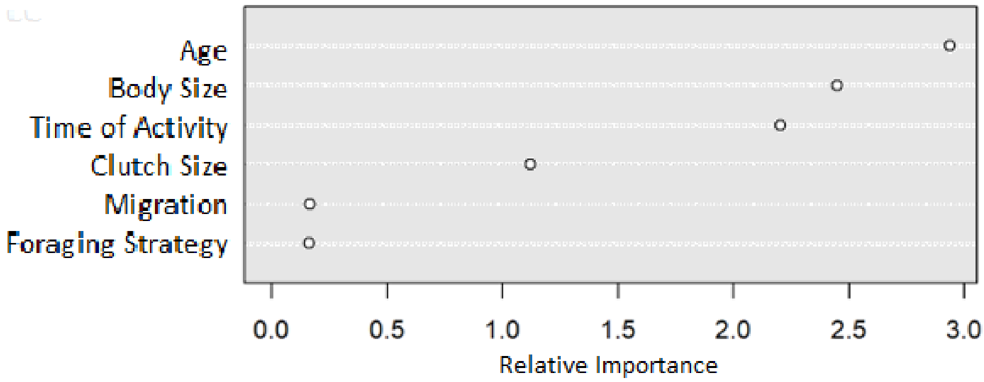

Figure 4.4: Relative importance of species and individual traits in a random forest regression model of road width at collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*). Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, FL.

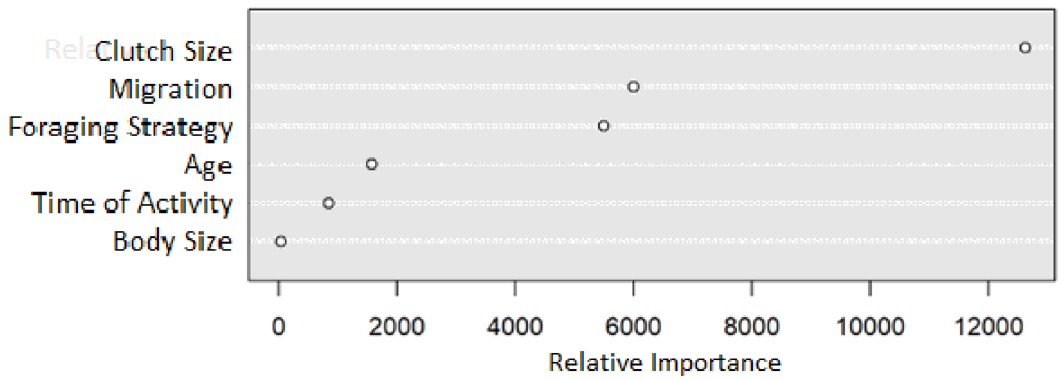

Figure 4.5: Relative importance of species and individual traits in a random forest regression model of speed limit at collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*). Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, FL.

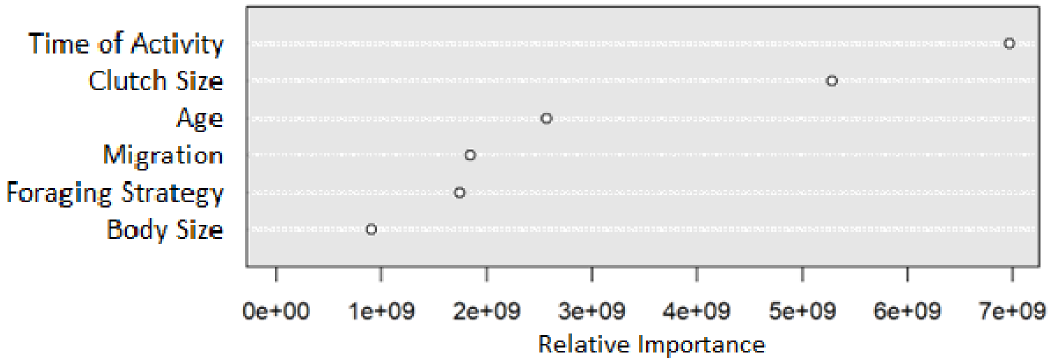

Figure 4.6: Relative importance of species and individual traits in a forest regression model of traffic volume at collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*). Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, FL.

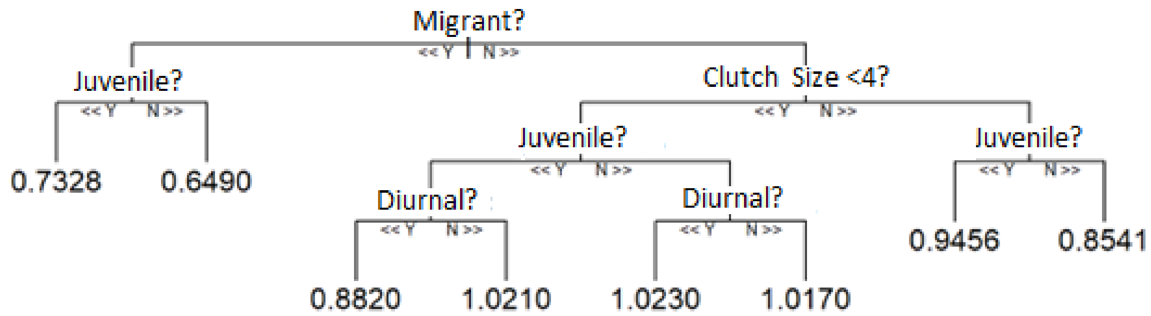

Figure 4.7: Random forest regression model of habitat suitability surrounding collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*) with respect to species and individual traits. Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, Florida, USA.

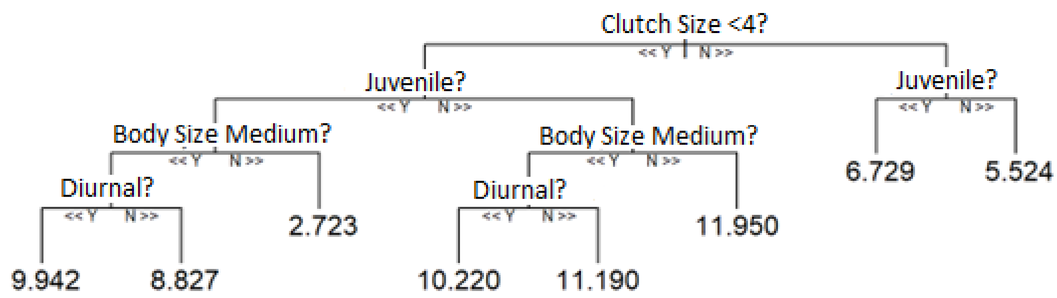

Figure 4.8: Random forest regression model of perch availability surrounding collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*) with respect to species and individual traits. Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, Florida, USA.

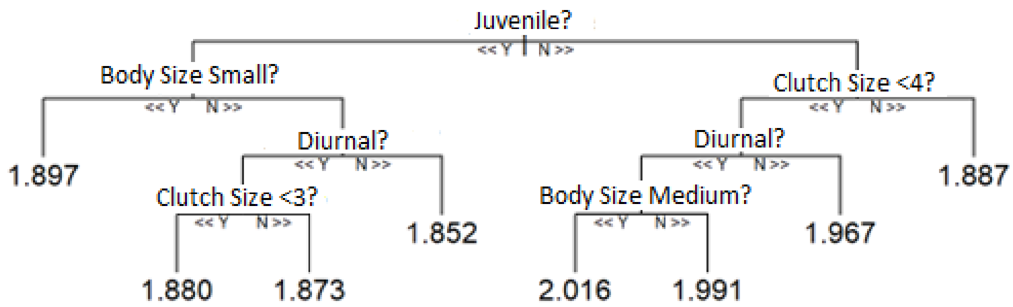

Figure 4.9: Random forest regression model of prey cover along road verges surrounding collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*) with respect to species and individual traits. Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, Florida, USA.

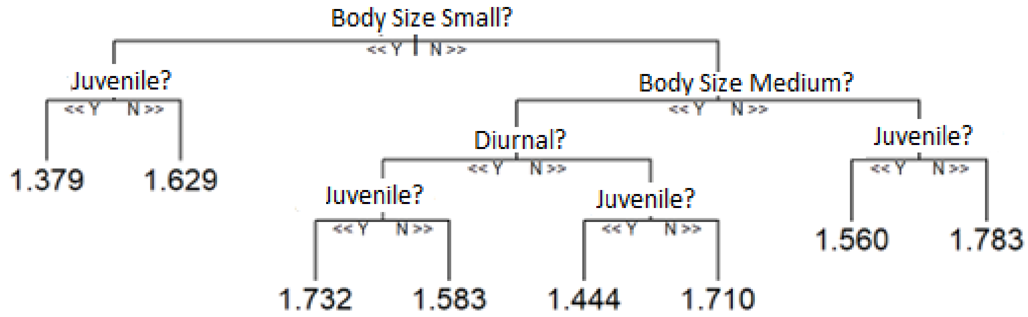

Figure 4.10: Random forest regression model of road width at collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*) with respect to species and individual traits. Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, Florida, USA.

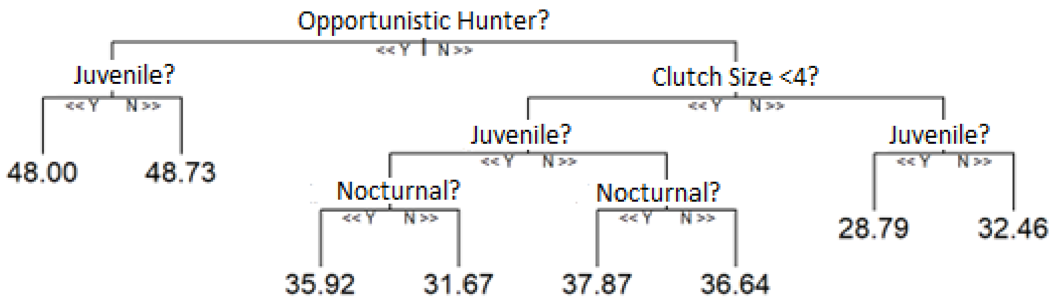

Figure 4.11: Random forest regression model of speed limit at collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*) with respect to species and individual traits. Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, Florida, USA.

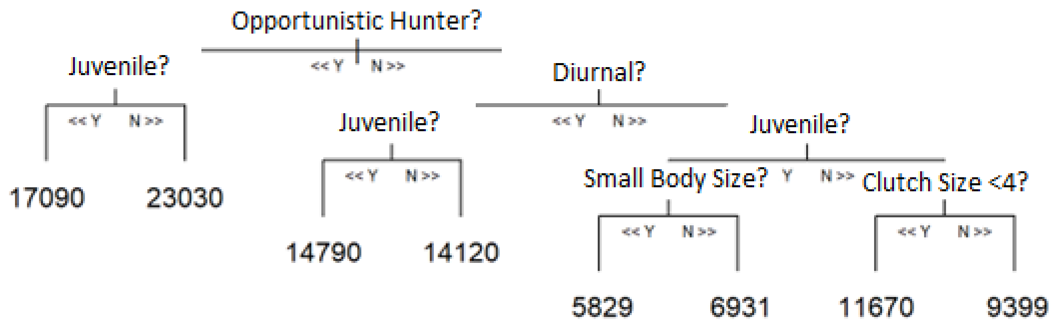

Figure 4.12: Random forest regression model of traffic volume at collision locations for the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Eastern Screech Owl (*Megascops asio*) and Red-Shouldered Hawk (*Buteo lineatus*) with respect to species and individual traits. Data derived from intake records at the Audubon Center for Birds of Prey in Maitland, Florida, USA.

Chapter 5: Discussion: How do Species Traits, Road Characteristics and Habitat Influence Collision Risk? Implications for Future Research and Mitigation

5.1 Discussion

The research presented here is the first of its kind both to compare vehicle collision risk between nocturnal and diurnal raptors and to analyze the effect of road verge habitat on vehicle collision risk for each of the species studied: the Bald Eagle (*Haliaeetus leucocephalus*), Barred Owl (*Strix varia*), Red-Shouldered Hawk (*Buteo lineatus*), and Eastern Screech Owl (*Megascops asio*). In addition, this research is the first to address the effect of species and individual traits along with roadway, road verge and habitat characteristics on vehicle collision risk for birds of prey.

In Chapter 2, I predicted that I would find a positive effect of road verge habitat, including perch availability and prey cover, on vehicle collision risk for the Barred Owl. For Chapter 3, I predicted that time of activity would serve as a differentiating factor for collision risk. To this end, I predicted that road verge vegetation would have a greater positive effect on collision risk for nocturnal raptors, and that traffic volume would create enough daytime disturbance to discourage the use of road verges by foraging diurnal raptors. In Chapter 4, I predicted that collision risk would be higher for juvenile and nocturnal raptors across the majority habitat and roadway conditions. Although I found a significant positive effect of prey cover for Barred Owls in Chapter 2, I observed a negative effect of perch availability in contrast with my expectations. In Chapter 3, my results show that traffic volume and habitat suitability are important predictors of collision risk for all species. Although I expected to observe a difference in results based on time of activity, I saw more similarities between the diurnal Red-Shouldered Hawk and nocturnal Barred Owl. In Chapter 4, I found that clutch size and body size were the most important predictors in most locations, where collision risk was higher for species with smaller clutch sizes and larger body size.

Several trends can be observed across my results. First, the analysis used for Chapters 2 and 3 show that habitat suitability and traffic volume (including traffic volume per meter road width) are significant predictors of vehicle collision risk across all species studied and in both locations: North Carolina and Florida, USA. In all analyses, risk was greater along roads with higher traffic volume. In all cases except for the Bald Eagle, risk was higher where the suitability of surrounding habitat was higher. In Chapter 4, roads with more traffic pose a higher risk for the Bald Eagle. In addition, habitat suitability was an important predictor of collision risk for both the Red-Shouldered Hawk and Barred Owl. For the Barred Owl, Eastern Screech Owl, and Red-Shouldered Hawk, the importance of suitable habitat in the form of forest cover for foraging and nesting territories has been well documented (Gelbach 1994, Mazur & James 2000, Dykstra et al. 2012). For the Bald Eagle, the selection of foraging grounds, especially during migration, is typically affected by the availability of prey, not by the presence (or absence) of vegetation, including forest cover (Spencer et al. 1991). Busy roads have been shown to have a negative impact on road mortality for a variety of vertebrate wildlife (Harding 1986, Shilling et al. 2021). For birds of prey, traffic volume appears to be a major factor in predicting the occurrence of vehicle collisions.

I predicted a positive effect of road verge habitat, including perch availability and prey cover, on vehicle collision risk in both Chapters 1 and 2. Although prey cover was identified as a significant predictor of collision risk for the Barred Owl in North Carolina and the Bald Eagle and Eastern Screech Owl in Florida, I did not find a significant positive effect of perch availability as predicted. I based my measurement of perch availability on the presence of forest cover along roadsides. My results show that forest cover along road verges is not an important predictor of collision risk at either location or for any species included in my study. However, I did not account for man-made perches such as buildings, fences or power lines. I also did not determine whether a minimum number of mature trees or natural perches is necessary to attract a foraging bird to a roadside. At least in the case of perch hunters, roadside foraging is likely determined by the presence of perches, whether in the form of man-made structures or trees. Further research should attempt to determine a minimum number and preferred type of perch used by raptors foraging along roadsides.

5.2 Future Research

Although the spatial distribution of relative predicted probability is fairly consistent across both study areas (North Carolina and Florida), the majority of vehicle collisions for all species are concentrated in the county or counties closest to the location of each rehabilitation center: Mecklenburg county in North Carolina and Seminole and Orange counties in Florida (Figure 5.1, 5.2, 5.3, 5.4 & 5.5). Although proximity to the centers could be a factor in determining the likelihood of an individual to intervene on a bird's behalf, Mecklenburg and Orange counties are home to the largest cities in each study area, and it is unclear whether the associated concentration of traffic and roads in these areas is a larger factor in determining the rate of raptor-vehicle collisions. I suggest that future research investigate factors that predispose individuals to react to injured wildlife, and in particular, to raptors, and the relative influence of urbanization and the proximity of rehabilitation centers to collisions. In addition, it is not clear how the population of these species is distributed in and around urban areas. To this end, an evaluation of population distribution could provide useful information in determining high-risk areas along roadways for raptors in and around urban areas.

My results show an increase in vulnerability to vehicle collisions along road verges with a high percentage of prey cover for three species: the Barred Owl, Eastern Screech Owl and Bald Eagle. Both the Barred Owl and Eastern Screech Owl are perch hunters that would presumably utilize road verges while foraging from a perched location. On the other hand, the Bald Eagle is an opportunist and commonly takes prey in flight or on the ground as a scavenger. An increase in road mortality risk has been documented by small birds and mammals that typically utilize roadside brush and shrubs (Orlowski 2008); however, it is unclear whether the importance of prey cover for the Bald Eagle is relative to the number of road-killed prey animals scavenged in proximity to complex vegetation habitat, or if this species typically hunts small birds or mammals in dense vegetation.

To this end, I suggest that future research focus on documenting the behavior of raptors in proximity to roads, particularly in urban areas where road density is higher and the opportunity to forage along roads may be a necessary key to success. Previous research has indicated a tendency of raptors to avoid roads with high traffic volume (Bautista et al. 2004, Planillo et al. 2015); however, a better understanding of where and how raptors are attracted to roads while foraging could better inform mitigation strategies designed to offset road mortality risk.

I was unable to show that road verge perch availability in the form of forest cover was an important predictor of collision vulnerability for raptors; however, it is likely that perches are an important component of the suitability of roadside habitat for foraging raptors. I suggest that future research focus on determining the minimum number of trees required to attract raptors to roads where adequate prey are available. That minimum number may not be enough to warrant forest cover classification. In addition, raptors almost certainly utilize and may even prefer man-made structures for use as perches. In the case of aerial hunters, or opportunistic foragers such as the Bald Eagle, trees may prove a hindrance to low flights over roads and could decrease vulnerability to road mortality, a mitigation strategy that has been suggested for the Barn Owl (*Tito alba*) (Massemin and Zorn 1998).

Due to the availability of suitable data, my analysis of species and individual traits was limited to four species. Therefore, my results do not represent a wide range of species traits common in raptors, including greater variation in clutch sizes and foraging strategies. I suggest that future research include a variety of raptor species in an effort to better understand how species traits influence vehicle collision risk across all birds of prey. In addition, more information would be gained by performing a similar analysis of species and individual traits at varied locations, instead of focusing on Florida.

Finally, I employed two types of statistical analysis in this dissertation. The first two analyses were completed using logistic regression, and the third used random forest regression. My random forest regression was completed using a train/test split for model validation. Although this type of validation is not commonly used in standard regression models used to evaluate ecological data, I suggest that repeating this analysis using validation techniques designed to assess the ability of the model to predict future outcomes would be useful in identifying potential “hot spots,” or areas of increased vehicle collision risk for raptors. This would be particularly useful where land use changes alter the characteristics of a landscape and the impact on road mortality risk is unknown.

5.3 Mitigation

My results show that increased prey cover along road verges is in many cases an important predictor of vehicle collision risk for raptors. Prey cover in the form of brush, shrubs, and tall grass provides habitat for small birds and mammals (Meunier et al. 1998, Silva et al. 2012), which are a staple food source for most raptors (Roth and Lima 2003; Hindmarch and Elliott 2015). Orlowski et al. (2008) found that the incidence of road mortality for Passerine songbirds increased along roads where complex vegetation was present. Mitigation for these birds takes the form of mowing grass along road verges and limiting hedges, shrubs and other complex vegetation in close proximity to road edges (Meunier et al. 1998, Orlowski et al. 2008). Grilo et al. (2014) suggested limiting availability of prey along road verges as a means to offset road mortality for Barn Owls. Similarly, my resuslts suggest that the management of road verges should focus on limiting prey cover, thus limiting access to birds and small mammals along roadsides, which will hopefully decrease the risk of vehicle collision for birds of prey.

The effect of verge habitat on collision risk is noteworthy because road verges and road verge vegetation can be more easily modified or regulated, whereas the regulation of surrounding habitat poses more complex, potentially insurmountable challenges. The presence (or absence) of verge vegetation, and a call for road verge management as a strategy to mitigate the risk of road mortality for various avian species, including raptors, has been discussed in previously published research (Massemin and Zorn 1998; Meunier et al. 1998; Orlowski 2008). Although no data exist to support or refute the efficacy of road verge management as a mitigation strategy to address road mortality in birds of prey, I suggest that this approach should be implemented, especially in corridors where surrounding habitat are likely to attract raptors to the area.

It is clear from my results that species and individual traits are important predictors of vehicle collision vulnerability. Based on my results, smaller clutch size and medium to large body size appear to be dominant predictors of collision risk. I also found that nocturnal species are at higher risk along roads where traffic volume is higher. Mitigation of road effects through the management of road verge vegetation may be most effective when focused on medium and large-sized raptors with smaller clutch sizes, and on nocturnal raptors along busy roads. This type of approach would require measuring the relative population density of at-risk species in areas where road mortality is of particular concern.

To this end, I suggest that efforts to offset collisions and road mortality for raptors should focus on areas where vehicle collisions involving raptors are most likely. My results indicate that habitat suitability, traffic volume, and speed limit are important factors in determining collision risk. I also found that medium and large-bodied raptors with smaller clutch sizes were more vulnerable to vehicle collision. Increased risk for these species takes the form of high habitat suitability, traffic volume, and increased speed limits. Based on these results, the most effective and feasible mitigation efforts involve managing or eliminating prey cover in the form of complex vegetation along roads surrounded by forest cover, and with high traffic volume and increased speed limits.

Conclusion

Why do we care about road effects and raptors? As top-level predators, the presence of raptors in an ecosystem is indicative of its overall health (Rodríguez-Estrella et al. 1998; Molina-Lopez and Darwich 2011). Identifying patterns in the incidence of vehicle collisions involving raptors represents an effort to understand (and potentially reduce) the impacts of human activity on the persistence of surrounding wildlife. It is my hope that continued efforts to better understand the interaction of humans and wildlife will persist and will feed global management and planning practices.

5.4 References

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FIGURES

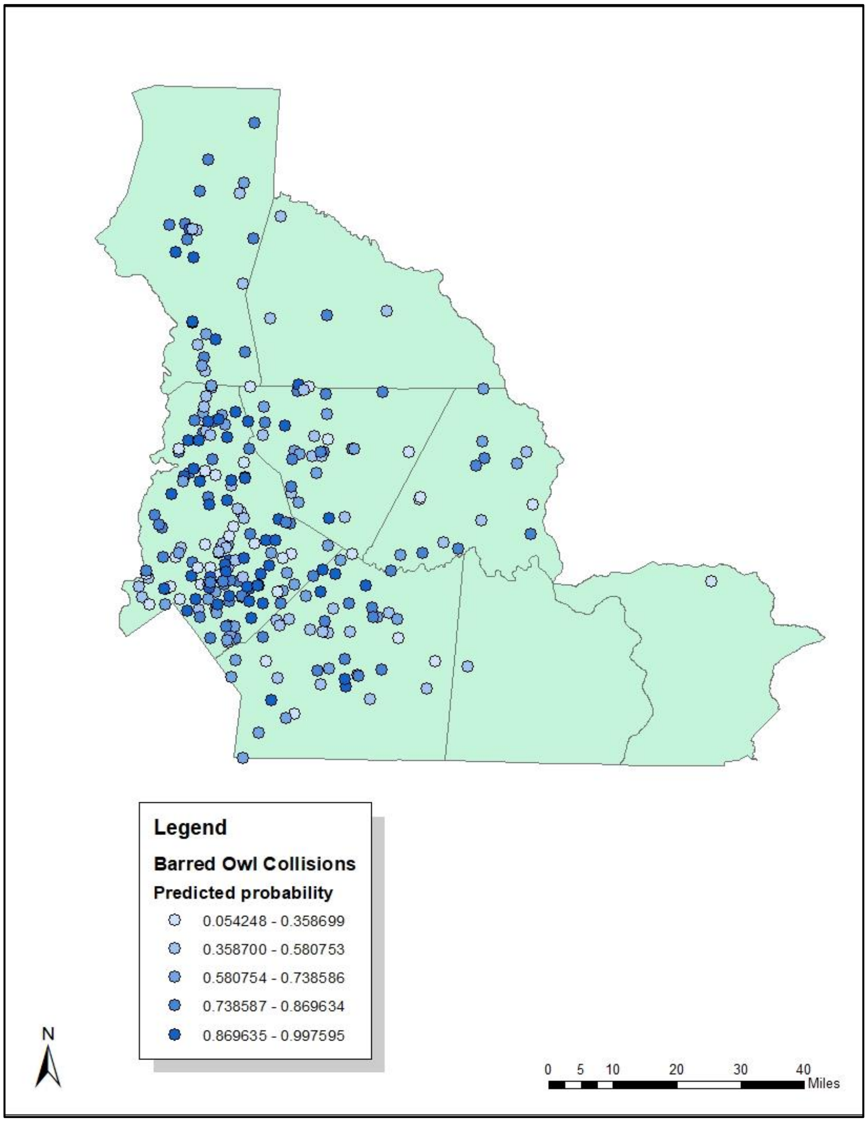

Figure 5.1: Color coded map showing a range of predicted probability associated with Barred Owl- vehicle collisions occurring in and around the Charlotte, NC USA area between 1996 and 2019.

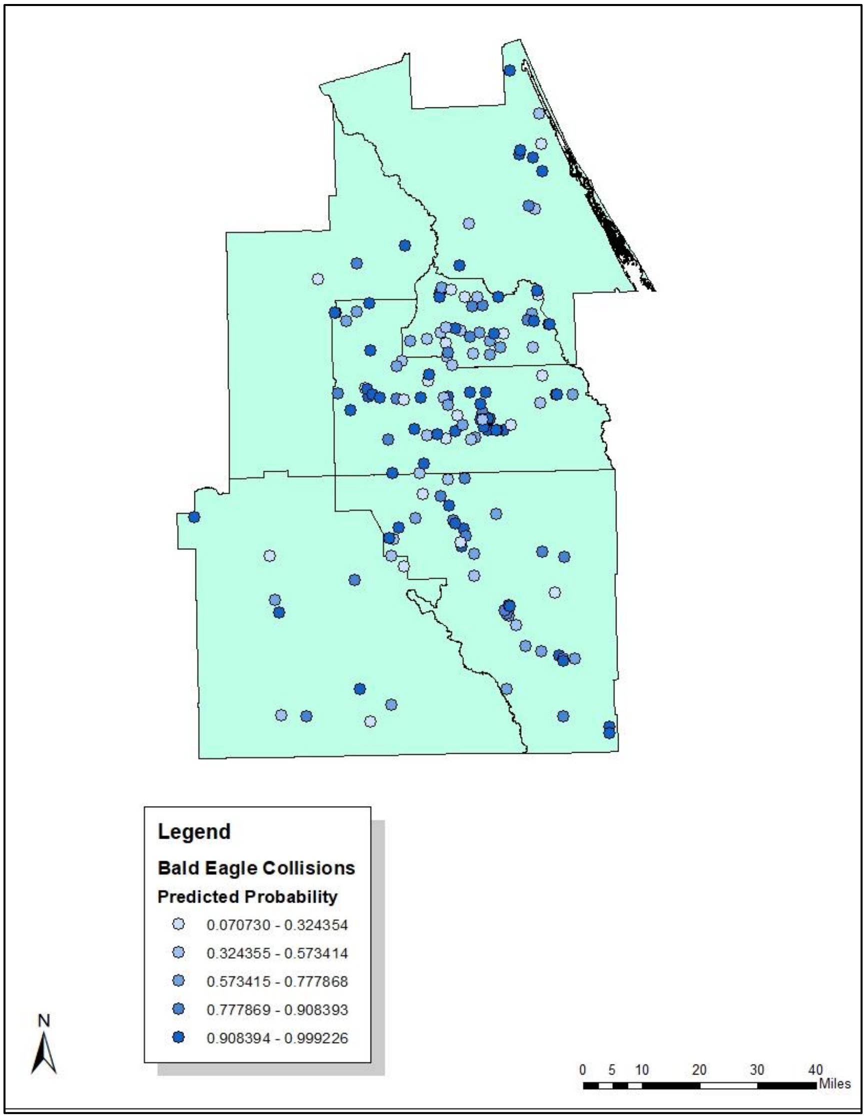

Figure 5.2: Color coded map showing a range of predicted probability associated with Bald Eagle- vehicle collisions occurring in and around the Orlando, FL USA area between 2000 and 2019.

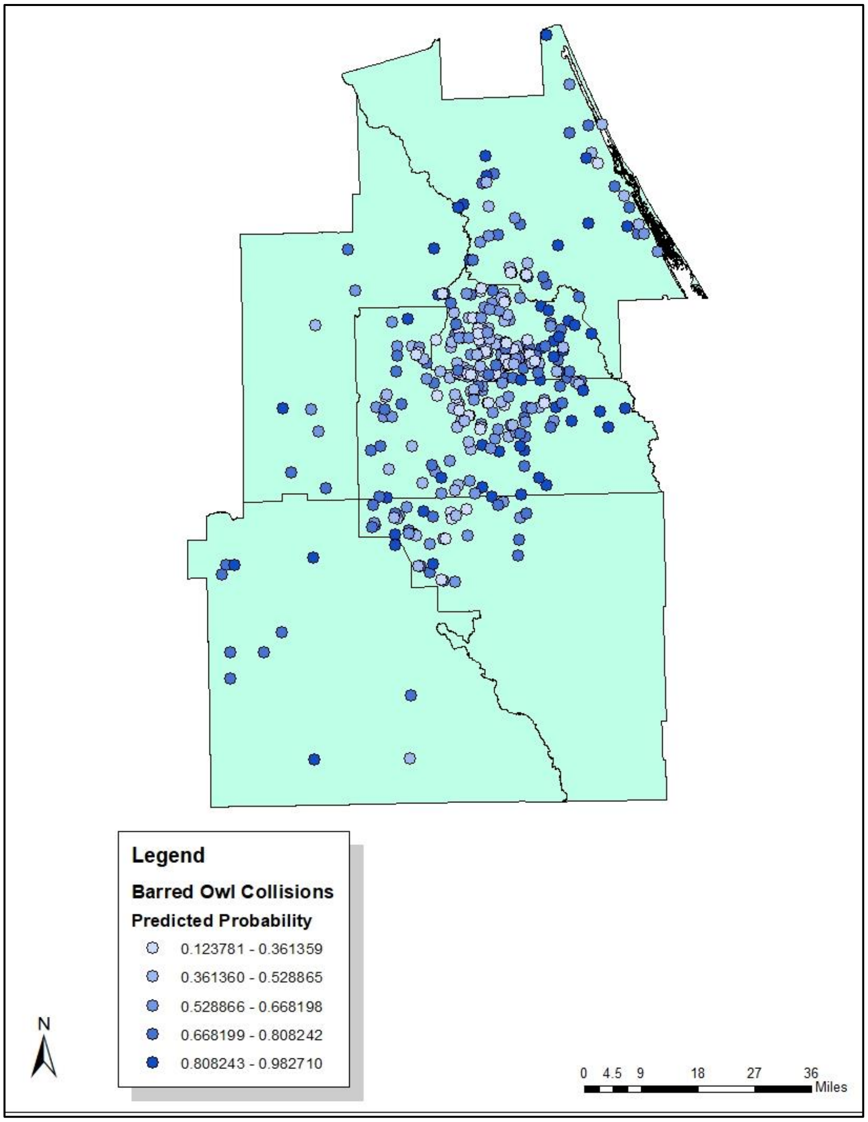

Figure 5.3: Color coded map showing a range of predicted probability associated with Barred Owl- vehicle collisions occurring in and around the Orlando, FL USA area between 2000 and 2019.

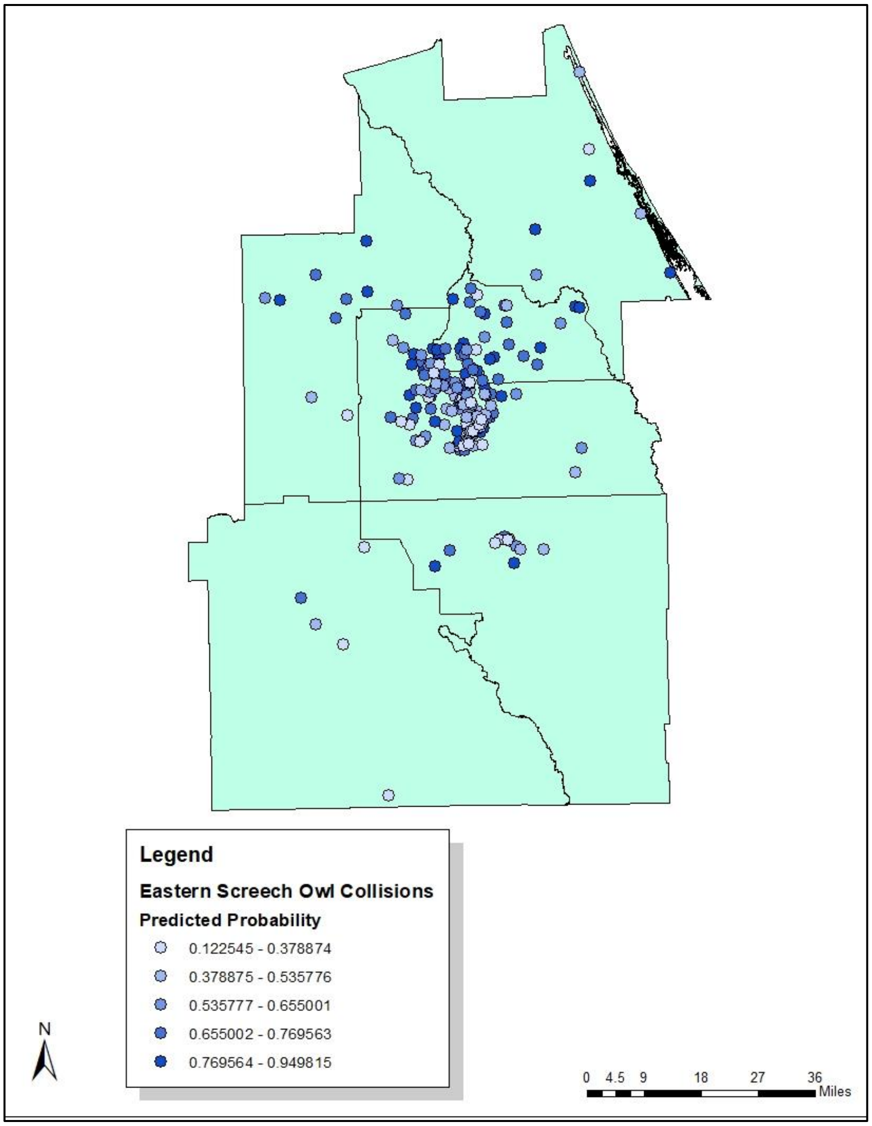

Figure 5.4: Color coded map showing a range of predicted probability associated with Eastern Screech Owl- vehicle collisions occurring in and around the Orlando, FL USA area between 2000 and 2019.

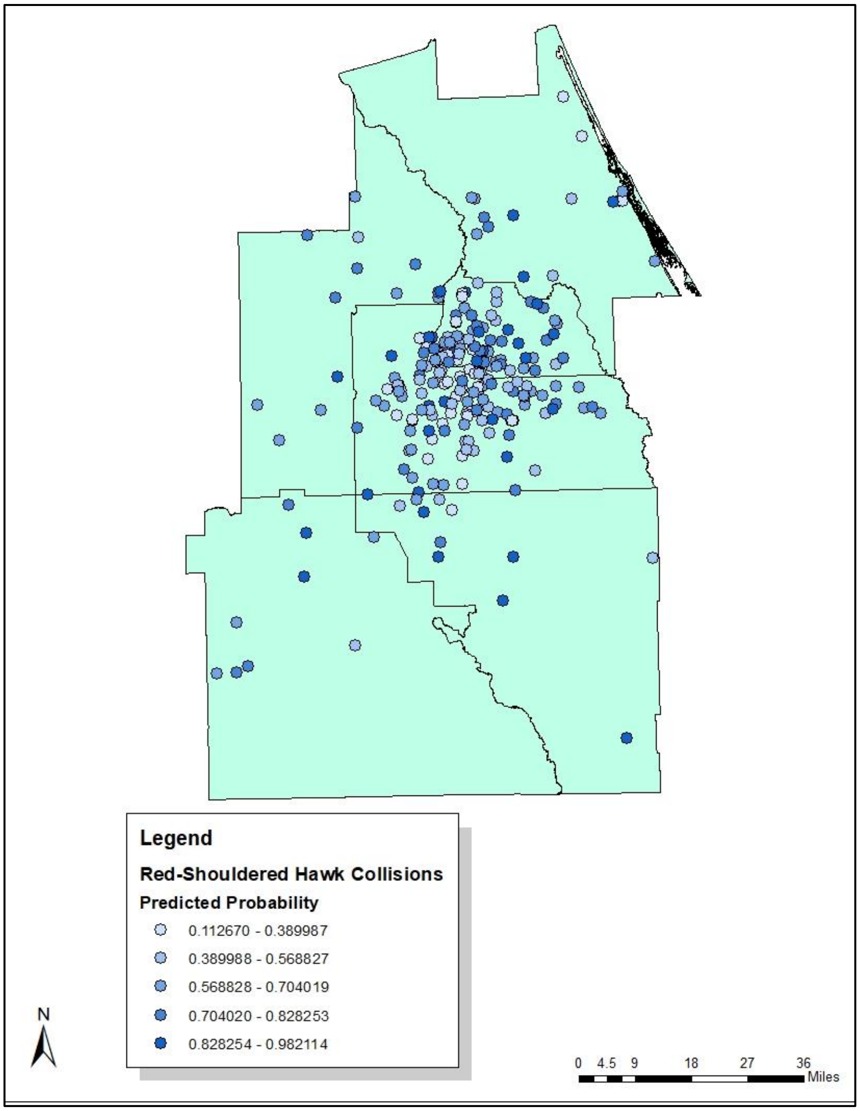

Figure 5.5: Color coded map showing a range of predicted probability associated with Red-Shouldered Hawk- vehicle collisions occurring in and around the Orlando, FL USA area between 2000 and 2019.