Identifying Areas of High Risk for Avian Mortality by Performing a Least Accumulated-Cost Analysis

by

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List of Abbreviations

AGL - Above Ground Level

AVHRR – Advanced Very High Resolution Radiometer

ANF_BCR – Atlantic Northern Forest Bird Conservation Region

BCC – Birds of Conservation Concern

BCR – Bird Conservation Region

BNA – Birds of North America

DEM – Digital Elevation Model

GIS – Geographic Information System

GPS – Global Positioning System

IDW – Inverse Distance Weighted

JCU – Jaguar Conservation Unit

NCDC – National Climatic Data Center

NOAA – National Oceanic and Atmospheric Administration

RSF – Resource Selection Function

UV – Ultraviolet

Abstract

Millions of birds are killed every year during their annual migration by colliding with tall communication towers and buildings. The goal of this study is to identify areas of specific concern for avian species during migration by modeling potential migration corridors for Red-eyed Vireo (*Vireo olivaceus*), Kirtland's Warbler (*Setophaga kirtlandii*), and Golden-cheeked Warbler (*Setophaga chrysoparia*) as a case study. These avian species perform transcontinental migrations each year. This study uses a least accumulated-cost analysis to predict probability of use of routes between winter and summer ranges by analyzing the presumed energetic cost of changing altitude (in response to topographic relief), traversing large bodies of water, and compensating for wind. Previous descriptions of migration pathways depict straight lines that do not take into account geographic barriers. This study compares the results of existing methods to the least accumulative cost model. The completion of the analysis on Red-eyed Vireo allows the same analysis to be performed on two more rare species, the Kirtland's Warbler and the Golden-cheeked Warbler. The results of this study show that least accumulated cost analyses are a viable option to assisting in determining preferred migration routes for migratory birds. Least accumulated-cost analyses demand significant computing resources, which can prevent studies of this size from being performed. Advances in technology now enable studies of this magnitude to be performed and this study is a proof-of-concept to illustrate the potential benefits of integrating these analyses into conservation planning.

Chapter 1 Introduction

Millions of birds are killed every year in collisions with tall communication towers and tall buildings (Klem 1990, Longcore et al. 2012, Loss et al. 2014). Studies have examined the effect on mortality rates of the characteristics of towers (Longcore 2006, Longcore 2008, Gehring et al. 2009, Gehring et al. 2011) and buildings (Klem 2009, Klem et al. 2009). The effects of landscape configuration on the number of birds colliding with towers and buildings is still largely unknown. Avian mortality at obstructions is influenced by the concentration of birds at an obstruction and the characteristics of the obstruction. Concentration of Neotropical migrants at a location is likely influenced by many factors, including the location of the breeding and wintering grounds, combined with static landscape features at several scales (ridgelines, mountains, water bodies), location of habitat patches that are somewhat fixed but vary over time, and ephemeral phenomena such as day-to-day weather conditions and prevailing winds.

Three primary factors affect the flight paths of migrating birds at the local level: (1) end destination, (2) fuel, and (3) wind (Alerstam 2011). The end destination is a long term/distance measure that is a guide for the bird’s flight direction. Fuel is necessary for birds to complete the migration. Stopping spots with foraging opportunities will influence birds to alter off the shortest route. Wind plays an important role in the amount of energy a bird must exert in order to arrive at the end destination. A tailwind is preferable because it reduces the amount of energy required. The balance of these factors will result in the optimal flight path for a migration.

1.1 Motivation

This project is not directed to relate the number of avian collisions with towers to geographic features. It is, however, poised to reduce the amount of mortalities of migratory birds. This is done by predicting migration corridors that depict where birds concentrate during migration. This information has the ability to decrease avian mortality by showing conservation organizations, governing bodies, and private enterprises the areas where more concern should be given when constructing tall towers or in assessing the risks of tall building construction. The development of this method of estimating migration routes also allows researchers to focus on specific areas, locate potentially important stopover points and better understand the risks facing species during migration.

The completion of this project will be valuable for the scientific community in that it does show that least accumulated-cost analyses are able to be performed for birds at this broad of scale. The previous methods of modeling bird migration do not take geographic features into account as major influences on migration. We know barriers have an effect on migration and the least cost analysis will help to model these effects. This analysis compares the previous methods to the benefits of the least cost analysis.

This study is performed with the small migratory songbirds as the subject but the concept of using the corridor tool at a continental scale can be used in many fields. Waterfowl are another species that conduct long migrations perennially. Millions of dollars are spent every year to aide in the conservation of waterfowl habitat. It is crucially important that these resources are allocated appropriately. The use of a transcontinental least accumulated-cost analysis could provide information as to the locations of high concentrations of migrating waterfowl. This information could be used to ensure that resources are being used correctly to conserve the habitats that waterfowl will visit during their annual migration. This is just one example of how this study could be used to inform future research directions.

This study is a proof of concept showing that least accumulated-cost analyses can be used to accurately model bird migration flyways. When performing least cost analyses it is critical that the variables are parameterized correctly. Results can be skewed easily so care must be taken to ensure weights are assigned appropriately. This study used a common species, the Red-eyed Vireo, of which the migration patterns are well documented to determine how to correctly parameterize the variables. Once successful, the same parameters were used to predict the migration flyways of two rarer species, the Kirtland's Warbler and the Golden-cheeked Warbler. The results of the analyses of the rarer species show that least accumulated-cost analyses are capable of predicting bird migration routes but also provides valuable information as to the attention to detail necessary to create reliable results.

Chapter 2 Related Work

The annual migration performed by countless birds every year is an important part of the global ecosystem and human development is making it increasingly difficult to complete. This chapter begins with a review of bird migration and how it has been modelled historically. A discussion of map projections is included because the different methods of modeling migration require the projection to have certain attributes. A description of similar analyses using the least cost method of modelling corridors is used to describe the benefits of this type of analysis. This chapter concludes with a summary of the Red-eyed Vireo and its migration, as well as the Kirtland's Warbler and Golden-cheeked Warbler. An examination of the effect human development is having on bird species will round out the chapter, discussing the implications of creating a model to help identify migratory routes.

2.1 Migration

The annual journey of migratory birds is an extraordinary example of the majesty of the natural world. The feats that some of the world's birds accomplish are breathtaking. It is during this migration that human development takes its greatest toll on the bird populations, from destruction of stopover habitats to the construction of deadly barriers. This analysis can aide in the reduction of avian mortality by accurately modelling migration patterns to provide information on conservation priority areas. This involves analyzing the influential factors that affect migration.

The three most important factors in determining migration route are end destination, fuel, and wind (Alerstam 2011). There are barriers such as mountain ranges and large water bodies that have an impact on the preferred route of migration. Birds allow a wind to veer them off course just to stay in a tailwind (Elkins 2004). The tailwind allows the birds to save energy and migrating birds follow the tailwind up to the point at which the extra mileage will begin to cost energy instead of saving energy. This analysis obviously includes the end destination but does focus on geographic barriers and how wind assists birds in overcoming them.

Large bodies of water can be significant barriers to migration. These can range in size from the size of local bay to the Gulf of Mexico to the Pacific Ocean. The Black Brant (*Branta bernicla nigricans*) is known to undertake a direct migration across the Gulf of Alaska that stretches over 5000 km without a chance to refuel (Purcell and Brodin 2007). They accomplish this from help of wind currents. A study of raptor migration in southern Spain showed that most species were more inclined to cross the Mediterranean Sea when there was a northern wind to aid the flight (Meyer et al. 1999).

This analysis of songbird migration contains two main barriers; the Appalachian Mountains and the Gulf of Mexico. The gulf is significant because seasonal wind patterns play an important role in whether vireo will cross or circumnavigate. A study in Louisiana of correlations between wind direction and passerine movement showed that the routes mimicked the wind direction (Able 1972). The same study analyzed wind patterns and determined that only under specific conditions where a strong front entered deep into the gulf were there preferable conditions for a southerly migration. Average wind direction for the Gulf of Mexico is of a southeasterly direction for both spring and fall .This influences passerines to circumnavigate during fall migration. The same wind patterns persist during spring while they contrarily persuade birds to cross the gulf during the spring migration. Many observers have reported underweight passerines along the north gulf coast during spring migration (Moore et al. 1990, Kuenzi and Moore 1991). This finding provides evidence that birds are crossing the gulf during the spring migration even though the energy costs are high.

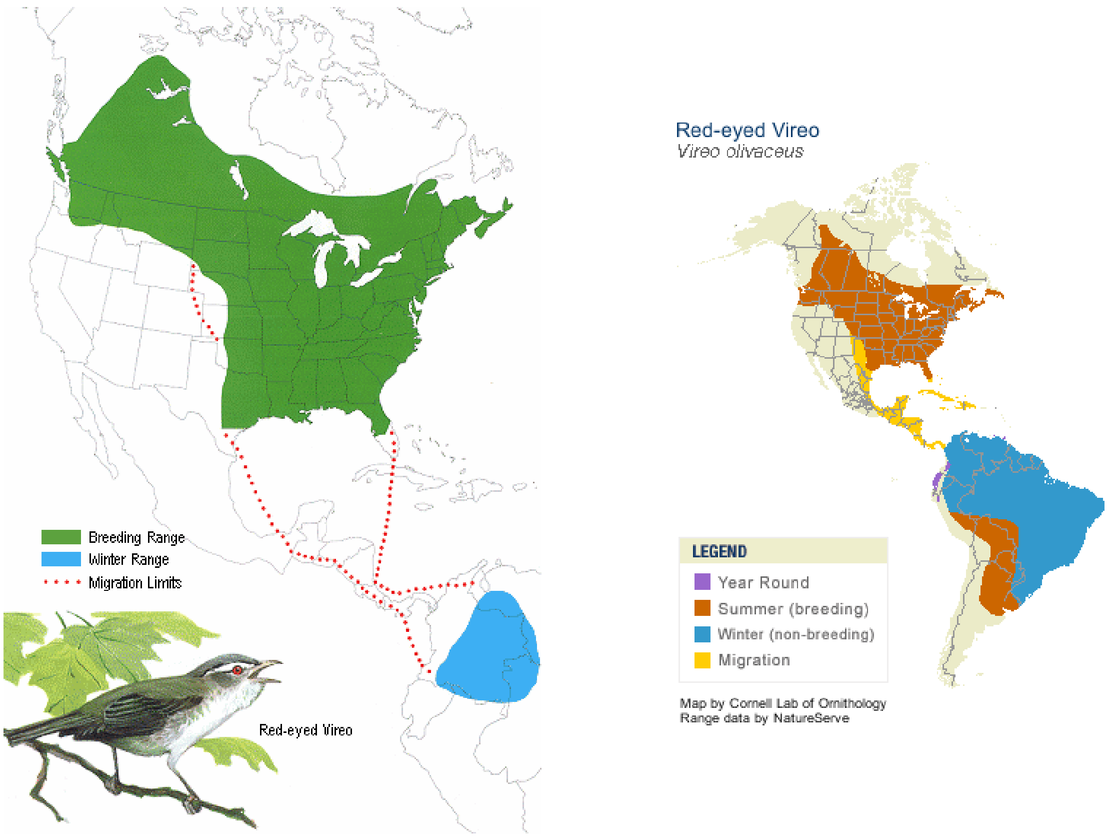

Figure 1 Maps of Red-eyed Vireo migration created from sighting location data. *Source*: Lehigh University (left) and Cornell University (right)

Some birds wait at stopover sites until a favorable wind appears and then take off in the preferred direction. A study of Turkey Vultures (*Cathartes aura*) in North America showed that during fall migration crosswinds were used by the vultures to gain elevation on the Appalachian Mountains, following which they would glide back down in a southerly direction (Mandel et al. 2011).

In the past, estimation of migratory routes was based on recorded sightings of a species. These estimates can be considered fairly accurate because they reflect actual sightings of birds during the migratory period. The problem is that migration maps of common species are vague because the species have a vast migration corridor. The rarer species often do not have enough recorded sightings to create a reasonable depiction of the migratory pathway. Radio transmitters have been used in the past but are short range and are used more often during breeding or wintering seasons (Nakamura et al. 2005). Advances in technology are enabling researchers to more accurately model the migration patterns of migratory birds. Large birds are able to wear GPS (Global Positioning System) collars which allow researchers to track their movements during migration (Mandel et al. 2011). Recently, the use of satellite transmitters have enabled birds as small as 100 grams to be tracked during migration (Fiedler 2009).

There have been methods developed to identify migration routes for a variety of animal species using a GIS (Geographic Information System) approach that do not take species distribution data into account. These methods use geographic features to predict the corridors animals use to traverse an area. Few studies have tried to use this technology to model bird movements. A simple answer for why this is would be that birds fly and terrain would therefore play a lesser role in determining their preferred route. While it may be true that birds can fly over obstacles but to say that geographic features do not affect avian migration would be false. This project suggests that geographic features play a more important role than previously believed and that they may be used to predict migration routes of bird species.

Historically, there have been two methods of theoretically modelling avian migration without species sighting records; constant bearing and shortest distance (Gudmundsson and Alerstam 1998). The constant bearing method assumes that birds know the exact direction of their destination from any given point on the Earth. They follow a constant bearing through their entire migration in order to reach their destination as mariners would use the North Star to navigate the open ocean. This however is not the shortest distance that one could travel between two points on the Earth. Gudmundsson and Alerstam (1998) proposed that birds may have the intuitive knowledge of shortest distance and will be constantly changing bearing to reduce the amount of ground they must cover.

Red-eyed Vireo have wide breeding and wintering ranges so connecting the two with migratory routes can be difficult. It is a common species so there are a lot of data on recorded sighting with which to create maps. Previous research shows that the birds migrate through Mexico or follow the Florida peninsula to reduce the amount of water necessary to cross (Figure 1). This preference is supported by data of recorded sightings. The problem is that the birds also cross the Gulf of Mexico directly (Able 1972). Crawford (1980) further supported this by analyzing the number of migratory birds killed along the northern gulf coast. The data used to create the existing maps use sighting data which are primarily unavailable for vast amounts of water bodies. This eliminates the possibility of including bird sighting over the Gulf of Mexico.

The United States Fish and Wildlife Service (2014) describes the Kirtland’s Warbler migration as following a narrow band directly between Michigan and the Bahamas. They note that the migration pattern is most likely the same for both spring and fall migrations. There are very few acceptable records of Kirtland's Warblers being seen during migration. These records do not however line up with the assumed notion that the birds follow a straight line between wintering and breeding grounds. Most publications do not attempt to create a migration map because of the limited amount of available data.

2.2 Map Projection

The coordinate system chosen to depict an area can influence results of analyses performed on the study area. The choice of map projection for a study with a small study area and a large-scale can have little effect on the outcome of analyses (Steinwand et al. 1995). With the increase in study area, it becomes more important to decide on the correct map projection. The analysis in this thesis of the migration of Neotropical passerines spans across both North and South America. In a geographic coordinate system the cell size of raster data is represented in degrees. The size of a degree changes with latitude. This creates error in spatial analysis because the cell size is not uniform throughout the study area.

To solve this problem the data must be projected into a planar coordinate system where the cell size remains constant for every cell in the study area. This transfer of data from a geographic coordinate system to a plane coordinate system can cause significant error if the wrong projection is selected or incorrect parameters are set (Usery and Seong 2001). Many different projections are available to choose from and historically there has been a lack of guidance in selection of map projections.

In 1923, J. P. Goode developed the Interrupted Goode Homolosine map projection. He recognized a solution to the downfalls of the standard projections in that each had areas of high distortion. He decided to combine the Sinusoidal projection with the Mollweide projection to limit distortion at a global scale. The Sinusoidal project has little error near the equator but as it approaches the poles distortion increases. The Mollweide project does the opposite as it has little error near the poles. The Interrupted Goode Homolosine projection takes advantage of both projections by splitting the projection at 40º44’11.8” North and South (Goode 1925). This latitude is where the two projections match up making it the perfect spot to merge. The projection is divided into 12 sections of accurate depictions of landmasses. The division of the projection pushes the distortions into the oceans so that analyses can be performed accurately on the land masses (Figure 2).

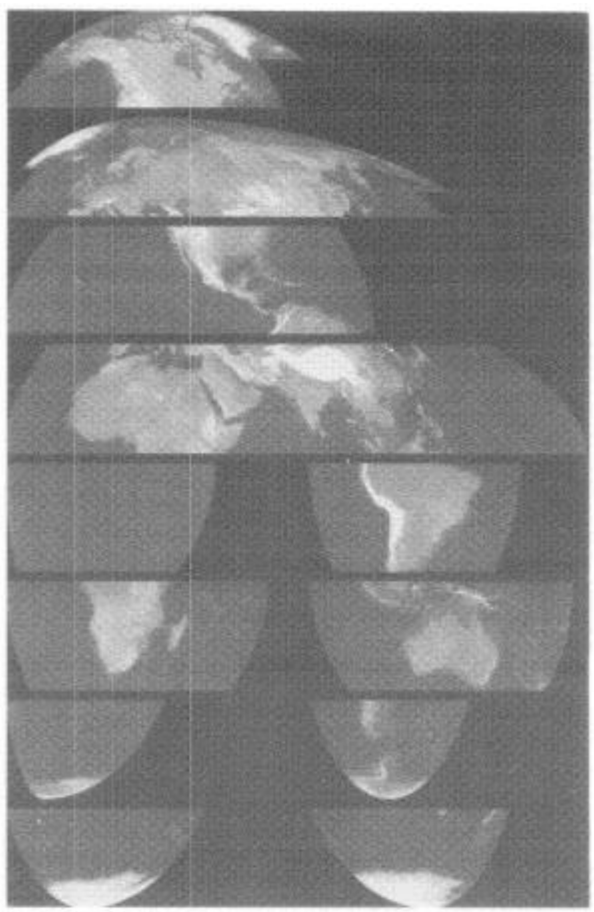

Figure 2 The 12 regions of the Interrupted Goode Homolosine Projection. *Source*: Steinwand (1994)

Steinwand et al. (1995) evaluated six map projections for use during analysis of global datasets. They suggested that the Interrupted Goode Homolosine map projection was best for global datasets because it resulted in the least amount of distortion across the globe. The Interrupted Goode Homolosine map projection was chosen for the Global Land Advanced Very High Resolution Radiometer (AVHRR) 1 km dataset as well as the AVHRR Pathfinder 8 km dataset (Steinwand 1994). The resolution of raster data also has an effect on accuracy. Usery and Seong (2001) quantified the error resulting from resampling. They determined that there is minimal error at resolutions under 8 km. The amount of distortion begins to increase steadily after 8 km.

While an equal-area map projection such as the Interrupted Goode Homolosine provides for accuracy for least cost analysis it does not maintain equal distances or bearings. This analysis compares the ideas that birds maintain constant bearing or follow the shortest route during migration with the concept that there are more factors involved than just the end destination. An orthodrome is the shortest distance between two points on Earth. A loxodrome is longer than an orthodrome but it is easier to use in navigation because it follows a constant bearing. Thus a second projection is needed. The Mercator projection is preferred for the constant bearing because it was created for just that purpose in maritime navigation. Determining the shortest distance between two points on the globe can be achieved with azimuthal projections (Gudmundsson and Alerstam 1998). The method used to predict the migration patterns directly influences the map projection used in the analysis.

2.3 Least Accumulated-Cost

An important focus in conservation is to locate corridors that link fragmented habitats. Least cost path analyses are a common tool used to do this. They use a raster with cost values assigned to each cell to determine the easiest path through a landscape. This method provides a single cell wide path to the destination. The least accumulated-cost method takes into account the cost values in addition to the distance (Etherington 2013). It can be used to identify a least cost corridor, which is more helpful when analyzing bird migration. A corridor allows for variation in migratory routes that are common with avian species.

In this thesis, I propose using a least accumulated-cost analysis to identify preferred migration corridors that birds would fly across the continents of North and South America. Red-eyed Vireo (*Vireo olivaceus*), which has a wide range spanning two continents and a known migratory pattern, is used to develop a methodology that is replicated for two rarer species. The methodology is used to examine the migration patterns of the Kirtland’s Warbler and the Golden-cheeked Warbler. Both species are rare and there is relatively little evidence on which to describe a migration corridor.

The method takes into consideration three main factors that would affect the flight pattern; slope, wind, and large bodies of water (Alerstam 2011). Slope affects the flight patterns similarly to elevation but is needed because not all locations with high elevations provide a barrier to migration. It depends on the elevation from which the bird is approaching. Not all birds refuse to fly over large water bodies. Some species prefer to fly across water and will only fly over land when necessary. These are more the exception than the rule. Migratory passerines like the Red-eyed Vireo do not prefer long water passages. In this study, large water bodies are assigned high cost values, which incorporates the difficulty of crossing water bodies into the corridor model. Wind had have positive and negative values that represent whether the wind assists or hinders the energy costs of migration.

The method used to perform this analysis began with calculating the cost distance from both summer breeding grounds and wintering locations. Calculating the accumulated-cost of traveling from one cell to a source location does this. Cost distance was calculated for every cell in the study area for both the breeding and wintering habitat locations. This study did not identify the least cost path because it is too specific and unrealistic of migrating birds. The goal was to find the corridor in the landscape that provides the easiest migration possible. A cost corridor displays the total cost to travel between two locations for every cell in a raster. A cost path simply shows the easiest single cell wide route between two locations (Etherington 2013). The vagueness of a corridor allows for the variability of migration patterns. The need for refueling at stopover sites and the advantageous use of a tailwind that might drift a bird off course create this variability in the flight paths. Once cost distance rasters are created for both habitat locations the least accumulated cost surface can be made. This surface is a combination of the three cost distance rasters. For every cell in the study area, the least cost path is found to both locations. The output raster depicts the area connecting the two habitat locations that has the least cost to travel. The result is a clearly defined corridor that represents the easiest migration route.

The least cost approach has been used to model portions of avian migration pathways. Downs and Horner (2008) used least cost modelling to determine the most efficient stopover locations for migrating birds. They examined a section of the migration and ran least cost analyses between known stopover locations to determine the best route for the birds. This shows that least cost analyses can be used for avian species.

It would be a rare instance that an animal would take the exact least cost path through a landscape. It follows the path of least resistance but there are many variables that cannot be taken into account. There could be temporary blocks to the least cost path making the use of corridors ideal. This idea of using wider corridors allowing for variability was tested by Cushman et al. (2009) in a study on Black bears (*Ursus americanus*). He stated that a broader scale of study will include this needed variability. His study consisted of 160 source locations and 160 destinations. He created single cell least cost paths between all source and destination locations. He then summed all paths together to show all possible routes. His study used the gene flow of bears in the north portion of the study area to determine the ease of movement through the landscape. This allowed the study to use empirical evidence to assign cost values instead of just expert opinion. Cushman et al. (2009) were not able to perform validation of his results because it would take extensive research of tracking many individual bears.

Having realized the importance of connectivity between habitats, Richard Walker and Lance Craighead (1997) conducted an analysis linking the Greater Yellowstone, Northern Continental Divide and Salmon-Selway ecosystems. They performed the analysis three times, once each for elk (*Cervus canadensis*), grizzly bears (*Ursus arctos*) and cougars (*Puma concolor*). They were required to assign different weights to the landscape inputs for the cost surface. The three inputs were habitat quality, amount of forest, and road density. The similarity in results shows limited sensitivity based on the weights of inputs to the cost surface. Sensitivity to changes in resistance values can vary between species. The species chosen for this study have similar habitat preferences so it makes sense that they would have similar migration corridors.

While studying Desert bighorn sheep (*Ovis canadensis nelson*) it was shown that different species have their own methods and preferences of traversing landscapes (Epps et al. 2007). These varying preferences can make predicting corridors difficult. It is often the case that expert opinions are used to determine the weighting structure of cost surfaces in corridor analyses. These expert opinions can cause error in prediction models because they could vary based on who the expert is. It is important that empirical evidence is used to assign cost values. This is often difficult if not impossible because of the lack of empirical evidence of movement preference. Epps et al. (2007) used genetic flow data collected from multiple sheep populations to provide this evidence. After the study, tracking collars proved the model successful.

Sawyer et al. (2011) expanded on the work of Epps et al. (2007) by comparing it to 23 similar studies. Their literature review resulted in the identification of three main faults exhibited in least cost studies. The first is that studies are performed solely on remotely sensed data without consideration as to whether or not habitat data is a good measure of ease of movement. Second is the lack of empirical evidence and use of expert opinion. They state that studies “must clarify biological processes on which resistance values are based.” Whether expert opinion or empirical evidence is used to determine cost structure it is important to perform a sensitivity analysis to see the degree to which variance in cost structure will affect results. Thirdly, there must be validation of results. Least cost path analyses can be very useful to conservation in that they show areas that link fragmented habitat. The multiple causes of error show that they must only be used as a first step in the conservation plan and must be validated by field studies. Sawyer et al. (2011) showed that only nine of 24 studies were able to validate results.

The scale to which resistance values are assigned to cost surfaces can greatly affect the results of a least cost path analysis. Beier et al. (2009) performed a theoretical study on the effects of varying cost values. They studied eight species using four habitat factors and showed little difference between models created using varying cost structures for the five herbivore species. The three carnivorous species had alternate results showing significant difference based on various cost allocations. Similarly, a different study showed that the assignment of cost values made a significant difference in the results (Dreizen et al. 2007). Their study of hedgehogs (*Erinaceous europaeus*) showed that in unfamiliar territory it is possible to predict movement when the proper resistance values are applied. A study of the Florida panther (*Puma concolor*) used a least cost path analysis to determine possible routes for panthers to use to perform northern migrations as their existing habitat is being destroyed (Kautz et al. 2006). This study performed a sensitivity analysis and determined that the weights of cost values made little difference in results. These examples show that the results of least cost analyses are dependent on many variables including but not limited to species, habitat, landscape, and scale.

Brooker et al. (1999) created a dispersal model to determine if birds use landscape corridors in flight. The birds studied were Blue-breasted Fairy-wrens (*Malurus pulcherrimus*) and White-browed Babblers (*Pomatostomus superciliosus*). Their analysis did conclude that birds are more likely to traverse through corridors of preferred habitat.

These are sedentary birds, meaning the study only demonstrates that non-migratory birds move through preferred habitat at small scales.

A study of the Speckled Wood Butterfly (*Pararge aegeria L.*) (Chardon et al. 2003) examined the difference between cost and Euclidean distances. Researchers recorded the locations of butterfly sightings along paths in two two-hectare sections of forest in Belgium. A cost distance surface was created to represent a theoretical model of movement through the study area. The presence-absence data collected in the surveys provided a control to compare both the cost distance and Euclidean distance surfaces. The results showed that the cost distance was a much better predictor of movement through the study area. Although the Euclidean distance may be the shortest route is may often not be the easiest route for an animal to use.

In the wake of the Wenchuan earthquake in 2008, important Giant Panda (*Ailuropoda melanoleuca*) habitats in the Wolong Nature Reserve in China were found to be destroyed or isolated. Li et al. (2010) conducted a least cost path analysis to determine the best corridors between the fragmented panda habitat. The results provided information on how and where the reconstruction efforts should be performed. Meegan and Maehr (2002) used land cover data to perform a least cost path analysis to identify corridors for migration of the Florida Panther to new potential habitats north of the Caloosahatchee River. Forest, urban and roads layers were used in the analysis with buffers applied to each. The analysis successfully provided a path to the new potential habitat. The results were validated with radio telemetry data. Between the years 1998 and 2000 three radio collared panthers were recorded crossing the river within four km of where the least cost path analysis predicted.

The California Tiger Salamander (*Ambystoma californiense*) is a threatened amphibian species which uses specific habitats. Wang et al. (2009) created a model of corridors between preferred salamander habitats using a least cost path analysis. Researchers surveyed salamanders in 12 ponds to perform a gene flow analysis. A least cost path analysis was then conducted between each of the ponds. The habitat was classified as grassland, chaparral, and oak woodland. The least cost path analysis in this study was used to determine the cost of moving through habitat instead of creating the corridors.

The use of expert opinions to create a cost raster can increase the risk of error in the results of a least cost path analysis. Opinions are inherently subjective and depending on the expert providing the opinion it can alter the outcome of the study. Chetkiewicz and Boyce (2009) developed a model that uses resource selection functions (RSF) to develop cost rasters to be used in least cost path analyses. The RSFs were created from telemetry data of cougars and grizzly bears wearing GPS collars. The telemetry data provided a model of preferred habitat from which they created the RSFs. High values of RSF meant preferred habitat so they were inverted to create the cost raster. The results showed that the RSFs can be used to more accurately model least cost paths than expert opinion.

Until recent years, most least-cost analyses created single cell wide paths between source locations. With the addition of the corridor function in ArcMap it is possible to model more realistic corridors of wildlife migration. Rabinowitz and Zeller (2011) used the corridor function to perform a least accumulated-cost analysis modeling linkages between Jaguar Conservation Units (JCU) in Central and South America. The corridor function then calculates a least-cost path for every cell in the study area between the two source locations that passes through the cell. These paths are all summed together to create a model of least-cost corridor.

The landscape characteristics used in Rabinowitz and Zeller's study were land cover, percentage tree and shrub cover, elevation, distance from roads, distance from settlements and human population density. All layers were resampled to one km^2 and projected in the same planar coordinate system. This study averaged the opinions of 15 experts who assigned cost values between 0–10. The six rasters were summed together with the raster calculator function. The cost distance function was run for each of the 90 JCUs included in the study. The corridor function was used for all proximate pairs of JCUs. The researchers used the minimum mosaic method to combine all the corridors together. All corridors found that had a width less than 10 km were marked as a concern that they may be severed if no actions were taken. The results of the study were validated with presence/absence data. This analysis on the Red-eyed Vireo followed a similar methodology to determine corridors of high bird concentrations during annual migration.

2.4 Species of Study

This study was aimed to test the possibility of using a least accumulated-cost analysis to model bird migration patterns. It was decided to use one common species, Red-eyed Vireo, of which the migration patterns are known to determine how to set the parameters of the study. Once the parameters were set so that the results of the analysis resembled the actual migration flyway the same parameters were transferred to two rarer bird species, the Kirtland's Warbler and Golden-cheeked Warbler. The following sections provide background information about these bird species that were included in the study.

2.4.1. Red-eyed Vireo

The Red-eyed Vireo is a small songbird that is one of the most common species in eastern North American forests. Red-eyed Vireo undertake a transcontinental migration every year. The peak periods of migration for the Red-eyed Vireo are in April and September. The Red-eyed Vireo have an extensive breeding range spanning from British Columbia, Canada to the northern part of Florida. Saskatchewan, Manitoba, Ontario, Quebec, Newfoundland are the Canadian provinces that hold vireo in the breeding season. The United States of America have vireo spending the breeding season in the Midwest, the northeast, the southeast, and the states of Washington, Oregon, Idaho and Montana. The annual migration takes the Red-eyed Vireo down to South America. Colombia, Venezuela, Guyana, Suriname, Ecuador, Peru, and western Brazil are the recorded wintering ground for the Red-eyed Vireo (Cimprich et al. 2002).

A migration from North to South America would either need to follow through Mexico, down the peninsula of Florida or cross the Gulf of Mexico. There is evidence that suggests that some Red-eyed Vireo do cross the Gulf of Mexico during their annual migration (Crawford 1980). A number of variables, however, factor in to whether the bird will attempt the crossing. Favorable weather and the amount of fat storage are the two that researchers have agreed upon (Able 1972, Alerstam 2011). Poor weather conditions may persuade a bird to utilize the safer route around the gulf. Records of captured birds during the spring migration on north coast of the Gulf of Mexico showed a mean mass of 15.9 grams which is only 1.3 grams above the fat free body mass of Red-eyed Vireo (Cimprich et al. 2002). Captured birds at the same location during the fall migration, before they cross the gulf, showed a mean mass of 19.7 grams, 5.1 grams above fat free body mass. This finding indicates that a large amount of fat storage is needed to cross the

Gulf of Mexico. Mean mass of vireo during the beginning stages of the fall migration is only 20.7 grams for an adult male (Cimprich et al. 2002). The implication of this measurement is that only a single gram is lost as the bird migrates across North America but it loses four grams crossing the gulf.

2.4.2. Kirtland's Warbler

The Kirtland's Warbler (*Setophaga kirtlandii*) is one of the rarest songbirds in North America (Bocetti et al. 2014). They have a very specific preference to habitat for both breeding and wintering. The breeding area for the species is mostly located in the northern section of the lower peninsula of Michigan. There have been records of some nests expanding into eastern Wisconsin. The Kirtland's Warbler winters almost exclusively on a single island in the Bahamas, Eleuthera. Existing maps of Kirtland's Warblers depict a straight line from Michigan to the Bahamas (Figure 3).

Figure 3 Map of estimated migration pathway of Kirtland's Warbler. *Source*: Bocetti et al. 2014

Estimates of the species population fell to as low as 400 individuals in 1972. (Mayfield 1972). The reduction of the preferred habitat was critical to the decline in population. Conservation efforts have been effective and by 2012 it is estimated that the population is over 4000 individuals. Even though the population is growing there are still threats to the species survival. Very few sightings of the Kirtland's Warbler during the migration months have been verified (Figure 4).

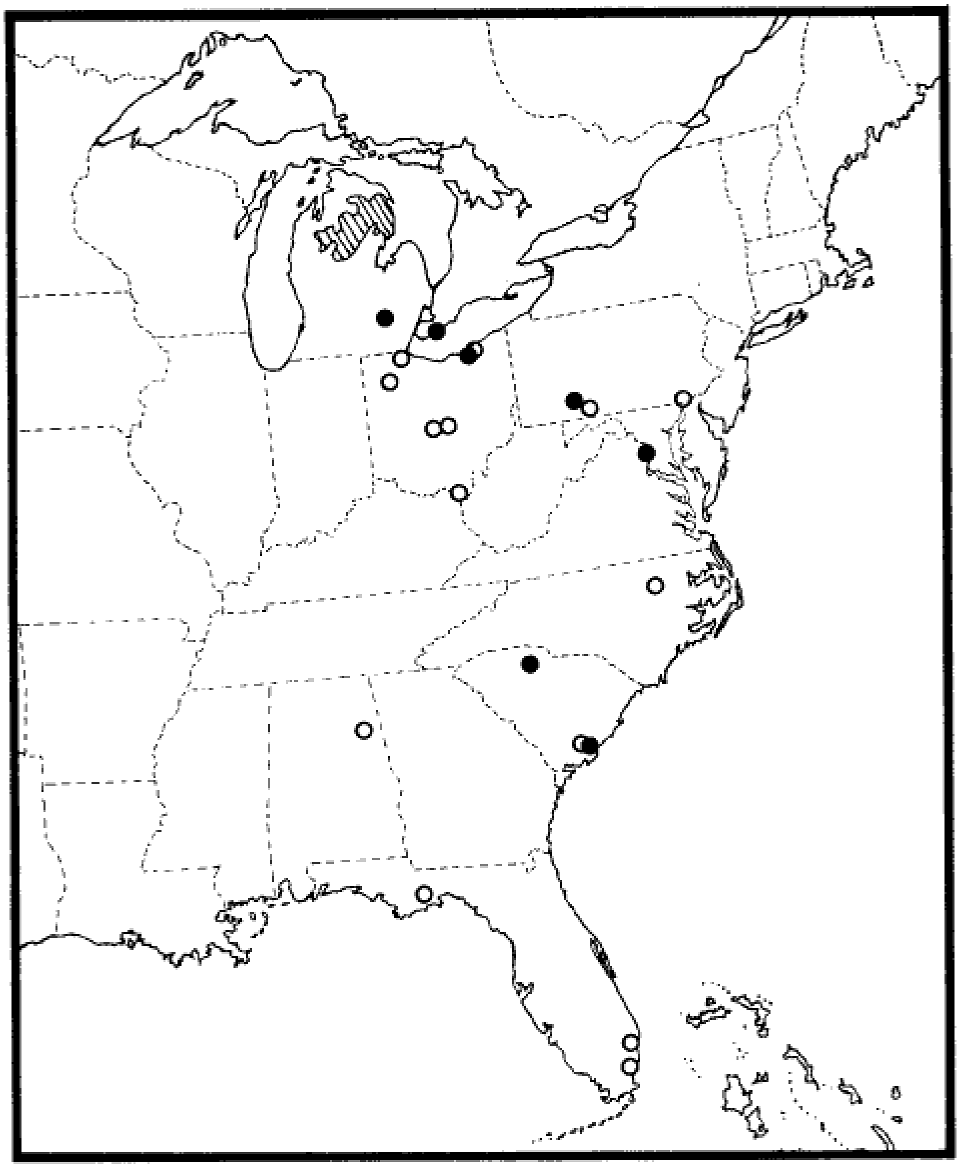

Figure 4 Records of Kirtland's Warbler during migration up to 1972. *Source*: Clench 1973

Petrucha et al. (2013) analyzed records of previous sightings and showed that the migration flyway of the Kirtland's Warbler is not as narrow as it was previously understood. Records of sightings range across the entire eastern United States (Figure 5). It is no longer reasonable to believe that an entire species will follow a narrow migration flyway, even when the population is as small as the Kirtland's Warbler. It has been noted that the breeding range is expanding into Wisconsin and with this expansion the migration flyway should expand westward as well.

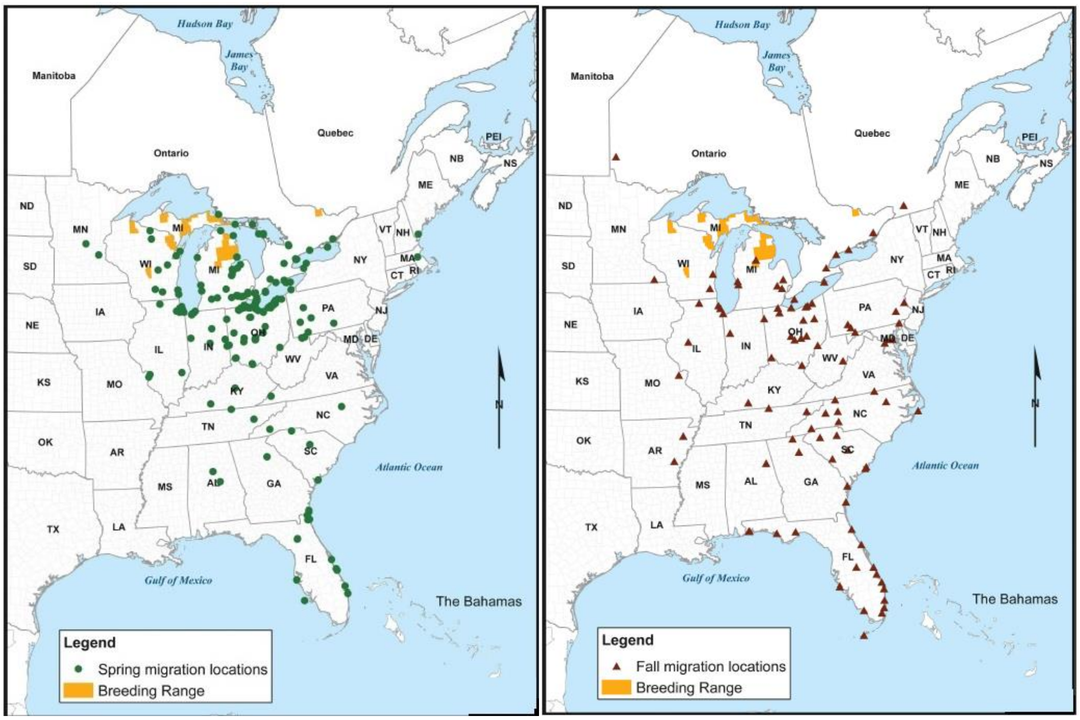

Figure 5 Spatial distribution of reputable spring (left) and fall (right) sightings of Kirtland's Warblers up to 2013. *Source*: Petrucha et al. 2013

2.4.3. Golden-cheeked Warbler

The Golden-cheeked Warbler (*Setophaga chrysoparia*) is another rare and endangered species that is at risk from collisions during its migration. The have been records of the species at elevations over 1000 meters along the Sierra Madre Oriental (Groce et al. 2010). The breeding range is located in central Texas while the wintering range is in southern Mexico and spans into neighboring Central American countries (Ladd and Gass 1999). The rarity of this species lends to gaps in knowledge pertaining to habitat and behavior.

2.5 Avian Mortalities in North America

Millions of birds are killed by tall structures every year. There have been studies that have evaluated the causes of these fatalities (Gehring 2009, Gehring 2011, Longcore 2006, Klem 2006). The studies can be divided into two categories: those that focus on fatalities by collision with communication towers and collisions with buildings. The characteristics of the two types of structures that affect mortality rates vary greatly.

Communication towers can be deadly obstacles to migrating birds. Gehring et al. (2009) performed a study that examined the characteristics of these towers to determine why more birds die at certain towers than at others. The study analyzed the number of fatalities that occurred at 24 towers throughout the state of Michigan during peak migration periods over three years. Three of the towers were over 147 meters above ground level (AGL) while the remaining were under 146 AGL. The study showed that towers equipped with flashing lights as well as non-flashing lights were responsible for most of the fatalities at communication towers. It is predicted that fatalities could be reduced by 50–70% by removing non-flashing lights from communication towers. The study also showed a higher mortality rate at the taller towers but there were not uniform light specifications so exact numbers could not be determined.

Gehring et al. (2011) used the same data that was collected for their previous study to analyze the affect that guy wires have on mortality rates. It is noted that Red-eyed Vireos were the most common species found during all study periods. The study states that the birds are colliding with guy wires and that 69–100% of fatalities could be prevented by constructing towers without guy wires. It is also shown that 68–86% fewer fatalities occur at the shorter communication towers (note that the tall towers are equipped with non-flashing lights).

Collisions with buildings occur at a higher rate than with communication towers simply because there are an exponentially larger amount of buildings than towers. This leads to the analysis of characteristics of buildings with higher mortality rates. In 1990, Dr. Daniel Klem Jr. performed a study to show that glass windows do kill birds and how to prevent avian fatalities. His study contained three experiments. One studied the collision occurrence rate at two homes in Illinois. One in a rural setting and the other in a suburban neighborhood. The study showed similar number of collisions and a mortality rate of over 50%. The field experiment used five glass panes located on the edge of an agricultural field with four of the five panes obstructed by bird deterrents. These deterrents were silhouettes of a swooping flacon and an owl, wind chimes and a border of lights around the glass pane. The results from the experiment showed that the deterrents were not successful. The final experiment was with captured Dark-eyed Juncos in flight cages. The flight cages were set up with two routes out; one clear and one obstructed. The only obstructions that worked were a solid cloth drapery and very tight patterns. The study cited an instance where an Indigo Bunting (*Passerina cyanea*) was banded after being wounded by a collision with a window and the same bird was recovered dead after hitting the same window one year later.

Dr. Klem stated in his 2009 study that the unintentional killing of birds by windows is the largest human associated source of avian mortality except habitat destruction. This later study follows a similar model to his 1990 study in that he used the same field and flight cage experiments. This study provides ways to prevent collision with windows by using Ultraviolet (UV)-reflecting and UV-absorbing window coverings. These coverings offer no obstruction to humans looking out but portray obstructions to birds, preventing collisions. The experiment with glass panes in the field showed that the films successfully deterred birds from colliding with the glass panes. The flight cage experiment showed that stripes of the UV-reflecting film and the ceramic frit dot pattern were most successful in the deterrence of birds. It is cited that the Swarthmore College has experienced as few as two collisions per year since installing windows with the ceramic frit dots. Similarly Muhlenberg College installed the dots on one side of a building and not a single collision had occurred in the first year since installation while the other side of the building, with clear glass panes, saw 12 instances in that same year.

A study was performed on Manhattan Island, NYC in 2009 to determine the effect the building design and landscape context have on the occurrence of birds colliding with buildings (Klem et al. 2009). The grounds surrounding 73 buildings in Manhattan were monitored daily over 56–58 days in the fall of 2006 and spring of 2007 to record deaths of birds by colliding with the buildings. Each building was assigned values of percentage of vegetation around the building and percentage of building façade made of glass. The amount of vegetation is important and can lead to higher collision rates because it provides habitat and also can be reflected in glass façade encouraging collisions. The results of the monitoring showed that 475 birds were killed in the fall while only 74 were killed in the spring. Over 80% of collisions were fatal during both study periods. Less than three-percent of fatalities occurred at buildings with little reflective glass on the façade of the building.

It is difficult to estimate the amount of birds that are killed every year by communication towers. The most recent study was performed by Longcore et al. (2012, 2013). They were the first to incorporate variation in mortality by region and species. The goal was to determine biological significance of the mortality rates of individual species. Longcore et al. define a biological significant impact as one that would "adversely affect a species or its habitat and could be expected to affect population growth or stability of species and influence population's long-term viability." It is estimated that 6.8 million birds are killed every year by collisions with communication towers (Longcore et al. 2012). The number of each species killed by towers was determined by multiplying the estimate of mortality by region by the average proportion each species found in tower kills by region. This study used many different reports of fatalities which increased the accuracy compared to previous studies. Weighting studies by species number only within the Bird Conservation Regions decreases the amount of geographic bias based on species distribution. The results of the follow-up study showed that 97.4% of birds killed at communication towers were Passerines (Longcore et al. 2013). 13 of 20 bird species killed most frequently, by percentage of population, are identified as Birds of Conservation Concern (BCC) or endangered. Every year, an estimated 9 and 5.6% of the Yellow Rail and Pied-billed Grebe populations are killed by communication towers. Both are on the BCC list.

Contrary to Klem (2009), Loss et al. (2014) stated the number of fatalities caused by collisions with buildings is second to predation by feral and pet cats. The difference in the statistics is because of an update in the estimate of number of birds killed by cats. Loss et al. (2014) conducted a literature review to estimate the number of birds killed annually by collisions with buildings. They reviewed 23 studies and collected over 92,000 fatality records. The study estimated between 365 and 988 million birds are killed every year by colliding with buildings. The study also attempted to determine species vulnerability. They standardized datasets and summed the counts for each species. Then the counts were regressed by log10(x+1) by population size. This resulted in seven species listed on the BCC list as being disproportionately vulnerable to building collisions.

The creation of a method that can predict the migratory pathways of birds could assist in developing policies to prevent avian mortality. As of now, finding dead birds is a useful tool in determining the migratory pathways. Geographic features play an integral role in which routes birds use during their migration. Being able to assign weights to different features will allow researchers to predict migration. Once a basic methodology is proven to be practical it can be expanded upon and used for more broad and specific applications.

Chapter 3 Methods

A study of the Red-eyed Vireo is used to create a method of predicting migratory pathways. A least accumulated-cost analysis is used to model the migration of Red-eyed Vireo by assigning weights to three of the main factors determining their route. The analysis combines multiple criteria in a single raster and determines the easiest route through the study area from both the breeding and wintering locations. The least accumulated-cost analysis combines both layers to create a corridor showing the easiest routes between both locations. Once a correct model of the vireo migration was created, the same parameters were used to predict the migration flyways of two rarer species, the Kirtland's Warbler and the Golden-cheeked Warbler.

3.1 Data Used

A least accumulated-cost analysis requires many data that come from various sources. It is important to combine all of these data properly. Some data were used purely as a guide for the parameterization of the resistance values, particularly data taken from the crowd-sourced website, ebird.com. This data shows the locations of sightings of species of birds around the world.

3.1.1 Digital Elevation Model

The GTOPO30 dataset includes DEM data for the entire globe. Copies of the GTOPO30 dataset for the continents of North and South America were downloaded from ArcGIS Online for use in this analysis. They were then merged together using the Mosaic function in ArcGIS and saved to the local hard drive. It was then projected into the Interrupted Goode Homolosine map projection with a resulting cell size of 1318.218206 meters. As mentioned earlier, the amount of error in the shape and size of the landmasses increases rapidly with cell sizes greater than eight kilometers, which is why the GTOPO30 data was chosen.

3.1.2 Source and Destination Areas

Red-eyed Vireo are a common species and much is known about their migration patterns. This assists in the development of a method to predict migratory routes because we know what the results should look like. A shapefile of the Bird Conservation Regions (BCR) in North America was downloaded from the United States Geological Survey website (www.pwrc.usgs.gov/bba/). It contained all of the BCRs while only the ANF_BCR was needed. The source features for the Cost Distance function are the Atlantic National Forest BCR (ANF_BCR) and the country of Ecuador. These locations were selected because they are known as breeding and wintering locations of Red-eyed Vireo. The path between the two locations have several barriers to migration which help in testing the hypothesis that we can model the migration without species distribution data. After the shapefile was imported into ArcGIS and the ANF_BCR was selected the feature was exported to a local database as its own shapefile. The shapefile for Ecuador was downloaded from ArcGIS Online and also copied to the local database.

3.2 Development of the Resistance Raster

A least accumulated-cost analysis spanning the entire length of North and South America would require higher processing capabilities than available so the study area was clipped to the exact extent necessary. The analysis of the Golden-cheeked Warbler had a small study area west of the other two species so a separate raster needed to be created. To do this, shapefiles were created and rectangles drawn around the study areas. The Clip function then used this outline to create new rasters of only the necessary extent. The cost rasters for the analysis were based off of a slope raster created from the DEM. This slope raster was modified to include water and wind values.

3.2.1. Calculation of Slope Resistance Values

Elevation is not in itself a good metric of the difficulty of moving through space. If the bird is already at 1000 m elevation then a cell of 1005 m would not be particularly difficult to cross. Therefore, the change in elevation, slope, was used as the resistance factor. Slope represents the steepness of the terrain. Heading up or downhill is a longer distance and therefore more energy expensive to birds. Positive and negative slope values were treated the same for this analysis because passerines are not great gliders and cannot take advantage of the downhill. Slope was calculated using the Slope function in ArcGIS. It is necessary to ensure the units of measure are the same for elevation and the X and Y cell lengths of the DEM. When projecting the DEM into the Interrupted Goode Homolosine projection the units of measurement for cell size were changed from decimal degrees into meters. This resulted in the cell size and elevation being measured in meters so the slope was calculated properly.

Least cost analyses require a cost raster that includes resistance values that can be added evenly to determine the cost of travel away from the source location. The raster was resymbolized from a stretched color ramp into 9 classes using the natural breaks method. The natural breaks classification method divides the data into classes that are based on natural groups in the data distribution. Most of the study area has a very low slope value so it was important when reclassifying to maintain the natural distribution patterns inside the data. Then the 9 classes were used to reclassify slope raster into values ranging from one to nine. A value of one is the lowest value and therefore the easiest to travel through. This range of values was chosen because it is a compromise between having too few value classes and the alternative of too many. It maintains simplicity for the integration of additional variables.

3.2.2. Water Resistance Value

The areas of water were represented by “NoData” values in the slope raster. This comes directly from the original DEM that only included data for land masses. All cells not representing landmasses were automatically assigned a value of “NoData”. Small bodies of water that would not show up on the raster were excluded automatically. If the water body is not at least the size of a whole cell then it was not included in the study. Birds are able to fly over water so these cells needed to be included in the analysis. To do this the raster was reclassified seven more times. The “NoData” values in the slope raster were reclassified separately into values ranging from two to eight creating seven individual cost rasters. Only water bodies large enough to be represented as “NoData” in the DEM were considered water bodies for this analysis. The analysis is a proof of concept and more attention to determining which water bodies constitute a barrier should be made in future analyses. The different values for water were assigned in order to perform a sensitivity analysis on the resistance values. The effect that alternate values have on the outcome of the analysis was evaluated to determine the appropriate values to properly model the migration patterns of the Red-eyed Vireo. Knowing that the vireo cross large bodies of water but only under certain conditions means that when evaluating the values I was looking for a model that displays the migration as crossing water and land.

3.2.2. Inclusion of Wind

Wind plays an integral role in determining migration patterns for any species of migratory bird (Alerstam 2011). Therefore it was important that it be included in a least accumulated-cost analysis of bird migration. The first step in including wind was done by identifying the wind patterns over the Gulf of Mexico. More broad wind data were included later in the study. During the spring migration there are favorable south east winds through the Gulf of Mexico (Figure 6). Able (1972) recorded winds as unfavorable for trans-gulf migration during fall months. A new shapefile was created and an outline of the Gulf of Mexico was sketched as a new feature to represent the springtime wind patterns. This new feature did not include the southern area of the gulf west of the Yucatan peninsula because while the winds are favorable it is still preferable that birds stay over land where they can rest. The area of the gulf east of the Yucatan peninsula was also omitted because if the birds head east from the peninsula they would be flying into a head wind which would have a negative effect on energy expenditure.

This new shapefile representing the Gulf of Mexico was turned into a raster with the Polygon to Raster function in ArcGIS. The raster was set to have the same dimensions and orientation as the resistance raster so that values in this raster could be used to modify the values in the resistance raster. The value for the cells inside the Gulf of Mexico wind raster were reclassified to a value that would, when added to the cost raster with the Raster Calculator, result in a value of one which represents the lowest cost to travel. This now depicts a lower cost to crossing the gulf from the Yucatan Peninsula to the northern gulf coast. Cost distance rasters were then created for both the breeding and wintering locations so that representations of migration could be made with the

Corridor function. These wind data were only included in the analysis of spring migration for the Red-eyed Vireo.

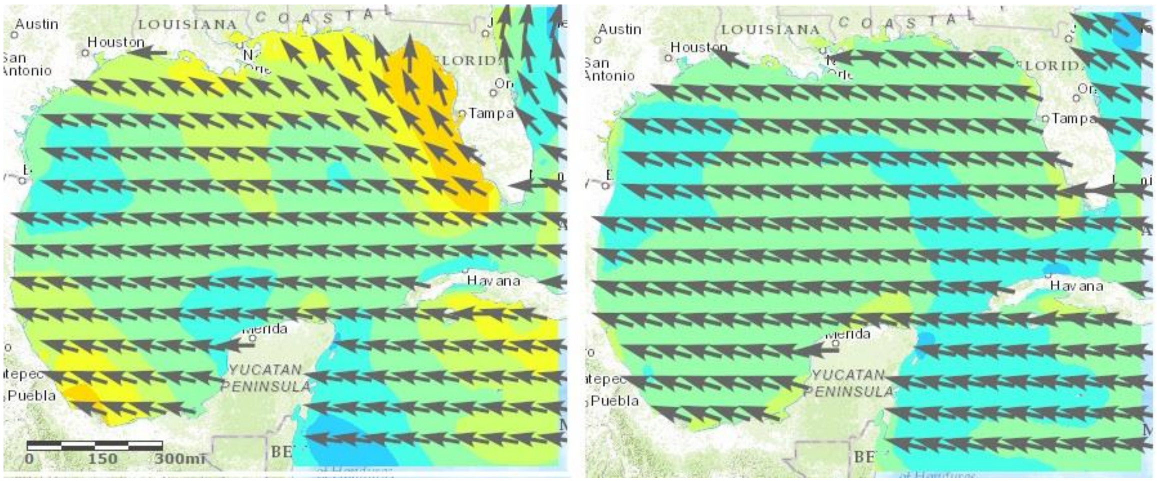

Figure 6 Depictions of the wind direction in the Gulf of Mexico for the spring (left) and fall (right) seasons. *Source*: NOAA.gov

The inclusion of the Gulf of Mexico wind data made it clear that wind should be calculated and included for the entire study area. There have been many attempts at recording prevailing wind data. Few of these data for prevailing winds have been documented in a way that could be easily included in a least cost analysis. This analysis is a proof of concept so the most sophisticated data available are not necessary. I obtained the average wind direction for cities across the United States from the National Oceanic and Atmospheric Association's (NOAA) website (NCDC 1998). The data are an average of records from the National Climatic Data Center (NCDC) dating from 1930 to 1996.

To include the City-based prevailing wind data in the least cost analysis it needed to be in raster format. A series of points were created as a new shapefile with one point for each city. Every point was assigned a value of 1–8 to represent the prevailing wind direction (Table 1). The points and their values were then interpolated using the Inverse

Distance Weighted (IDW) function. IDW interpolation assigns values to unmeasured locations based on the values of measured locations with closer locations given a greater influence. This created a raster of wind direction for the study area. Resistance values for wind direction were determined by assuming that in a south west migration a north east wind would reduce cost while a south west wind would increase cost. The wind value is meant to adjust the overall resistance value of each cell. Each classification, one through eight, was then reclassified to corresponding values from Table 1. A raster for spring and fall were each produced with inverse values.

Table 1 Resistance values assigned for wind direction

Value	Wind Direction	Fall REVI	Spring REVI	Fall KW	Spring KW	Sensitivity Analysis REVI
1	N	-1	1	-1	1	2
2	NE	-2	2	-1	1	3
3	E	0	0	0	0	0
4	SE	1	-1	2	-2	-2
5	S	1	-1	1	-1	-2
6	SW	2	-2	1	-1	-3
7	W	0	0	0	0	0
8	NW	-1	1	-2	2	2

The new wind direction rasters were added, using the addition key in the Raster Calculator, separately to the cost raster. Then the cost raster had to be reclassified once again because negative and zero values existed. Least cost analyses cannot run with negative or zero values. The negative and zero values were reclassified to hold a value of one because it is the lowest acceptable value. As with other factors the wind values had to be tested for sensitivity to the results. Higher values were assigned to a new wind direction raster. This was used to create an additional cost raster that were used to assess the effect different wind values have on the results.

3.3 Corridor Analysis

Cost distance rasters show the cost necessary to travel through space to every point in the study area from the source location. Cost distance rasters from both the source and end locations are necessary to create models of migration corridors. The Cost Distance function in ArcGIS was used to create cost distance rasters from all seven cost rasters for both the ANF_BCR and Ecuador. This resulted in 14 cost distance rasters. Each time the function was performed the processing extent was set to match the study area outline to ensure the entire study area was processed. The output coordinate system was always set to the same as the input cost raster to keep the raster in the Interrupted Goode Homolosine projection.

Corridors were created from all seven sets of cost distance rasters to analyze the effect the assigned resistance values had on the outcome. Corresponding cost distance rasters were entered into the Corridor function in ArcGIS to create seven models of migration corridors. This depicts a narrower corridor than the broad corridor the initial symbology represented. These corridors were compared to evaluate which resistance value for the water cells resulted in the best representation of the migration corridors recorded by Able et al. (1972), Kuenzi et al. (1991), Moore et al. (1990) and eBird data (2015).

Every factor that is included in the cost raster must be analyzed to determine if the values assigned deliver results that match what we already know of the migration routes. Two additional cost distance rasters were created to test the sensitivity of resistance values for slope. The slope value was tested by creating new slope rasters where the values were resymbolized using equal interval and standard deviation classifications. The change in resistance values exaggerated the difference in the lower values in slope to extenuate the less than dramatic topography in the southeastern US. This analysis was performed after the appropriate value for water bodies was found.

The various corridor maps with different resistance values were compared to studies on the migration routes of Red-eyed Vireo. The species has a wide range so it is difficult to find a map of only the birds migrating from a specific region. Able et al. (1972), Kuenzi et al. (1991), Moore et al. (1990) and eBird data provided information that was used to evaluate the migratory flight patterns predicted in the models (Figure 7). The best models were chosen by comparing them to what we know about the migration patterns of Red-eyed Vireo. Migrating Red-eyed Vireos travel down the Florida Peninsula in the fall and more likely to cross the gulf in the spring. The results of the analysis were compared to this pattern to select the best parameterization of the migration model.

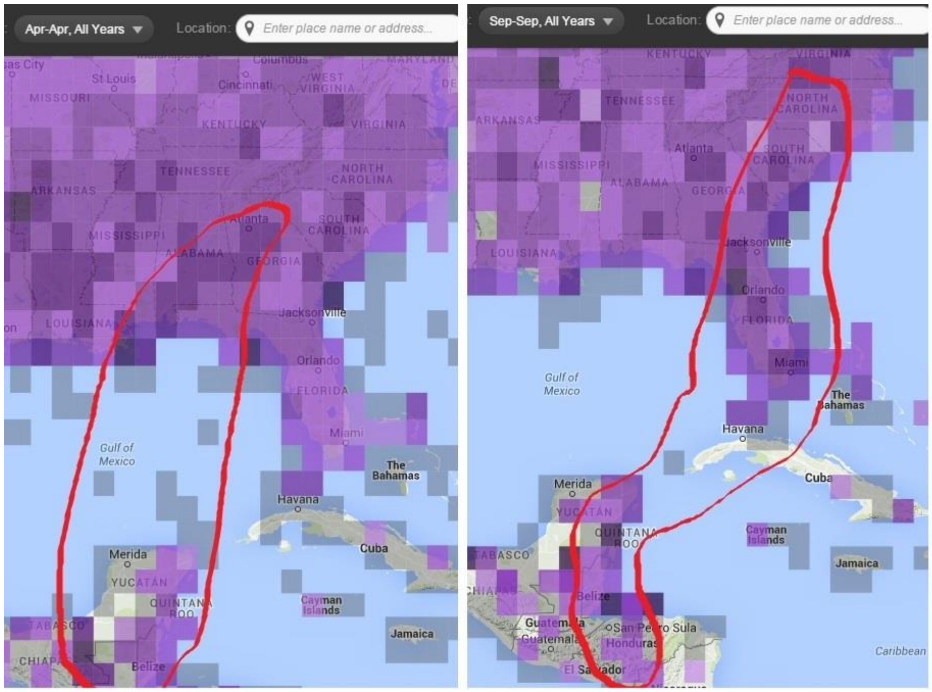

Figure 7 eBird data depicting the higher concentrations of Red-eyed Vireo during the spring (through the Florida panhandle; left) and fall (through peninsular Florida; right) with the darker shades of purple symbolizing more sightings

3.3.1 Application of Analysis to Other Species

The analysis of Red-eyed Vireo was meant to determine how to parameterize the different variables influencing bird migration routes. Once these parameters were set they were transferred to more rare species, the Kirtland's Warbler and the Golden-cheeked Warbler. Less is known about the rarer species' migration patterns so the least accumulated-cost analyses may be able to provide some insight into the flyways of rarer species.

3.3.1.1. Kirtland's Warbler Analysis

The cost-surface values that resulted in the corridor routes that best matched known migration pathways for the common and well-studied Red-eyed Vireo were then used to develop predicted migration routes for Kirkland's Warbler. The flyway for the

Kirtland’s Warbler (*Setophaga kirtlandii*) is still unknown but the compiling of sighting records by Petrucha et al. (2013) provides some information on the migratory routes. The core breeding grounds for the species are located in the northern Lower Michigan and the wintering grounds mainly on the island of Eleuthera in the Bahamas. These habitats were used as the source locations for the analysis and used in concert with the cost rasters created during the Red-eyed Vireo analysis.

The cost raster with the water value set at 2 was chosen because previous migration models (Bocetti et al. 2014) assumed that the warblers are not opposed to traveling across water. There are many records of warblers in Ohio which suggest the crossing of Lake Erie (Figure 8). The resulting cost distance rasters were used to calculate the migration flyway with the Corridor function in ArcMap.

Kirtland’s Warblers migrate in north-west and south-east directions. This required that additional rasters be created to represent how wind affects flight paths. They were created by reclassifying the ones used in the Red-eyed Vireo analysis (Table 1) to reflect the different overall migration direction. These rasters were added and the analysis was performed as before.

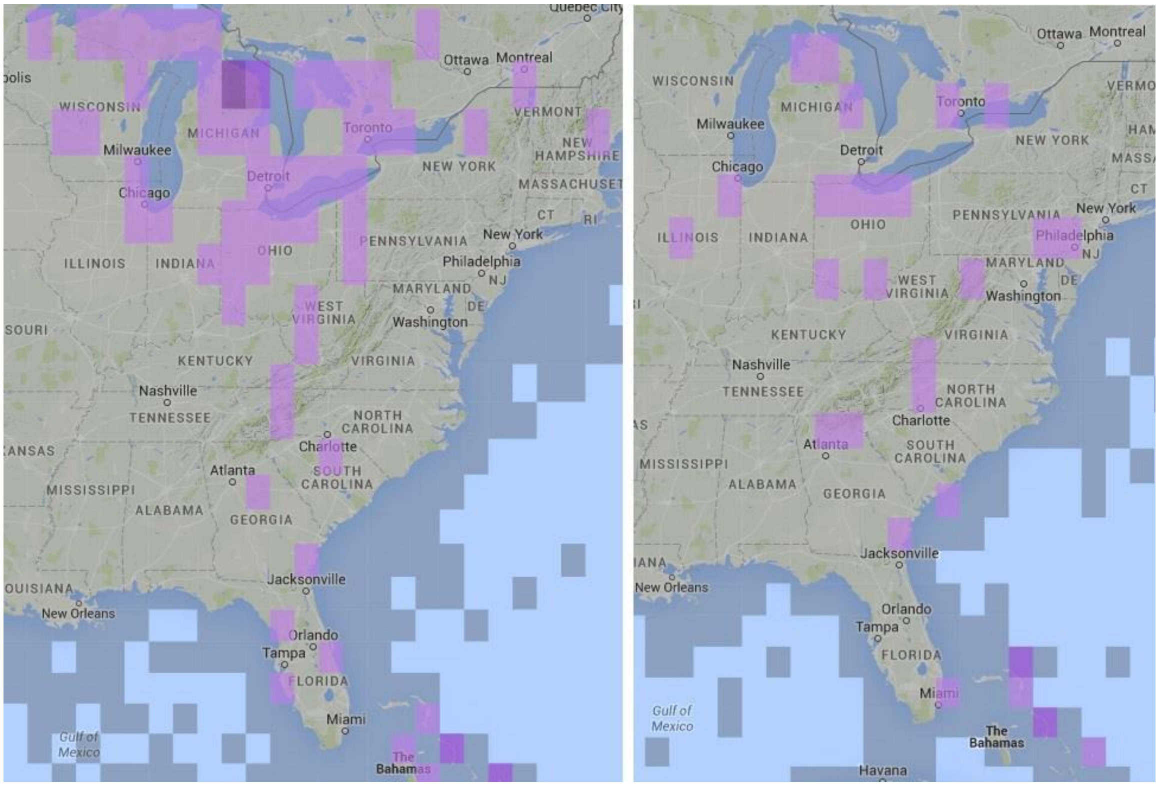

Figure 8 eBird.org data depicting the locations of Kirtland's Warbler sightings for the spring (left) and fall (right) with the darker shades of purple symbolizing more sightings *Source*: eBird.org

To evaluate the results of the analysis, I created point shapefiles for the spring and fall sightings of Kirtland's Warbler compiled by Petrucha et al. (2013). Locations for reliable sightings of Kirtland's Warblers were transferred manually from Petrucha et al. (2013) and were used to verify the results of the study. These shapefiles were then overlaid on top of the results from the least accumulated cost analysis.

3.3.1.2. Golden-cheeked Warbler Analysis

A smaller study area was created for the least cost analysis of the migration of the Golden-cheeked Warbler. Shapefiles of the breeding locations in Texas and wintering locations in Central America were created for use in the analysis. Similar processes for the Red-eyed Vireo and Kirtland's Warbler were used to perform the analysis on the Golden-cheeked Warbler's migration patterns.

Slope, water bodies and wind were all included in the analysis. As in the Red-eyed Vireo analysis, a value of three was given to the water bodies. The analysis was performed with and without the NOAA wind data. This is because the points that were used to create the raster are only located in a small area of the study area and do not reflect the local wind patterns. A separate raster was created to represent the inclusion of the south-east winds that occur in the Gulf of Mexico, similar to that of the vireo analysis. This raster was only included in the creation of a spring migration map.

Verifying the results of the Golden-cheeked Warbler analysis was difficult because of the lack of information on the migratory route of the species. Only the research of Groce et al. (2010), Ladd and Gass (1999) and the eBird data (Figure 9) could be used to assess the results.

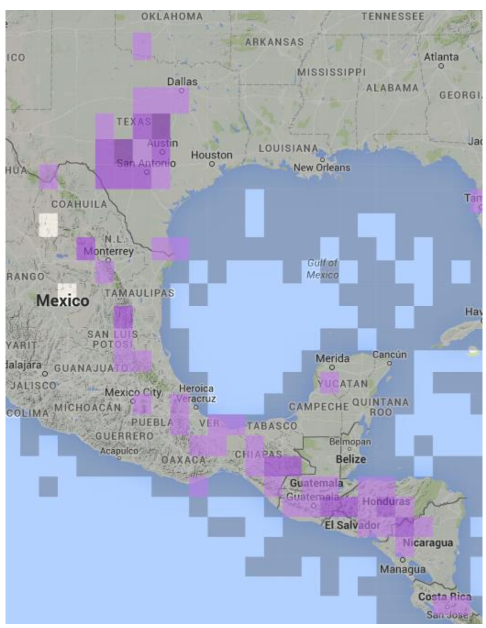

Figure 9 eBird data depicting locations of Golden-cheeked Warbler observations with the darker shades of purple symbolizing more sightings *Source*: eBird.org

Chapter 4 Results

The least accumulated-cost analyses performed as part of this study provided a wide array of results. The Red-eyed Vireo analysis provided information on how to correctly assign weights to the different criteria involved in the analysis. The results of the vireo analysis enabled the methodology to be transferred to rarer species. The Kirtland's Warbler analysis showed how that this technology can be used to accurately predict migration pathways of birds. The analysis of the Golden-cheeked Warbler highlighted the shortcomings of least accumulated-cost analyses by providing results that are not supported by species sighting records. This is useful information because it emphasizes the importance of including all necessary information and assigning the proper values to factors specific to individual species that affect flight patterns.

4.1 Red-eyed Vireo

As mentioned before, the Red-eyed Vireo analysis was used to determine the appropriate values for the different resistance values. This section details the outcome of the Red-eyed Vireo analysis and describes how the values were chosen from the results of the analysis.

4.1.1. Choice of Water Resistance Value

The review of existing migration flyway information for the Red-eyed Vireo showed the preferred routes of migrating vireo. The results of the sensitivity analysis for the resistance values of water bodies were analyzed to determine which value provided the most accurate depiction of the flyways. Existing information about migrating vireo shows that the birds do not prefer to fly over large bodies of water but will if the conditions are right. A value of three for the water resistance value portrays this behavior. A value of two would create a map that would have the vireo only fly over water which is unlikely because there is not any sources of food to replenish necessary energy (Figure 10). Values higher than three would depict migration patterns that would show that vireo would not fly over water for any reason, which is not true.

4.1.2. Wind resistance value

The addition of wind values to the analysis provided a level of detail that was unattainable with only slope and water bodies. Including only the wind layer for the Gulf of Mexico provided a spring migration where the vireo cross directly over the Gulf of Mexico and has the fall migration as completely avoiding the gulf (Figure 11). The two major pathways for vireos from the east coast are to follow the Florida peninsula down to the Caribbean or perform a direct gulf crossing between the Yucatan peninsula and the northern gulf coast. The inclusion of the wind layer in the cost raster depicted routes that represent these notions. The fall migration is depicted as following Florida south and crossing through the Caribbean or performing a trans-gulf flight directly to the Yucatan Peninsula (Figure 12). The maps for the spring migration show that the vireo cross the gulf from the Yucatan Peninsula and may follow along either the east or western side of the Appalachian Mountains (Figure 12). That is, based on slope, water, and wind alone, the model predicts a path through peninsular Florida in the fall and a path that bypasses the peninsula and makes landfall in the panhandle in the spring.

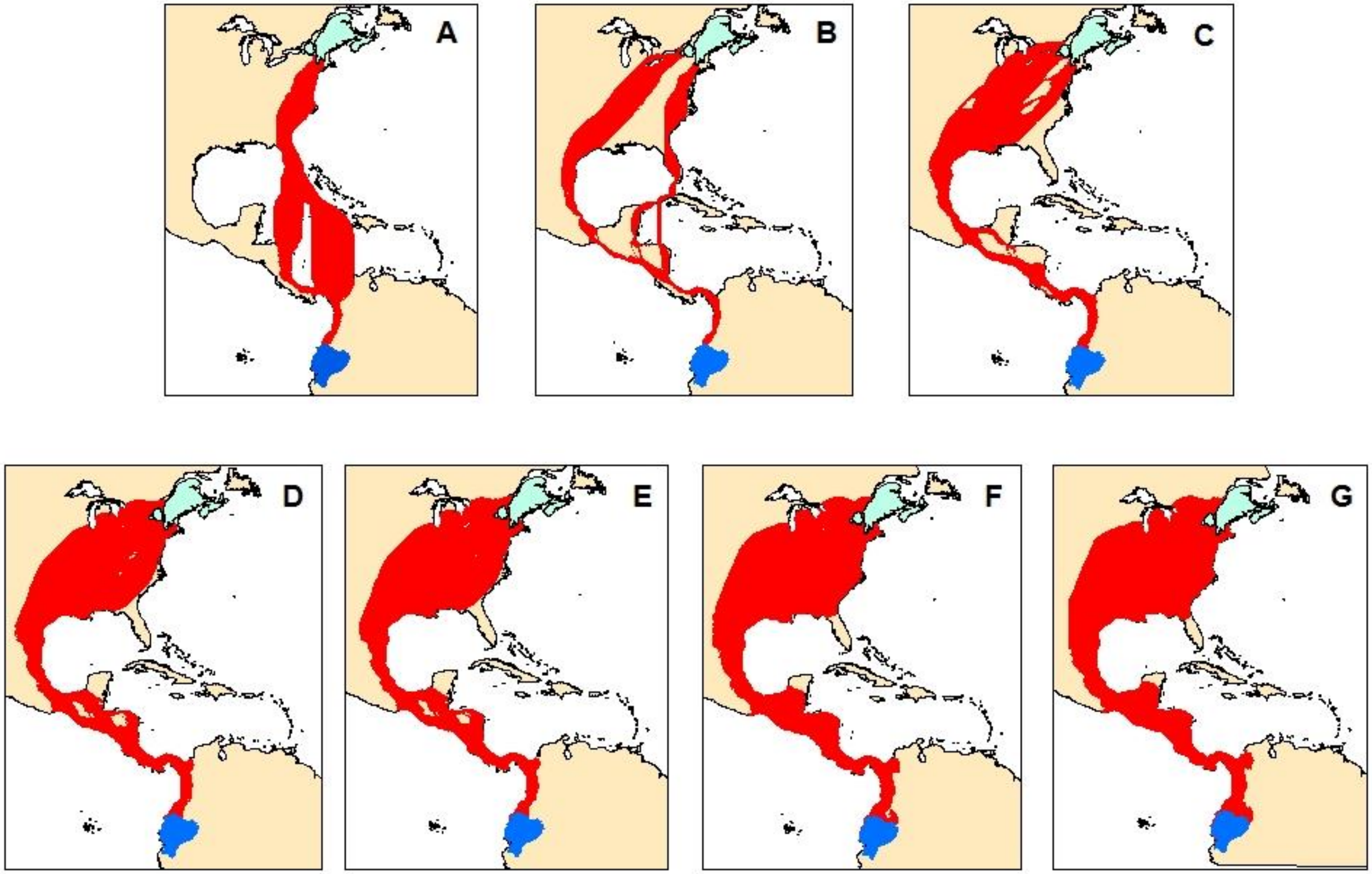

Figure 10 Results of the sensitivity analysis on the water values without wind, Map B depicts the flyway that most closely resembles that of the Red-eyed Vireo

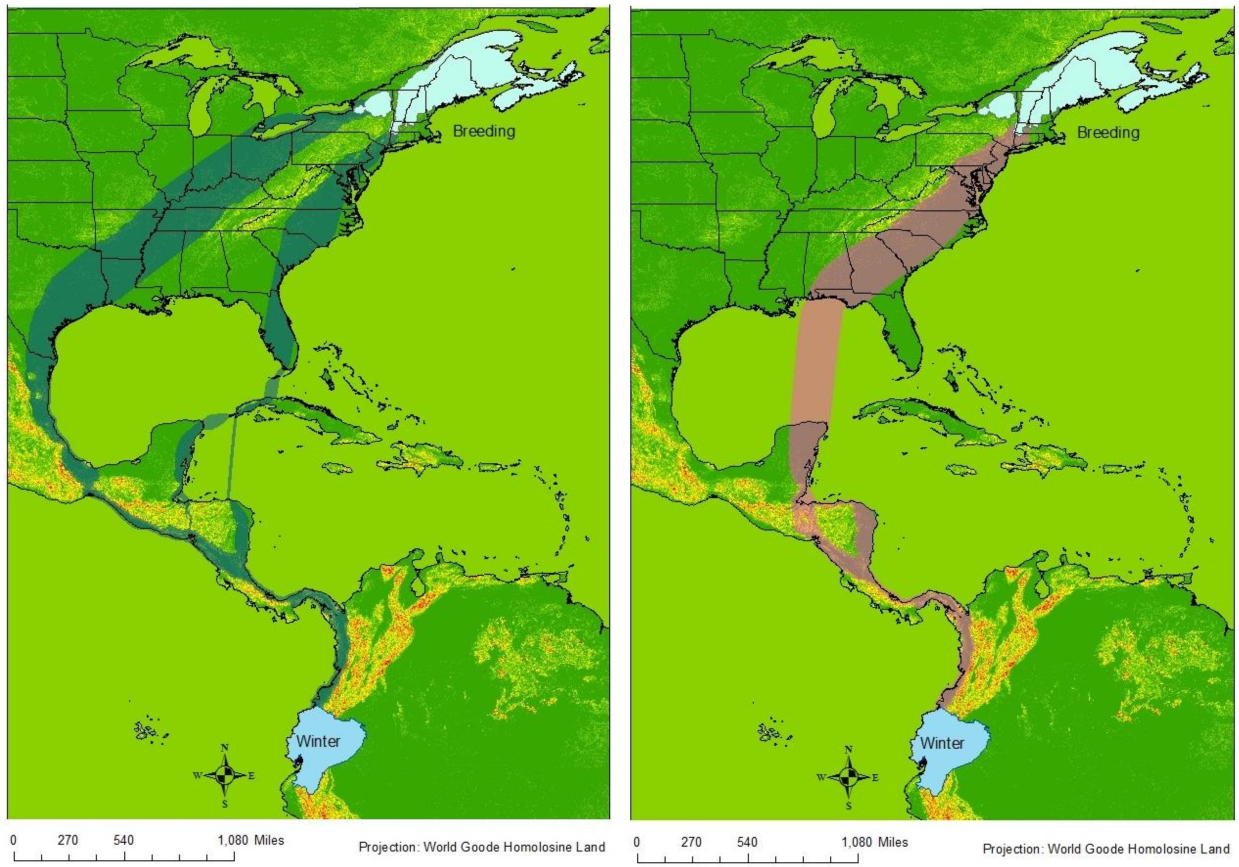

Figure 11 Predicted Migration corridors for Red-eyed Vireo without wind data for Fall (left) and Spring (right)

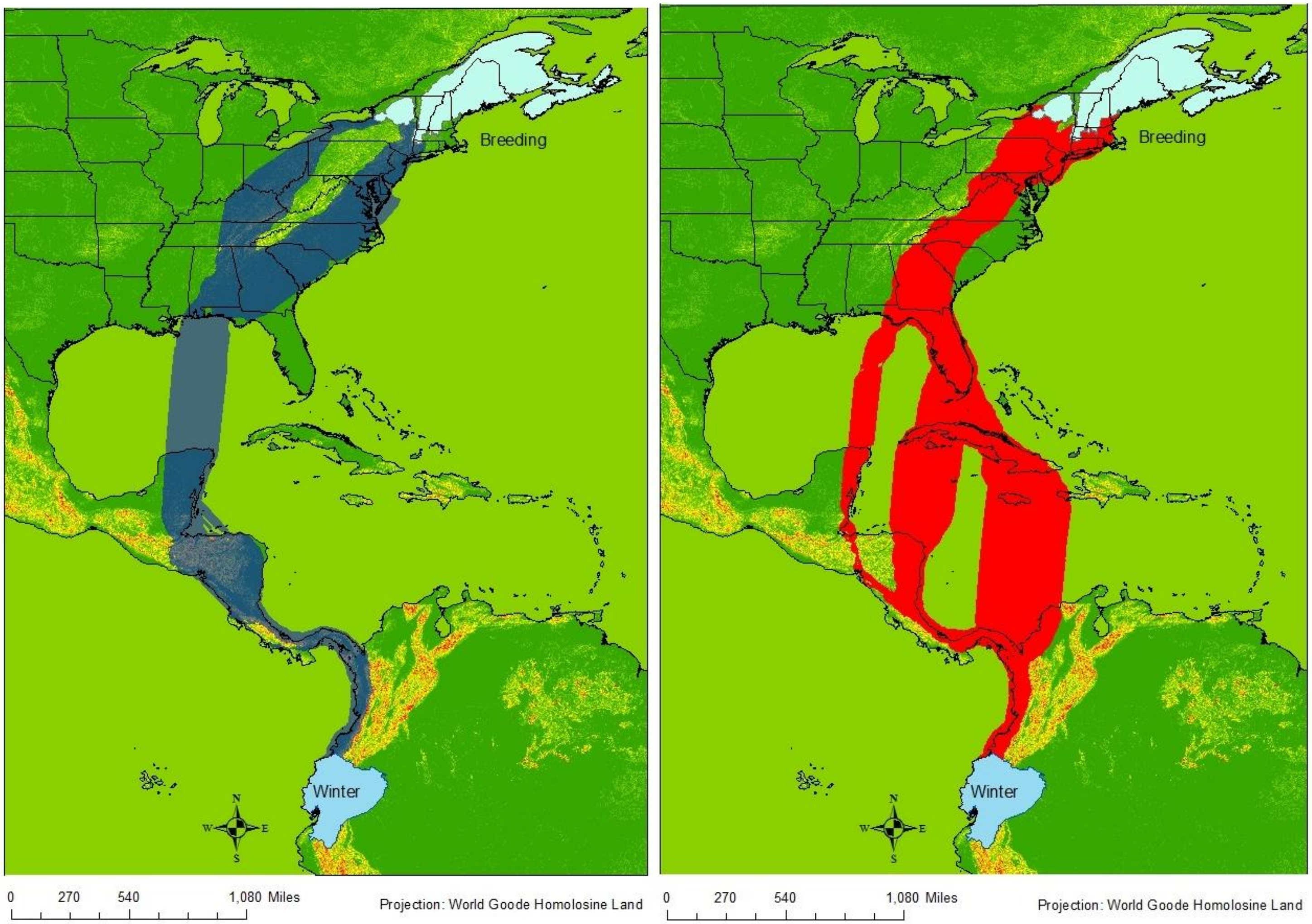

Figure 12 Predictions of Red-eyed Vireo migration flyways using wind data for Spring (left) and Fall (right)

The inclusion of the wind values required another sensitivity analysis to take place. The results of this analysis showed that the initial values set for wind in the cost raster provided results that resembled patterns of migration that have been observed. The higher values exaggerated the effect wind had on the outcome. The resulting map depicted the flyway for the Red-eyed Vireo as traversing the Atlantic Ocean and only occasionally crossing land (Figure 13). This is a near impossible route for a migratory passerine to undertake and therefore provides the evidence needed to be assured that reasonable wind values were used in the initial cost raster.

Figure 7 shows data collected from the crowdsourced database eBird that depicts high concentrations of Red-eyed Vireo in peninsular Florida during September and higher concentrations of the vireo along the northern coast of the gulf during the month of April. This is further evidence supporting the claim that Red-eyed Vireo choose to cross the gulf during spring migration but will circumnavigate during fall.

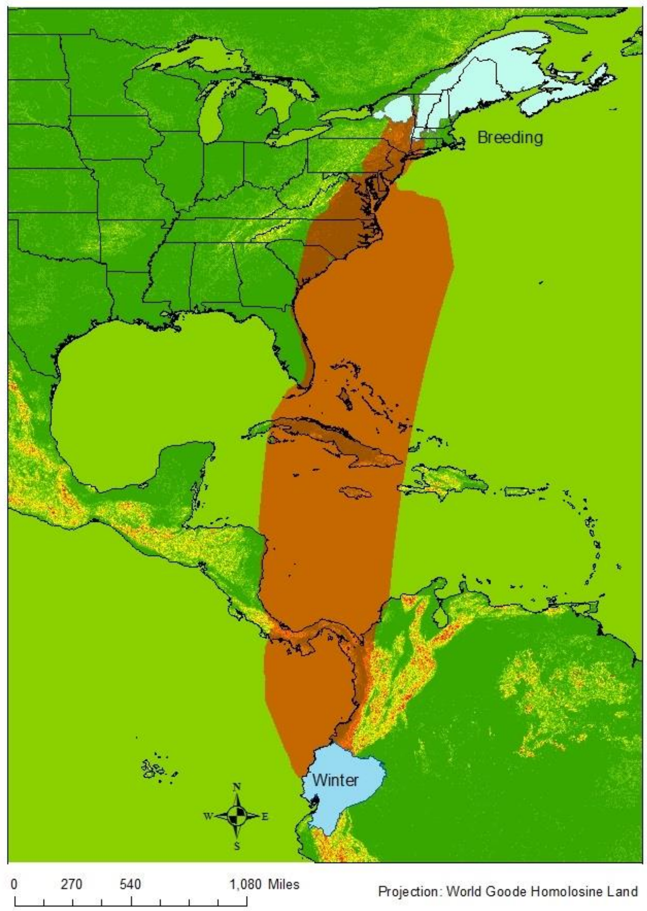

Figure 13 Predicted migration flyway for Red-eyed Vireo using exaggerated cost values for wind

4.2 Kirtland's Warbler

The least accumulated-cost analysis of the migration pattern for the Kirtland's Warbler resulted in a model (Figure 14) that does not mirror the model proposed by Bocetti et al. (2014) in Birds of North America. The initial analysis, not including wind, depicts a corridor that heads south from the breeding ground and includes all of Ohio and Indiana (Figure 14). The model then splits as some birds venture across the southern

Appalachian Mountains through West Virginia. There is another split in the flyway in Tennessee that shows a possible area for high concentrations of migrating warblers. The widest section of the flyway continues south to the gulf coast before heading east to the Bahamas.

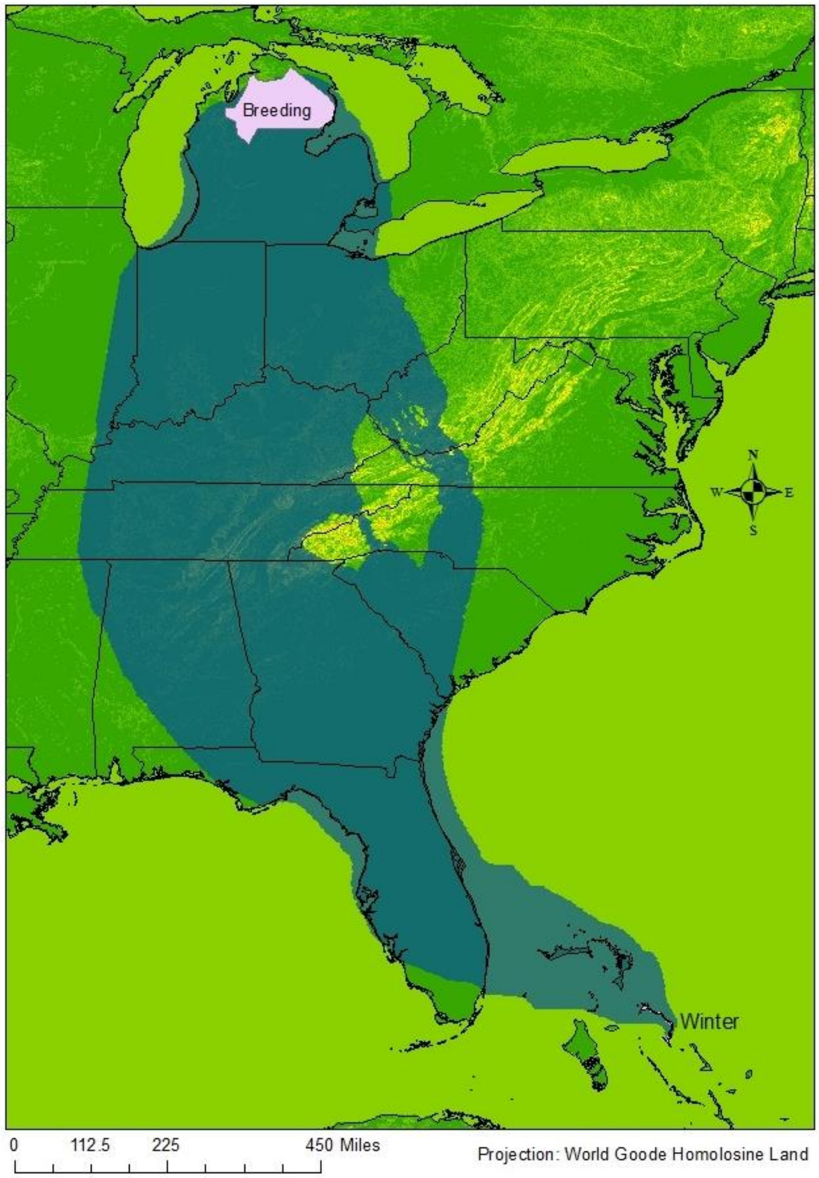

Figure 14 Predicted migration flyway for Kirtland's Warbler based on slope and water resistance values only

The results of the analysis of spring migration showed only a slight difference from the analysis without wind. That difference is that the warblers crossed Lake Erie and ventured into Ontario before settling back in Michigan (Figure 15). The map of fall migration with wind showed that the warblers began the migration by heading almost due east from Michigan (Figure 15). The birds then proceeded south but stayed away from the coast and flew along the eastern side of the Appalachian Mountains. They do not cross over to the Bahamas until down in southern Florida. The map of spring migration created in this analysis contained 256 (82%) of the 311 data points provided by Petrucha et al. (2013) while the fall migration map contained 64 (56%) of the 114 data points (Figures 16 & 17).

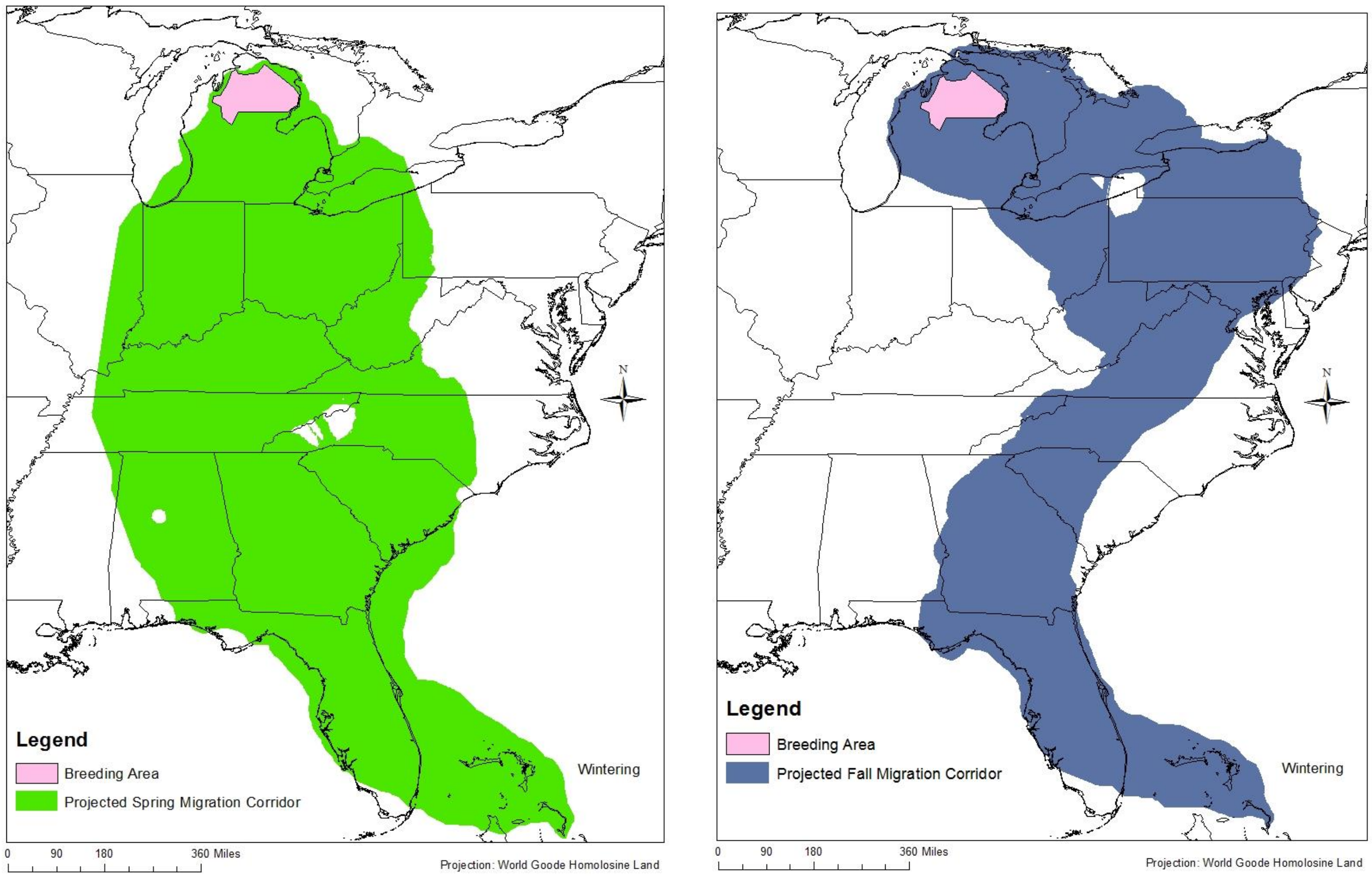

Figure 15 Representations of the migration corridors of Kirtland's Warbler for the spring (left) and fall (right) created from a least accumulated-cost analysis that included slope, water, and wind as influencing factors

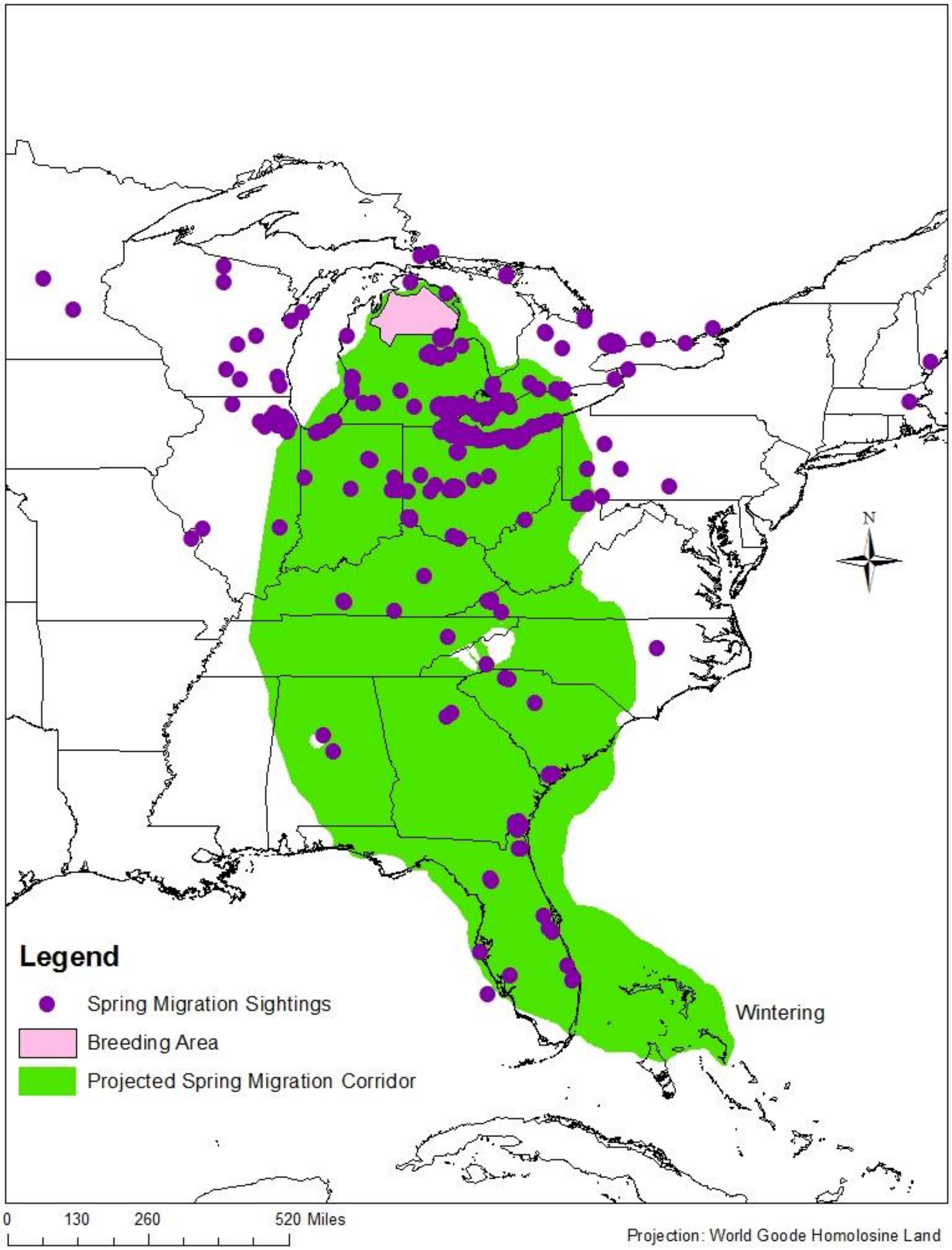

Figure 16 Map of the predicted spring migration of the Kirtland's Warbler. Recorded sightings from Petrucha et al. (2013) are transposed on the map for validation of the model

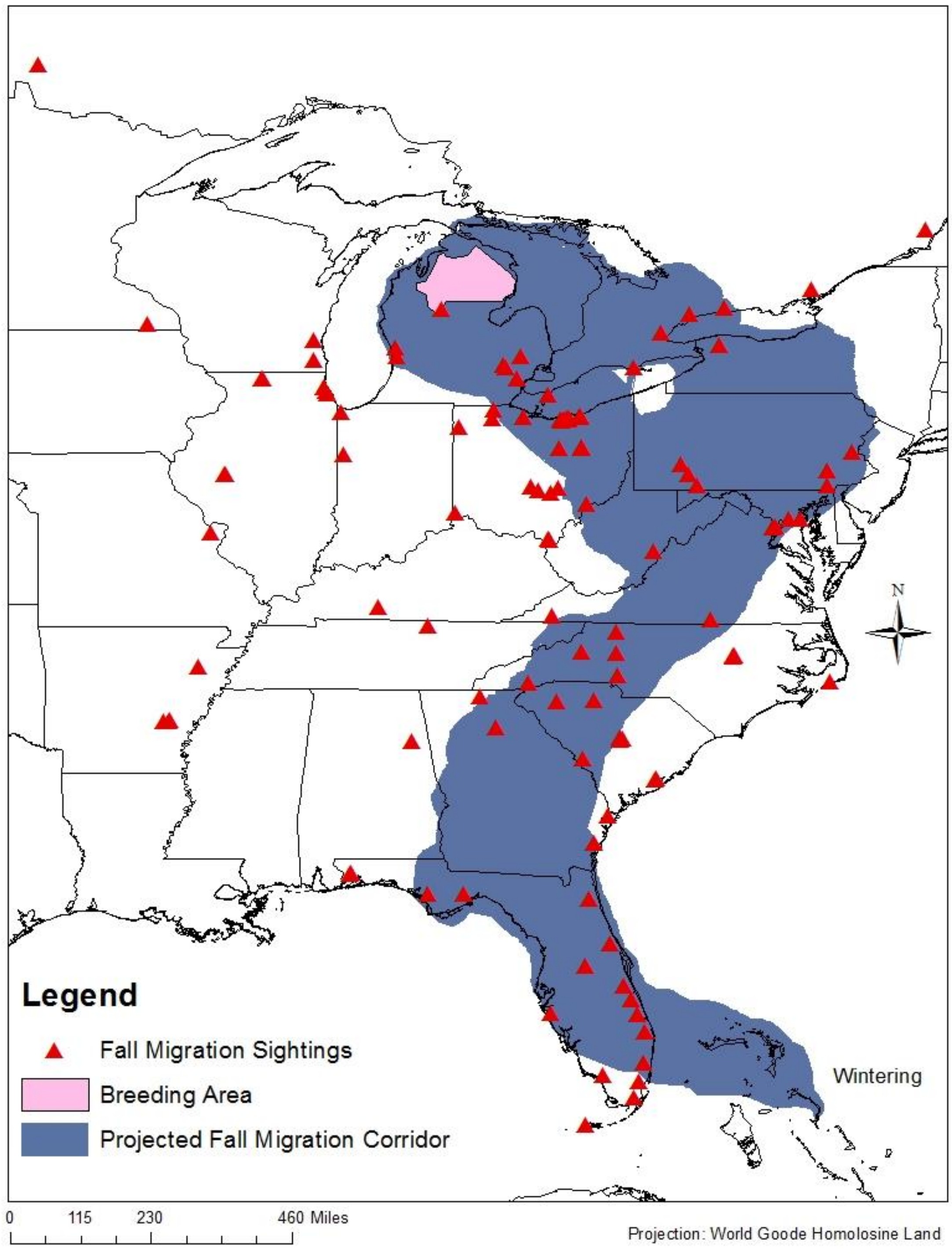

Figure 17 Map of the projected fall migration of the Kirtland's Warbler created with a least accumulated-cost analysis. Data of recorded sightings (Petrucha et al. 2013) are layered on top of the map to validate the analytical method

4.3 Golden-cheeked Warbler

The least accumulated-cost analysis of the Golden-cheeked Warbler's migration predicted a migration corridor that follows the east edge of the Sierra Madre Oriental mountain range and extends to the gulf coast of Mexico and Central America (Figure 18). The analysis that included an adjustment for the prevailing southeastern wind in the Gulf of Mexico offered different results. This model showed that it is possible that Golden-cheeked Warblers undertake a trans-gulf flight (Figure 18). These prevailing winds are only advantageous to migrating birds during a northern migration so it was only included in the analysis of spring migration. The resistance value of water is enough to prevent the analysis from predicting a gulf crossing during fall when the winds are not advantageous.

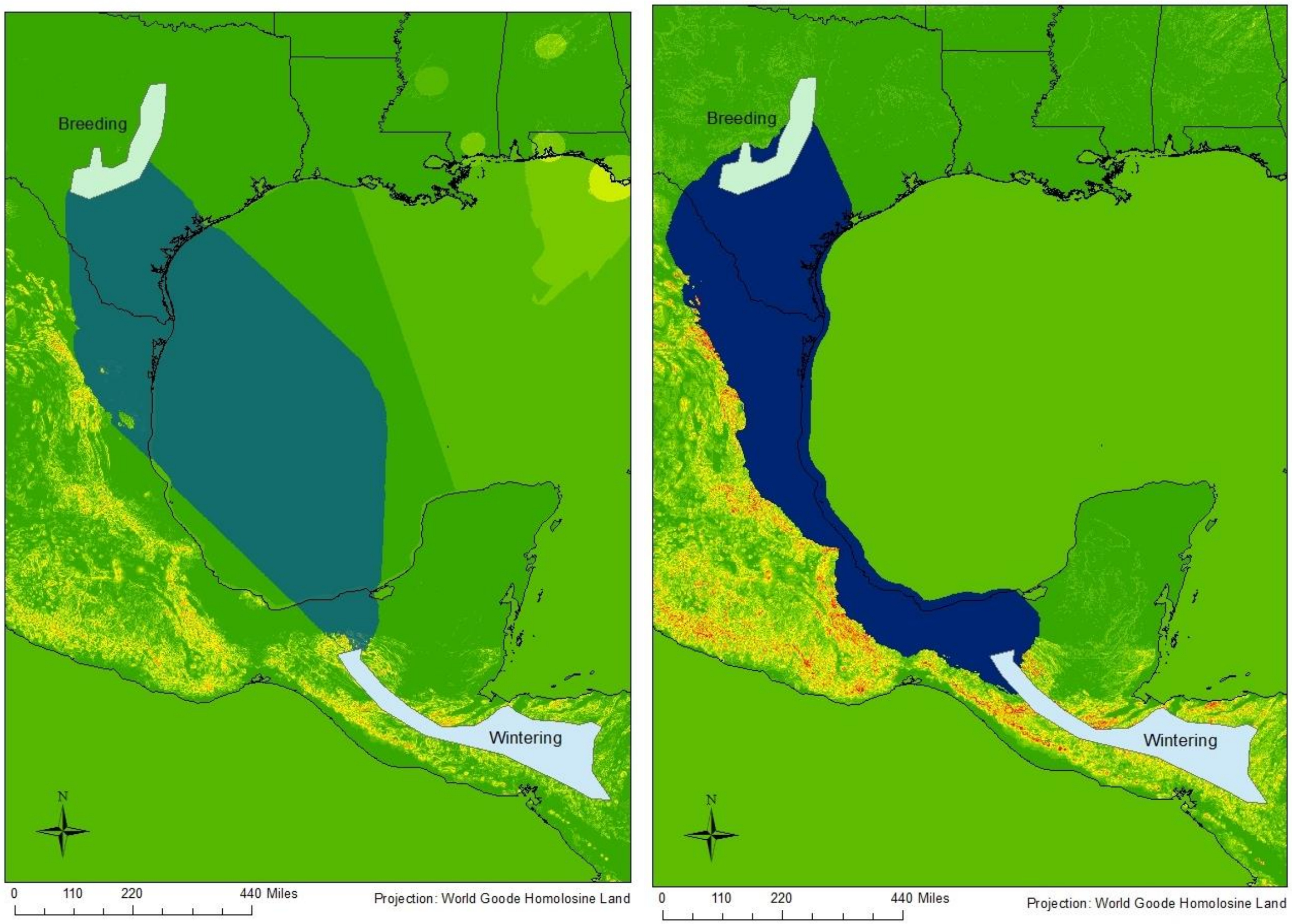

Figure 18 Migration corridors for Golden-cheeked Warbler, Fall (left) and Spring (right)

Chapter 5 Discussion

The analysis reported here is different than previous studies in that it did not use expert opinion to determine the resistance values of the cost raster. Expert opinions were used but only to determine the already known migration patterns of the Red-eyed Vireo. The resistance values were determined through a series of sensitivity analyses that resulted in a model that is able to create maps that depict an accurate representation of the known migration patterns. The accurate depiction of the vireo migration shows that the resistance values are set at the proper level and can be transferred to other species. It should be noted that every species is different and some alterations to the resistance values must be made. The results of this study are encouraging to the concept of modeling long distance bird migration using a least accumulated-cost analysis. While this study ignored important criteria involved in migration it was useful in proving that the method is sound and could be expanded upon in future research.

5.1 Kirtland's Warbler

The map of the migration flyway provided by the Birds of North America (BNA) only stretches as wide as a single state with a due heading towards the Bahamas from the Michigan breeding range. This map excludes Indiana and the states west of the Appalachian Mountains except Ohio. Petrucha et al. (2013) collected records of migratory Kirtland's Warblers and included 425 records in a study to describe the bird's migratory patterns. In that study, Indiana and Illinois have more acceptable sightings than West Virginia, Virginia, Pennsylvania and North Carolina. The latter are states that the BNA map depicts as making up most of the corridor. There are substantial records in these states but the migration corridor for the Kirtland's Warbler extends outside of the BNA model.

The findings of Petrucha et al. (2013) similarly show that there is a difference between the flyways used during the spring and fall migrations (Figure 5). Prevailing wind patterns have a substantial influence on the flight patterns of migrating birds. The inclusion of wind into the analysis resulted in alternate flyways for spring and fall migrations. These predicted migration flyways were compared to the data provided by Petrucha et al. (2013). There will always be considerable variation in bird migration but accuracy ratings of 82 percent for spring migrations and 56 percent for fall migrations illustrates that a least accumulated-cost analysis is a promising method of predicting bird migration flyways. While 56% does not appear to be a promising number it is promising because some of the sightings outside of the predicted flyway are of birds that breed in Wisconsin which would have them begin their migration west of the breeding location used in this study.

The predicted model of the spring migration illustrates the birds cross over into Florida directly before heading north to the breeding grounds in northern Michigan. It is apparent that the warblers decide to cross the Appalachian Mountains as soon as possible if they do not circumnavigate south of the barrier. The map shows a section of the mountain range where birds do not want to cross but within that stretch there is a break in the barrier which could be a critical migration corridor. This break in the barrier is probably the result of the locations of the Pigeon and French Broad Rivers. These two rivers cross the mountain range from North Carolina into Tennessee. The rivers have cut out low lying areas that allow for easier crossing for the birds. The data points from

Petrucha et al. (2013) form a line that crosses through this area and there are eBird records of sightings in the area. From that point the warblers are able to head north to the breeding ground. Similar to Petrucha et al. (2013) and this analysis, the eBird data shows more sightings west of the Appalachians and in the state directly south of Michigan. A majority of the data points are inside Michigan, Ohio and Ontario because they are in close proximity to the breeding grounds. This results in a high percentage within the corridor boundary. Some birds head west of Lake Michigan and nest in northern Wisconsin. This explains the data points bordering the southwestern end of the lake.

A dramatic difference is seen between the fall and spring migration maps. While the spring has the birds mostly to the west of the Appalachians, the fall map shows a more eastern route. The fall migration map predicts that the warblers head east from their Michigan breeding grounds. They travel through Ontario and Ohio to reach Pennsylvania before turning south. The spring and fall corridors share a border cutting West Virginia in half while only sharing a margin of the state. Once across the mountains the warblers then follow south along the side of the range, avoiding the coast. The eBird data include more sightings of the Kirtland's Warbler on the east side of the Appalachians during fall migration further lending support to the model. There are few records of the warblers being spotted along the coast until Georgia. The birds then continue south over land until they are close enough to the Bahamas to traverse the sea.

The only large group of recorded fall sighting of the Kirtland's Warbler that do not align with the predicted fall migration flyway are those bordering the western shore of Lake Michigan. This is easily explained by the spread of the Kirtland's Warbler breeding area into northern Wisconsin. This analysis did not include these breeding grounds, which resulted in the lower than expected results in the assessment of model accuracy. Inspection of the data points in Petrucha et al. (2013) indicate that it could be possible that the warblers that nest there perform a different migratory pattern then their Michigan neighbors. A separate analysis should be performed for the different breeding areas instead of trying to combine them in future analyses.

The specificity of breeding habitat requirements for the Kirtland’s Warbler presents a threat to the future survival of the species. While work is being done to preserve critical habitat in the breeding range, little is known of the habitat the birds use as stopover points. These stopover points are crucial to migrating birds as they provide much need food to fuel the continuation of their journey. It is possible that the warblers follow specific migration routes in order to make use of certain habitats as stopover sights. This information should be included in future least cost analyses. Land cover data describing the preferred habitat could be assimilated into the cost raster. This would show that areas with preferred habitat are of lower energy cost because they actually increase the physical energy of the birds. The inclusion of this information could lead to a more accurate model of the migration routes of Kirtland’s Warblers.

Existing models of the migration flyway for the Kirtland’s Warbler depicts a constant bearing between the species’ breeding and wintering locations. It was once customary practice to believe that the end destination was the sole focus of the bird and any detours were due to weather and purely accidental. This also implies that a bird would stop only when it sees food and would not detour off course to save energy. It is now known there are more factors at play than just the end destination (Alerstam 2001). The other factors should be included in the creation of migration models, as I have done here. The least accumulated-cost analysis does this by developing a cost structure to the landscape. The end destination is still the primary motive as the analyses aim to find the easiest route instead of the shortest.

Bird migration is one of the great spectacles of nature because an entire species performs a mass exodus to a more favorable climate every year. It is unreasonable to think an entire species will follow the same route during migration. Migration requires stopovers to replenish energy by feeding. A single path across the continent could not supply an entire species with enough food to complete the journey. Therefore multiple paths are taken, creating a wide migration corridor. While the existing models show a corridor it is not wide enough to include the range of migration paths used by Kirtland's Warblers. This least cost analysis created a model that does depict a much wider corridor that allows for the variation of paths between individual birds. Kirtland's Warblers are particular about habitat and it can be assumed that a wide corridor is necessary to allow for each bird to find its preferred habitat.

5.2 Golden-cheeked Warbler

Few records of migrating Golden-cheeked Warblers have been published. The breeding and wintering ranges are known but only assumptions exist about the behavior during migration. Most of the breeding range is in the hill country of Texas and the wintering range is in the mountains with elevations well over 1000 meters. The species seems to prefer hilly and mountainous terrain. Could we assume they would prefer it during migration as well? A straight line between the two ranges extends directly across the Gulf of Mexico. The results of the analysis show two possibilities. Following along the east side of the mountains and crossing the gulf.

The strong association with mountainous terrain and the Golden-cheeked Warbler imply that additional information should be included in analysis. Sightings of the warblers have been recorded during migration along the Sierra Madre Oriental at elevations (Groce et al. 2010). This would lead some to suspect the birds follow the mountain range at heights ranging from 1,100 to 1,500 meters. The birds favor pine oak forests which are common along the mountains at this elevation. An inclusion of the preferred food sources of the Golden-cheeked Warbler could create a model that depicts the use of the mountain range as its primary migration route. The analysis of the Golden-cheeked Warbler is an example as to why every model must be adapted to a specific species. The parameters set from the analysis of the Red-eyed Vireo were able to be transferred to the Kirtland's Warbler with only directional adjustments to the wind data because of their similar nature.

The south east winds coming off the Gulf of Mexico may offer some insight into the migration of the Golden-cheeked Warbler. With winds beating up against the mountain range it is possible for large birds, such as Turkey Vultures, to use the draft to gain elevation along the mountains (Mandel et al. 2011). It would then use gravity to glide down the mountain side in its preferred direction. This would allow the bird to save energy and also provides easy access to its more favorable food sources. While this is possible for large winged birds, passerines are not usually seen gliding because of their small wings.

The inclusion of the southeasterly winds in the Gulf of Mexico in the analysis result in a model that supports the idea that Golden-cheeked Warblers may cross the gulf during spring migration. The warblers are small birds and a trans-gulf crossing is difficult but birds of similar size perform longer passages across the gulf with the aid of the same winds. The only evidence that supports this theory are some records in the eBird database of sightings near Corpus Christi, Texas during the spring migration months. Corpus Christi is located where the birds would finish their passage. It is also a popular location for bird watchers looking for migrating birds. This could explain the high number of sightings but also the bird watchers are there because the migrants fly through Corpus Christi.

5.3 Future Research

This analysis provides a proof of concept in that least accumulative cost analyses can be used to model the migrations of birds. The success in creating maps that reasonably depict known migrations of Red-eyed Vireo lead to building maps of Kirtland's Warbler migrations. While less information is known on the migration of the Kirtland's Warbler, the data currently available does show that the maps created in this analysis could provide a new look on their migration patterns. The results of this study are only a first step. More data and sophisticated parameterization would need to be included in future analyses.

The slope raster was used as a basis for the rest of the resistance values. The slope percentage may not have been the best way to quantify the barrier. The slope length would have more accurately described the resistance to travel because it allows for the calculation of the difference in length between flat ground and the sloped terrain. It may also be beneficial to perform the analysis with a larger cell size. This would help to more easily calculate the difference in elevation between cells. This would more generalize the slope and eliminate the effect small scale elevation changes have on the slope values.

The wind data used in this study was based on historical averages from 1930 to 1996. The method for creating the wind data shapefiles allowed for error and could be improved upon if not replaced. More recent and precise data should be utilized in future research. Also, it is reasonable to think that wind pattern forecasts could be used in the creation of a model that could predict future migration patterns.

It was noted earlier that fuel is one of the three most important factors in determining flight patterns of birds (Alerstam 2011). This factor was not included in this analysis. It may prove difficult to include this information. Different species all have their own preferred habitats and their preferred nesting habitats may differ from stopover points. Research must be done for each species so as to determine the preferred stopover habitat and therefore assign the correct resistance value to land cover. Land cover can also be very difficult to identify properly. There can be multiple layers of various land covers at any given location. If the analysis was studying a raptor species then the ground cover might be most important as it would lend more information as to what kind of small game is inhabiting the area. Some land cover data would not be able to provide this information so it is important to include data that depicts the land cover classifications needed. There is a vast array of different land cover types and it would require considerable time to go through an entire continents worth of classifications and assign proper resistance values.

Few animals are able to supply themselves with energy by consuming the same foods year round. Food sources appear at various times of the year and animals change their diets accordingly. It is intuitive to place different values on wind direction based on the time of year and direction of migration. The time of year also impacts the value of various land cover types because birds may not get as much nutrition from those areas in fall as they do in spring. An example would be how on a fall migration it would be common to find migrating waterfowl to be feeding in cut corn fields during their fall migration. The left over corn the birds are eating will not be present in those fields during the return migration in the spring.

One reason for determining bird migration flyways is to prevent collisions with tall building and towers. Some species have wide breeding and wintering ranges. The analysis of the Red-eyed Vireo only studied the flyways from one section of the breeding range to another section of the wintering range. In order to isolate the main concentrations of migrating birds it would be necessary to include all of the breeding and wintering ranges into the analysis. This could be done by performing the analysis as before except multiple times. Once for each section of the breeding range to link to each section of the wintering range. This is similar to the study of Black bear migration performed by Cushman et al. (2009). They created least cost paths between 160 source and 160 destination locations and averaged the results to create a migration corridor. Instead of averaging paths to create a corridor, it would be averaging corridors to define a more concentrated corridor.

The use of least accumulated-cost analyses for modeling bird migration patterns can provide valuable information to preserving the natural environment. The identification of high concentrations of migrating birds can assist in developing policies that control where and how tall structures are built. The limitation of certain structure heights, materials and designs can significantly reduce the number of migrating birds are killed every year. This same information about flyway concentrations can be used to identify areas of high concern for the preservation of critical stopover habitat. The least accumulated-cost analysis could be performed at more local levels inside the already identified corridors to determine exact land areas that need to be conserved. Human development is constantly altering the environment and these changes can impact flight patterns. When we destroy habitat birds will have to detour in order to find refueling sites during their migration. The least accumulated-cost analysis could be done in advance of development to determine the impact the project would have on the natural environment and wildlife migration.

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