Use of Least-Cost Path Analysis to Identify Potential Movement Corridors for Jaguars Across the US-Mexico Border

by

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To Hannah

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List of Abbreviations

CP	Cost Path
CB	Current Border
DEM	Digital Elevation Model
EPW1	Expanded Pedestrian Wall/Barrier One
EPW2	Expanded Pedestrian Wall/Barrier Two
EPW3	Expanded Pedestrian Wall/Barrier Three
GIS	Geographic information system
GLAD	Global Land Analysis and Discovery
IUCN	International Union for Conservation of Nature
Km	Kilometers
LiDAR	Light Detection and Ranging
LCP	Least-Cost Path
NAD	North American Datum
NB	No Border
SEDAC	Socioeconomic Data and Applications Center
U.S.	United States
USFWS	United States Fish and Wildlife Service
USGS	United States Geologic Survey
UTM	Universal Transverse Mercator
VB	Vehicle Barrier

Abstract

Human activity has always impacted wildlife and the environment, fragmenting and reducing habitats on a global scale. The jaguar (*Panthera onca*) once extended from Argentina to the American Southwest. After being hunted to extinction in the United States 60 years ago and with 54% of its habitat reduced, the jaguar is at its highest risk of extinction historically. However, jaguars have finally started dispersing back into Southern Arizona and New Mexico. Jaguars are known to disperse to set up new territories or reclaim lost habitat; males have been observed to disperse hundreds of kilometers from their original territory. In order to make sure that jaguars have a way to grow in population and expand their territory into the United States, there must be a path for them to enter the United States from Mexico and into new habitable territory. However, existing and future physical structures along the United States-Mexican border affect their path. In this study, multiple border structure expansion scenarios were investigated to determine the change in cost to jaguar dispersal paths crossing the border into habitable areas of the United States. Evaluating change in cost refers to the change in difficulty of terrain, distance, and other factors that affect the jaguar's ease of movement. Paths across the border were analyzed and the most sensitive locations to jaguar dispersal cost were identified. These paths were investigated using least-cost path analysis. As the border structures expanded under each scenario and the ability to move across the border diminished for the jaguars, the cost of travel increased. The increase in cost was minimal and gradual at first, then dramatically increased when the paths into the United States eventually closed. The most sensitive locations to border structures for jaguar dispersal were identified to provide the proper jurisdictions with information on where to either implement wildlife corridors that create a safe path across the border or avoid building future border structures in those areas.

Chapter 1 Introduction

This project examined the dispersal paths that jaguars might use to expand into the United States (U.S.) in the Sky Island Mountains region of the U.S.–Mexican border, which spans from Sasabe, Arizona to Columbus, New Mexico. This study used least-cost path (LCP) analysis methods, following Epps (2007) and using data from Rabinowitz and Zeller (2010). Physical barrier expansions were simulated to block unwalled sections or reinforce vehicle barriers with pedestrian barriers to analyze how dispersal paths would be altered, and how that would affect jaguar repopulation into the U.S.

Various types of border structures affect the jaguar species differently. By defining a cost change to the border structures, we can evaluate a jaguar's ability to move across the border under differing barrier expansions. A cost change in this study refers to the impedance or cost to move planimetrically through each cell in a raster with a calculated value based on different variables that affect jaguar's movement. The scale of cost is 0-9 with low values corresponding to low cost or impedance to jaguar movement through each cell while high values correspond to a higher cost or impedance. Then, by finding where the most common jaguar paths are for dispersal across the border and where expanding the border barriers would be most costly for the jaguar, wildlife corridors can be planned to help the jaguars disperse into the U.S. more easily. This is important for determining the effects of additional barriers on the jaguar's ability to expand its range, and it will help reduce the cost effect by determining the most suitable locations for a wildlife corridor where border structures exist and where future border structures will be the most detrimental to the jaguar.

Each border structure scenario came with nine potential routes that a jaguar might take to nine potential habitats in the U.S. Each route has a cost associated with it that changes with each border structure scenario. This cost is used to represent the difficulty a jaguar has, to disperse into the U.S. A lower cost is ideal for strong jaguar movement between habitats and to hopefully establish a permanent residence in the U.S. Identifying the most common paths found in the analysis can be emphasized to show where not to expand barriers or where to build a wildlife corridor in existing barriers.

1.1. Motivation

President Trump first promised to build a border wall that spans the entirety of the U.S. southern border during his 2016 presidential campaign. He later clarified in 2018 that mountains, rivers, and other natural barriers would suffice for half of the border, and a barrier would not be necessary for those regions (Cummings 2019). The southern border already is composed of 1052 kilometers (km) of border structures – 569 km of pedestrian barriers and 482 km of anti-vehicle barriers. So far, the U.S. Congress has approved $1.7 billion in funding for 98 km of new border structures and 64 km of replacement barriers (Chillida 2019). A 51 km section of pedestrian barrier has also been approved by the federal government near the Tucson area starting in late 2019 (Customs and Border Protection 2018). President Trump is still asking Congress for $5.7 billion more for more physical barriers along the border. The success of President Trump’s request is ongoing, and as of the completion of this study, he has not succeeded in receiving full funding. Whether or not the border structures help mitigate illegal immigration as they are intended, it will certainly influence the environment and wildlife (Cordovo 2007).

The diverse and complicated ecosystem of the border region between the U.S. and Mexico is the result of thousands of years of longitudinal migration of flora and fauna (Cordovo

2007). Historically, the American jaguar (*Panthera onca*) ranged throughout the entire American Southwest to Argentina before they were hunted to extinction north of the U.S.-Mexican border by the American government and farmers (Childs 2008). Today, the jaguar is considered near threatened with populations decreasing in Central and South America. Jaguars started to make occasional appearances in the U.S. in 1996, which were the first sightings since 1963. Sightings have increased since 2011, as there may be one or two permanent residents (Loomis 2019). As apex predators, jaguars need space to hunt and grow in population. If the government builds more barriers along the border, it may be more difficult for jaguars to disperse and settle in the U.S. Jaguars need safe routes across the border that are unobstructed and far from human interaction. As the jaguar population grows, there will be more sightings and possibly more permanent U.S. residents that can get U.S. protection. In order to ensure that this is possible, this study will explore how current border structures and potential future border structures will affect the dispersal of the jaguar across the border.

1.2. Study Area

Jaguars will travel long distances over extended periods of time to establish new territory or reclaim lost habitat. This is known as dispersal and is essential for jaguars to establish new hunting grounds and allow their population to expand. Based on jaguar sightings data, the dispersal routes that the jaguars use are in a mountain range known as the Madrean Sky Islands. The Madrean Sky Islands span 257 km of border from Sasabe, Arizona, to Columbus, New Mexico (Figure 1). These mountains are called the Sky Islands because they feature high elevation lower temperature forests that area surrounded by hot dry desert valleys. There are forests in these mountains that are separated and surrounded by desert which makes them look like floating islands of green above the desert below. The Madrean Sky Islands are known as the ideal habitat for jaguars in the Southwestern U.S., and thus this is an appropriate study area. The elevated forests have high biodiversity in stark contrast to the dry deserts below. The jaguar prefers tree cover and the availability of prey. These mountains have several types of barriers intersecting them.

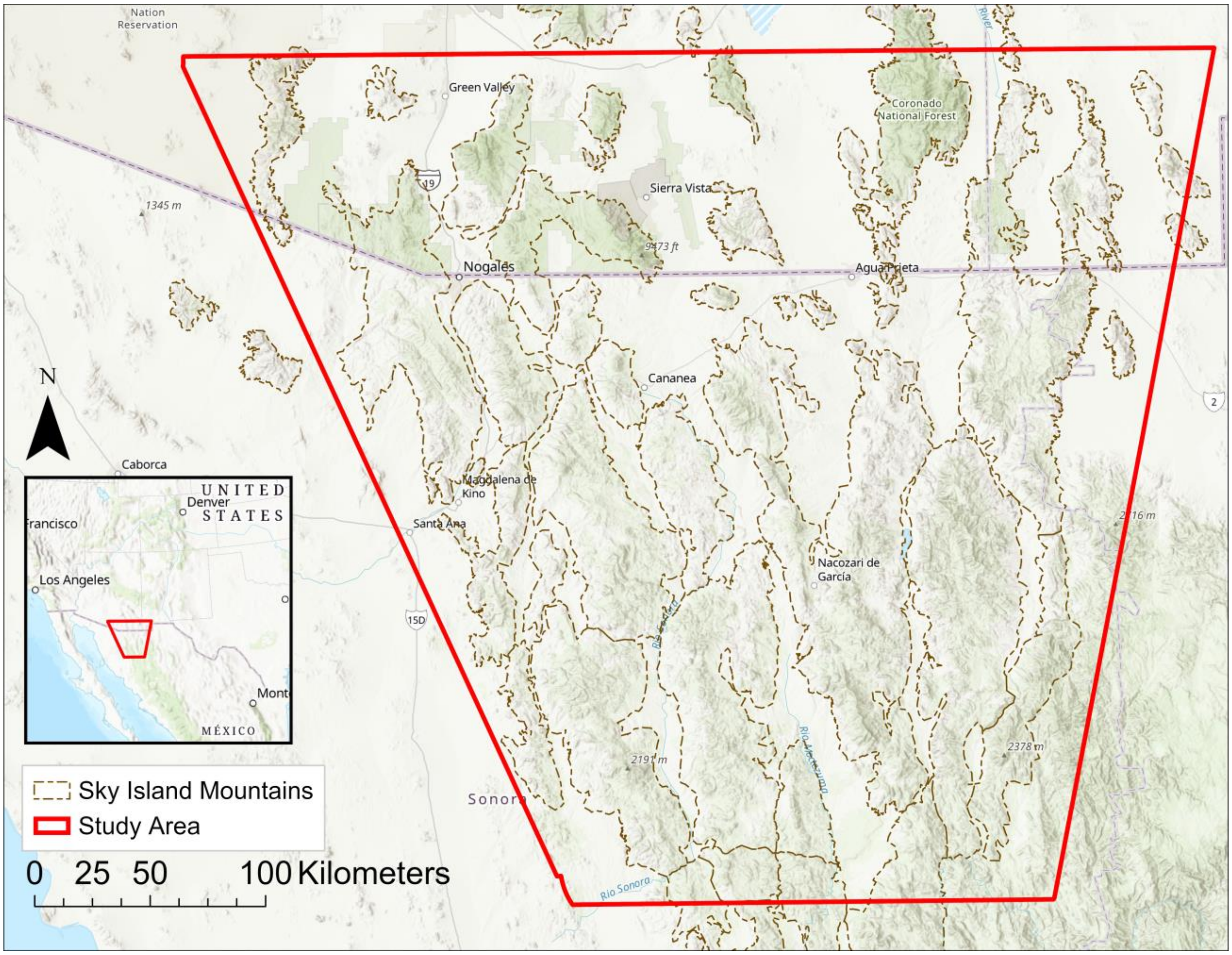

Figure 1. The study area for this analysis including the Sky Islands

There are pedestrian barriers made of concrete and steel that are impassable by wildlife, and there are shorter, cross-hatched vehicle barriers that wildlife and humans can bypass (Figure 2). The vehicle barriers are less expensive to build than the pedestrian barriers and are used to prevent vehicles from crossing the border or disable vehicles that attempt to cross. They are typically deployed in more remote areas of the border as a less expensive method to deter illegal immigration. The intent is that in the remote regions of the border, illegal immigrants are more likely to cross by vehicle than by foot. While these barriers are difficult to cross for vehicles, they are not impassable. Animals and humans can walk past the barrier relatively easily, meaning the jaguar is not inhibited by vehicle barriers. Jaguar sightings indicate that the unblocked sections or sections that contain vehicle barriers are the current dispersal routes across the border for the jaguars, especially in the west around Nogales (Childs 2008). The sections of the border around Nogales that are open utilize the Sky Island mountains as a natural barrier.

Figure 2. *Left*, example of a vehicle barrier; *right*, example of a pedestrian barrier

1.3. Threat to the Jaguar

Right now, there are several conservation efforts trying to help the jaguar repopulate the U.S. Jaguar habitat is shrinking even though there are strong conservation efforts aimed at protecting them. As Central and South America industrialize, the jaguar’s habitats are at risk of becoming increasingly fragmented, possibly reducing the population size. The jaguars are being isolated into smaller separate populations with limited interaction, leading to a reduction or loss in genetic exchange that increases in-breeding, reduces fitness, and contributes to extinction risk (Rabinowitz and Zeller 2010).

Connectivity of jaguar habitat is particularly important due to the implications of climate change (U.S. Fish and Wildlife Service 2016). As temperatures increase due to climate change, jaguars need to migrate to more favorable conditions. Therefore, corridors into the U.S. are essential to jaguar survival. An expansion of the species into the U.S. would allow the U.S. government to protect them and let them grow in population. A jaguar needs a large territory to hunt away from other jaguars, so, as their population grows, they will need more space (U.S. Fish and Wildlife Service 2016). Since their habitat is shrinking in Central and South America, the best option is to try to move them into the habitable American Southwest. A barrier would not allow them to move north- rather, it would confine their available territory. This project will hopefully enable the administration to carefully decide how to expand the border structures, if they choose to do so, while also being responsible for wildlife.

1.4. Research Objective

This project was intended to provide information to decision makers about future border structures and how they may impact jaguar dispersal. The main objective of this study was to determine the change in cost associated with border structure expansion to the jaguar's path across the border. Then, determine the most sensitive locations that impact jaguar dispersal. The outcomes of this study could be utilized in planning border structures insofar as to where to include areas possible to jaguar passage across the border. To achieve these goals, this study sought to:

1. Create a realistic cost surface of jaguar populations in the Sky Islands based on Rabinowitz and Zeller (2010)

2. Determine realistic starting and ending points for LCP analysis based on current and potential habitats

3. Create border structure scenarios that might be installed along the U.S.-Mexico border in the study area

4. Create LCPs for the potential routes that the jaguar might take

5. Analyze the cost change over all the scenarios for each path and determine the most sensitive locations to build border structures.

The success of this study relied on understanding jaguar behavior and creating the LCPs in the most realistic way possible. Following the study by Rabinowitz and Zeller (2010) was appropriate to get the most accurate LCP results.

1.5. Study Expectations

This study's purpose is to determine where wildlife corridors should and could be implemented for current and future border structure locations. Due to the impassable nature of pedestrian barriers, it is expected that their presence will be an impedance to the dispersal of jaguars into the U.S. Therefore, the current border is expected to increase the cost of dispersal compared to a scenario with no border. Then, every border scenario that expands the border structures will increase the cost of travel gradually until the border is impassable. At that point, the cost will increase significantly as the jaguars will have to find much longer routes around the new border structures.

Chapter 2 Related Work

This chapter reviews literature related to the underlying concepts behind habitat data, corridor modeling, and LCP modeling. The goal of this section is to provide background information on the processes used within this study.

2.1. Habitat

In order to complete a LCP analysis, the starting point and the destination must be clearly defined for the purpose of the analysis. Understanding a jaguar's preferred habitat is critical to understand where to reasonably start and end jaguar dispersal in the U.S. for the LCP analysis.

2.1.1. Jaguar's Preferred Habitat

Jaguars are known to live in different biomes. They inhabit lowland wet communities like tropical rain forests (U.S. Fish and Wildlife Service 2016) as well as arid areas, including lowland desert, mesquite grassland, Madrean oak woodland, and pine-oak woodland communities located in Northwestern Mexico and Southwestern U.S. (Childs 2008). This area is known as the Madrean Sky Islands and is the study area used in this analysis. The Sky Islands are located in between the Rocky Mountains and the Sierra Madre Occidental in Southern Arizona and Northwestern Mexico. These mountains are unique in that they provide a cool and wet environment which is in stark contrast to the hot and arid environment of the valleys between each mountain in the range (Skroch 2008). Jaguars are known for living in low wetlands, but the desert that surround the cooler mountains are often too hot, and thus some have been documented dispersing north in the mountains where the temperature is cooler. The jaguars, then, tend to stick to higher elevations where there is plenty of prey, including javelina, coati, big-horn sheep, and black-tailed prairie dogs. The borderlands region is mostly desert, which is unsuitable for the jaguar, making the Sky Islands the best dispersal path into the U.S.

2.1.2. Habitat Modelling

There have been several studies determining the most habitable areas that jaguars would live in Mexico and the Southwestern U.S. (Sanderson 2013; Rodriguez-Soto 2011; Hatten 2005; Rabinowitz and Zeller 2010; Stoner 2015; Theobald 2017). These studies were conducted by consulting jaguar experts and used jaguar sighting data and Geographic Information Systems (GIS) habitat mapping software. Experts agree that jaguars prefer rocky terrain, elevation between 0 meters and 2000 meters, above average temperatures, increased tree cover, proximity to water source, and isolation from human activity. Each study used a habitat suitability model to determine where the jaguars are most likely to live in Mexico or Arizona. Similar locations of suitable jaguar habitats in Northwestern Mexico were found across different analyses (Sanderson 2013; Rodriguez-Soto 2011; Rabinowitz and Zeller 2010; Theobald 2017; Stoner 2015). One location that is highly habitable for the jaguar is located near Sahuaripa, Mexico at the southern tip of the Sky Islands and is known as the Northern Jaguar Reserve (Rodriguez-Soto 2011). The conservationists at the Northern Jaguar Reserve study the jaguars and help protect them from human interference while giving them a secure area to live. It is the northernmost permanent habitat of the jaguar which makes it an ideal starting point for jaguars to begin their dispersal north into the U.S.

The reserve has high habitability and carrying capacity (Sanderson 2013; Rodriguez-Soto 2011; Stoner 2015; Theobald 2017) and it serves as the best starting point for the LCP analysis. The Sky Islands have a lower jaguar carrying capacity than the Northern Jaguar Reserve and the region directly south of the reserve (Sanderson 2013). However, on the other side of the border in the U.S., the carrying capacity is slightly higher and could be capable of a permanent jaguar population (Stoner 2015; Sanderson 2013; Theobald 2017). The parts of the Sky Islands that are within 72 km north of the U.S.-Mexican border are habitable to the jaguar and have had numerous jaguar sightings to help support their claim (Stoner 2015; Hatten 2005; Sanderson 2013). The U.S. Fish and Wildlife Service (USFWS), in their “Endangered and Threatened Wildlife and Plants; Designation of Critical Habitat for Jaguar” final ruling, outlined these areas in a map (Figure 3) as the known and potential habitats for a permanent U.S. jaguar population (U.S. Fish and Wildlife Service 2014).

Thus, past research has shown the Sky Islands to be suitable for jaguars while also providing an ideal route between potential U.S. habitats and the current Mexican habitat. This makes these areas ideal for the destinations in the LCP analysis and validates the importance of a study creating realistic LCPs between the two habitats.

2.1.3. Jaguar Dispersal Range

It is difficult to measure the distance of a jaguar’s movement, let alone the dispersal of a jaguar. Dispersal can be gradual or quick, making it troublesome to measure dispersal distances and speed. Not much is known about the mechanics of jaguar dispersal except that the males are the ones to typically disperse long distance and can travel 64 km (Quigley and Crawshaw 1992) and up to 800 km (Rabinowitz and Zeller 2010) to seek out new territory. Jaguars, on average, travel 2.56 km in one day depending on the season when they are not dispersing (U.S. Fish and Wildlife Service 2016). The most a jaguar has been measured to move in one day was 39 km, and jaguars frequently move up to 20 km in one night often finishing where they began. The average maximum distance a jaguar travels in a day is 9.19 ± 3.78 km (U.S. Fish and Wildlife Service 2016). With such a broad range of movement distances that the jaguars have been known to travel, this study will assume that jaguars will move an average of 9.19 km a day when they are dispersing.

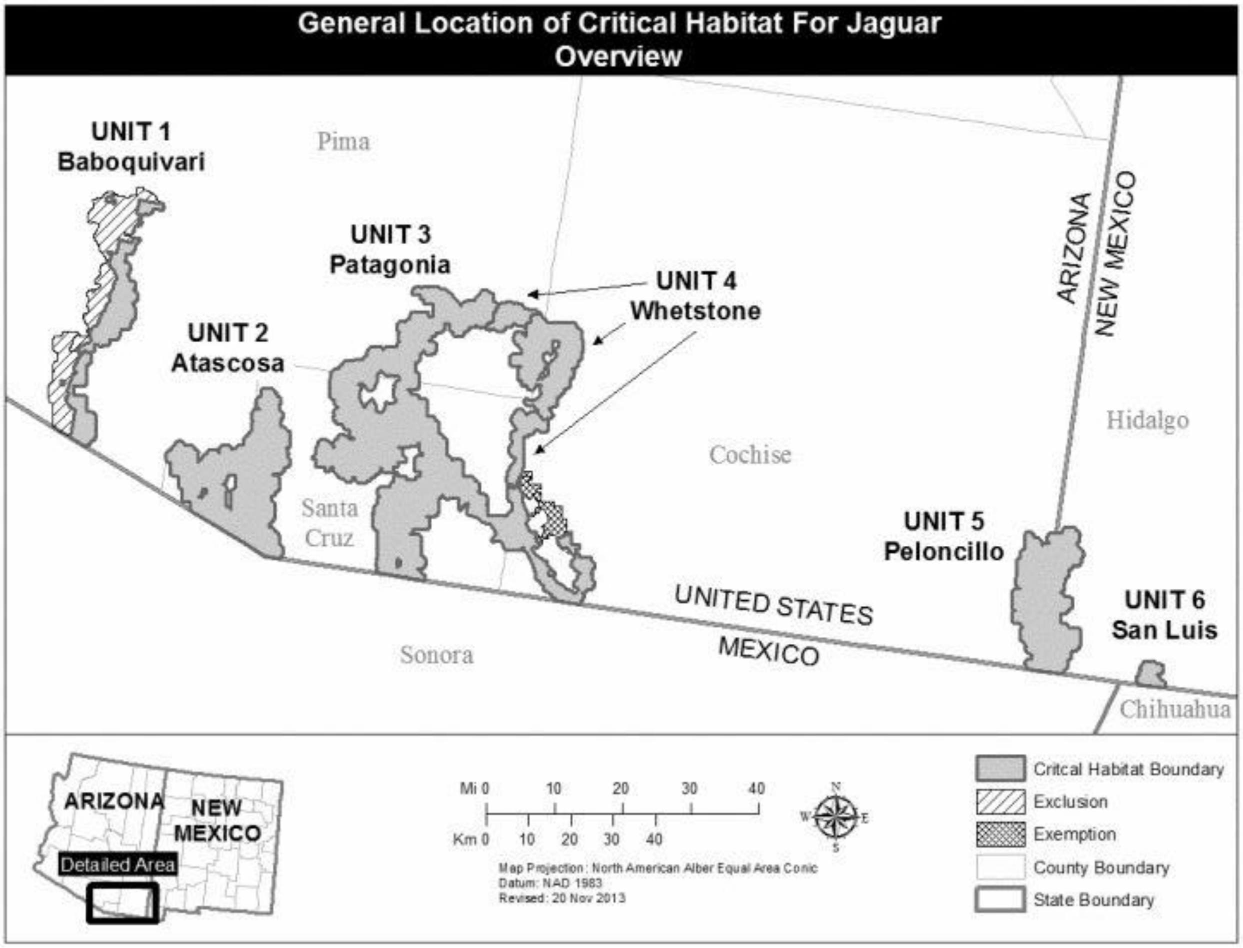

Figure 3. Overview of critical habitats for the jaguar. Map from USFWS 2014 Figure 1

2.2. Corridor Modelling

Rabinowitz and Zeller (2010) analyzed corridors between jaguar habitats in Central and South America. They looked at 90 known fragmented jaguar habitats in Central and South America and used spatial analyst tools to find corridors between each habitat to determine the most at risk habitats to being isolated or fragmented. To determine the most realistic cost values for jaguar dispersal, they interviewed fifteen jaguar experts. The cost layers that they used were land cover, percent tree and shrub cover, elevation, distance from settlements, distance from roads, and human population density (Table 1). They used ArcGIS cost distance tool with their cost layers to determine the cost when travelling between habitats. Then, they used the Cost Distance Function and Corridor Function in Spatial Analyst of ArcGIS V9 software to analyze jaguar range for corridors. Any corridors with a width of 10 km or less were designated as a corridor for concern, as they have the potential to be severed or become genetic bottlenecks. When this occurs, the jaguars are at risk to genetic fragmentation which reduces the strength of their gene pool and increases their risk of extinction.

The researchers were able to create a habitat connectivity map for the jaguars and determine what corridors were most at risk (Figure 4). What they could not determine was how wide the corridor between habitats needed to be. The width of a corridor is important so that animals can find their way into the path. Previous studies have suggested that cougars need a corridor only 400 meters wide, whereas Florida panthers needed somewhere between three to seven kilometers (Beier 1993, Kautz et al. 2006). Rabinowitz and Zeller (2010) averaged those suggestions to predict that any corridor less than 1 kilometer wide would be insufficient for supporting jaguar dispersal while maintaining that any corridor less than 10 km wide was a corridor of concern.

Table 1. Table of cost values including the elevation cost change for this study

Land Cover Type		**Percent Tree and Shrub Cover**		**Human Population Density (people/km^2)**		**Elevation (meters)**		**Distance from Roads (kilometers)**		**Distance from Settlements (kilometers)**	
Class	***Cost Value***	***Class***	***Cost Value***	***Class***	***Cost Value***	***Class***	***Cost Value***	***Class***	***Cost Value***	***Class***	***Cost Value***
Tree Cover, broadleaved, evergreen	0	0 – 10%	9	0-20	1	0 – 1000	~~0~~ ⇨ 2	0 to 2	7	0 – 2	8
Tree Cover, broadleaved, deciduous	0	10% - 20%	7	20-40	5	1000 – 2000	~~2~~ ⇨ 0	2 to 4	4	2 – 4	5
Tree Cover, needle- leaved, evergreen	1	20% - 40%	5	40-80	7	2000 – 3000	7	4 to 8	2	4 – 8	4
Tree Cover, mixed leaf Type	0	40% - 60%	2	80 - 160	9	3000 – 5000	10	80 to 160	1	8 - 16	1
Tree Cover, regularly flooded, fresh water	2	60% - 80%	0	160-320	10	>5000	N/A	> 16	0	> 16	0
Tree Cover, regularly flooded, saline water	2	80% - 100%	0	>320	N/A						
Mosaic: Tree cover/other natural vegetation	1										
Shrub Cover, evergreen	2										
Shrub Cover, deciduous	3										
Herbaceous Cover	5										
Sparse herbaceous or sparse shrub cover	6										
Regularly flooded shrub and/or herbaceous cover	5										
Cultivated and managed areas	8										
Mosaic: Cropland/Tree Cover/ Other natural Vegetation	5										
Mosaic: Cropland/Shrub or grass cover	7										
Bare areas	8										
Water Bodies	6										
Snow and Ice	N/A										
Artificial surfaces and associated areas	10										

Source: Data from Rabinowitz and Zeller 2010 Table 2

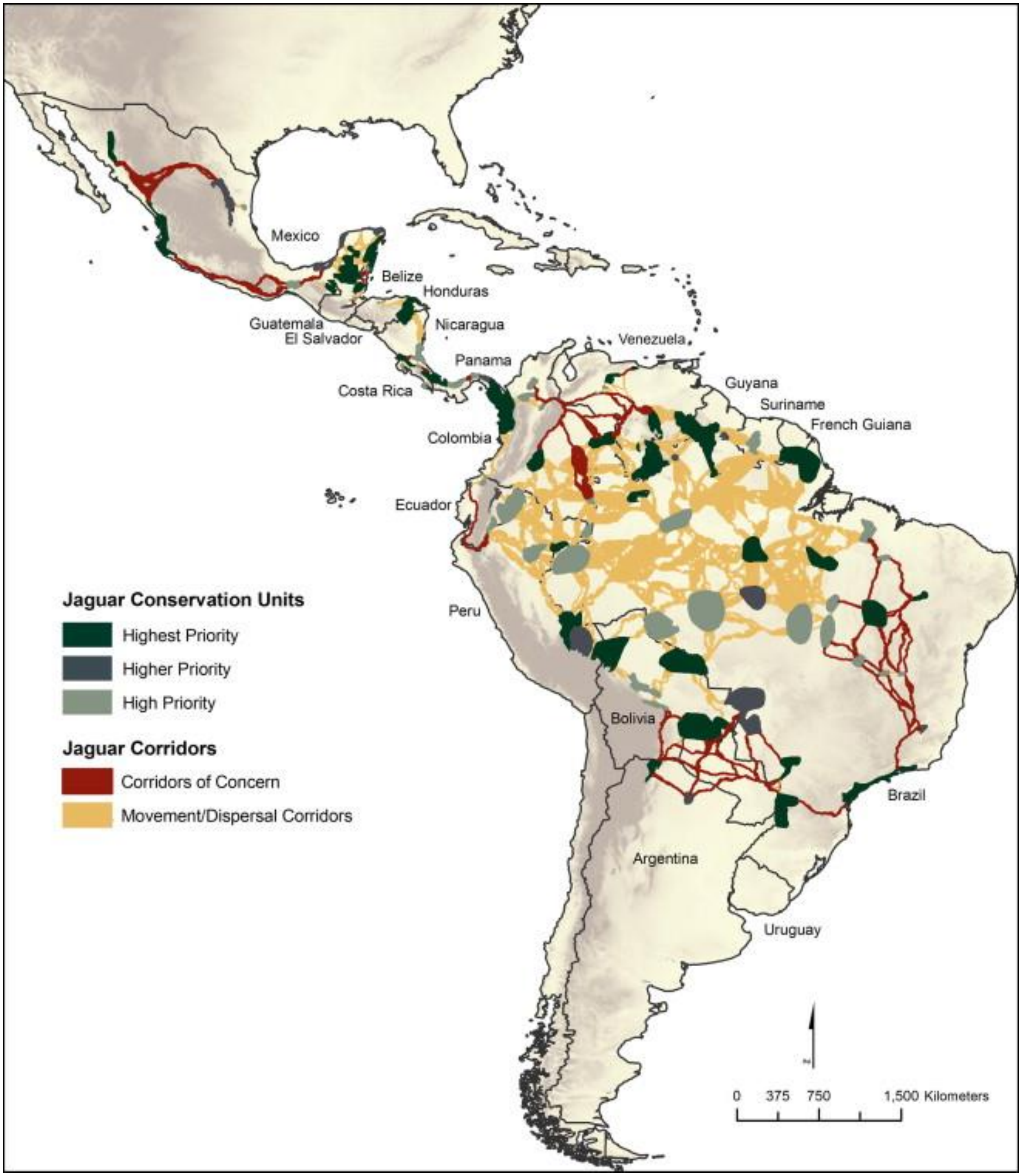

Figure 4. Jaguar corridors in Central and South America. Map from Rabinowitz and Zeller 2010 Figure 2

What Rabinowitz and Zeller (2010) did not do was to model corridors that extend into the U.S. This study uses many of the same data sources and cost values to create a similar study into the U.S., starting from the most northern jaguar habitat in the Northern Jaguar Reserve. However, this study slightly modifies the cost values of the elevation data (Table 1). This is because in Central and South America, Jaguars prefer the cooler lowlands with high percentage tree cover and plentiful prey. In the Sky Islands, those variables are switched; the higher elevations are cooler than the desert lowlands and have much more tree cover and boast plentiful prey. The Sky Island's lowlands are Sonoran deserts. Therefore, the cost value for elevation switches for the 0-1000 meters and the 1000-2000 meters ranges.

Stoner (2015) used CircuitScape, a type of software designed to analyze connectivity, to suggest a corridor between potential U.S. habitats and the Northern Jaguar Reserve. Stoner (2015) modelled the corridors and identified highways that intersect them. This was to determine where wildlife corridors could be placed to protect jaguars and other species from crossing highways. The method utilized electrical circuit theory and applied it to a model of jaguar habitat suitability to predict the movement of jaguars across the landscape. Ten intersections were discovered where over or underpasses needed to be built to protect wildlife. The current border structures were included in their analysis. The study discusses the problematic nature of border structures and ways in which future expansions inhibit jaguar dispersal. The resulting map from Stoner (2015) (Figure 5) showcases the corridors, potential habitats, and dangerous highway crossings for the jaguar from Mexico into the U.S. This project aims to expand on this research to analyze how the border affects jaguar movement and where wildlife corridors should be placed, but it looks at the U.S. border rather than highways. The corridors found in Stoner (2015) avoid the border structures and are important for comparison. If the LCPs of this study match the corridors for Stoner (2015), the results can be validated, albeit suggestively.

Stoner (2015) followed Sanderson and Fisher's (2011, 2013) by modelling tree cover, terrain rockiness, distance to water, anthropogenic influences, and habitat type instead of the layers used in Rabinowitz and Zeller (2010). Stoner (2015) mentions that other variables such as prey availability, local landscape and habitat features, and jaguar behavioral responses to highways and other forms of anthropogenic land use could be used to further their study, but those factors were too difficult to utilize as they were too complex and on a much finer scale than their study could accurately model.

For this analysis, the variables from Rabinowitz and Zeller (2010) will be the only ones used in order to avoid over-complicating the analysis. It can be difficult to predict robust results using LCP analysis when the number of variables and cost layers is high. At a certain point, too many variables can lead to inconclusive results (Selonen and Haski 2012). By limiting the number of variables to those used by Rabinowitz and Zeller (2010), there is both methodological consistency and a limited risk of over-complicating the analysis.

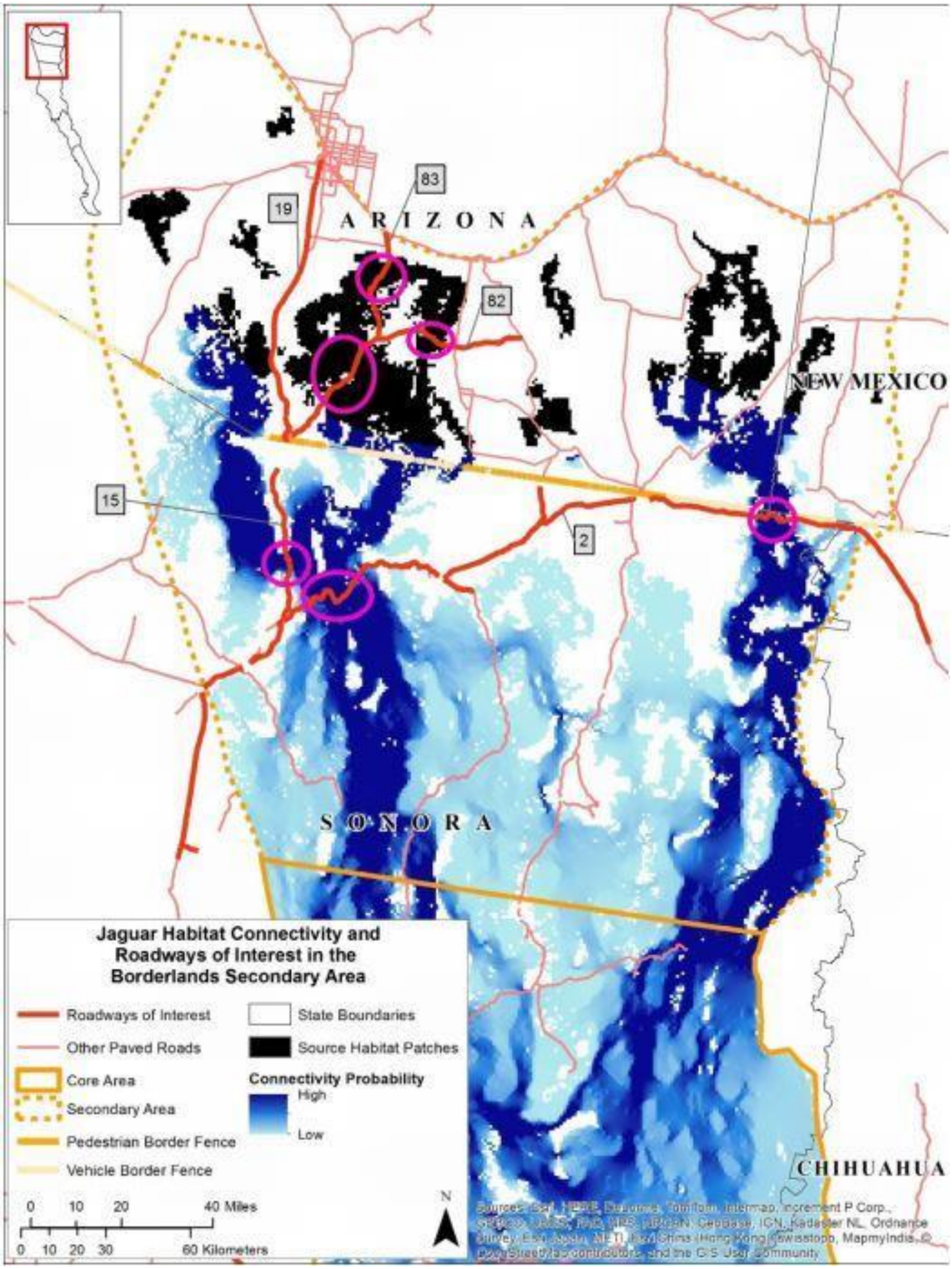

Figure 5. Model results for jaguar corridor connectivity between U.S. and Mexico highlighting highways that require wildlife corridors. Map from Stoner 2015 Figure 6

2.3. Least Cost Path Analysis

In the early development of LCP analysis, Adriaensen et al. (2003) studied the theory and function of LCP to link potential habitats for virtual organisms using a map in Belgium. The location is real, used for its diverse landscape, and the organism was created for the study as a test organism to understand how the analysis operated. Before testing real life behavior of animals, they wanted to make a generic organism for simplicity. Instead of cost, as used in this study, they used resistances, which serves the same function to study the preferred route of an organism travelling from one forest to another. A cost value of one was used for any habitat cells, five was used for habitat-like cells, forty for hostile cells, two hundred for physical barriers, and twenty for all other cells in their analysis. It was determined that the best way to decide the values for resistances is to adopt a “starter kit” of resistances and study the sensitivities of each resistance to select the best value. They found an issue in that the LCP determines the resistance of a path taken but does not consider the behavior of the organism travelling. Developing a behavior cost is important to fully optimize the most accurate route. The study analyzed how LCP works and the best ways to implement it in habitat modelling. The methods were experimental and unusable for this study, but the ideas and understanding are important to develop the best model for habitat corridors. Instead of the methods, this study can learn from the basics of cell connectivity and determining the best ways to implement LCP analysis for organism behavior.

In order to create better results for the corridor modelling, behavioral variables need to be applied to an LCP analysis. Big-horn sheep for example, prefer traversing steep slopes over any other type of landcover when dispersing (Epps et al. 2007). Therefore, a slope cost layer would be more significant than a land use cost layer when studying dispersal and habitat connectivity.

Epps et al. (2007) used this behavior modelling in a LCP analysis to determine gene flow between big-horn sheep in California, where the analysis involved LCPs for an organism between habitats. Epps et al. (2007) used three different types of matrices to determine the bounds of different populations and the paths between each population. The paths were developed using slope cost rather than landcover cost. The slope cost was determined by using different cutoffs for maximum and minimum slopes, knowing that bighorn sheep do not travel on flat surfaces or cliffs steeper than 90%. The model was run six times with different slope cell values that affect the three chosen cutoff points. The analysis developed LCPs between the habitats with the slope cost layers and validated the results with known routes. The study used eighteen combinations of slope cell weights, resulting in thorough results in order to match known routes of the big-horn sheep. Using a behavioral cost layer is vital for the success for an LCP analysis. Being thorough with weights and cost values helps validate results as well as eliminates uncertainty.

One behavioral layer can significantly impact the results of a LCP analysis, but having more can make the results increasingly complex and revealing. Animal and human behavior is intricate and there are many operators that affect the ability to choose a path. Alexander et al. (2016) conducted a study in which LCP was utilized to establish corridors for the swift fox in Montana between known habitats. The study aimed to uncover the most suitable sites to reintroduce swift foxes in a developed area between two large established habitats. The known habitats became disconnected because of human development. The reintroduction sites would be used to help establish increased connectivity for the two habitats. The study developed a habitat suitability model by using the six fox behavioral cost values of brightness, crop density, greenness, road density, terrain ruggedness, and wetness. The cost layers were cross analyzed with fox observation data to determine which variables would be most significant to determining the swift fox's habitat. A weighted cost raster was created from each of these layers that were weighted for their significance to a swift fox's behavior. This was used to develop the LCPs between the known habitats. Several paths were created and were used to suggest reintroduction sites, after which a site suitability analysis was conducted to determine which reintroduction sites would be the most impactful. A limitation of the study was that while swift fox habitat and migration could be improved, cost values could have been miscalculated and better data could have led to a more complete report. A thorough understanding of the species being studied is a challenge, in addition to locating the best data and cost values. All swift foxes are unique, and it is impossible to predict the behavior of an individual based on aggregated analysis of a species. Understanding the limitations of a LCP analysis is important in evaluating its success. Following how Alexander et al. (2016) determined the weights and cost values for the swift foxes, as well as understanding the fundamental limitations of this approach, is key to an honest LCP analysis.

Chapter 3 Methods

The LCP analysis in this study used cost values from Rabinowitz and Zeller (2010) to construct the cost layers. The data included landcover type, percent tree and shrub cover, human population density, elevation, distance from roads, and distance from settlements (Table 2). These land cover types were given values from fifteen subject matter experts on jaguars. The Northern Jaguar Reserve acted as the starting point for the jaguar dispersal. The end points consisted of nine locations chosen based the lowest cost cells within the USFWS known habitat locations (Figure 6). There were nine end points to reduce path overlap and maximize distribution. The nine points lied within known habitats per USFWS, and/or are in the most habitable locations based on the cost layer described below. The known habitable locations could be influenced by current border structures, so other points in habitable locations were selected to reduce bias.

The starting point was the Northern Jaguar Reserve whose location was given by the International Union for Conservation of Nature's (IUCN) website (Table 2). The end points were based off the lowest cost cells in the cost layer along with a known habitat map from the USFWS. The study area was the region between the Northern Jaguar Reserve and the destinations. The Sky Islands are the jaguar's known route into the U.S., so the study area ends 24 km past the furthest east and west points of the Sky Islands. The northern and southern bounds of the study area were dictated by the start and end points. The border structures layer was taken from the Center for Investigative Reporting and cross checked with satellite images from Google Earth for accuracy. The elevation data was from the United States Geologic Survey (USGS). This study used land cover data from Global Landcover 2000.

The percent tree and shrub cover layer data were from the Global Land Analysis and Discovery (GLAD). The population centers layer was found in the World Bank website, and the roads layer was constructed from data collected by the Socioeconomic Data and Applications Center (SEDAC). All map layouts and data storage were created using ArcGIS Pro 2.3.2 with the Spatial Analyst extension.

Table 2. Data description

Dataset	Format	Resolution	Source	Year
Starting Habitat	Shapefile		International Union for Conservation of Nature (IUCN)	2017
Ending Habitat	Shapefile		U.S. Fish and Wildlife Service (USFWS)	2018
Study Area	Shapefile		U.S. Fish and Wildlife Service (USFWS)	2018
Border Structures	Shapefile		Reveal from The Center for Investigative Reporting and OpenStreetMap contributors	2017
Population Centers	Shapefile		The World Bank	2017
Roads	Shapefile	50 meters	Socioeconomic Data and Applications Center (SEDAC)	2010
Elevation	Raster	30 meters	USGS	2013
Land cover type	Raster	1 km	Global Land Cover 2000	2003
Percent tree and shrub cover	Raster	30 meters	Global Land Analysis & Discovery (GLAD)	2019
Human population density	Raster	1 km	Oak Ridge National Laboratory	2017

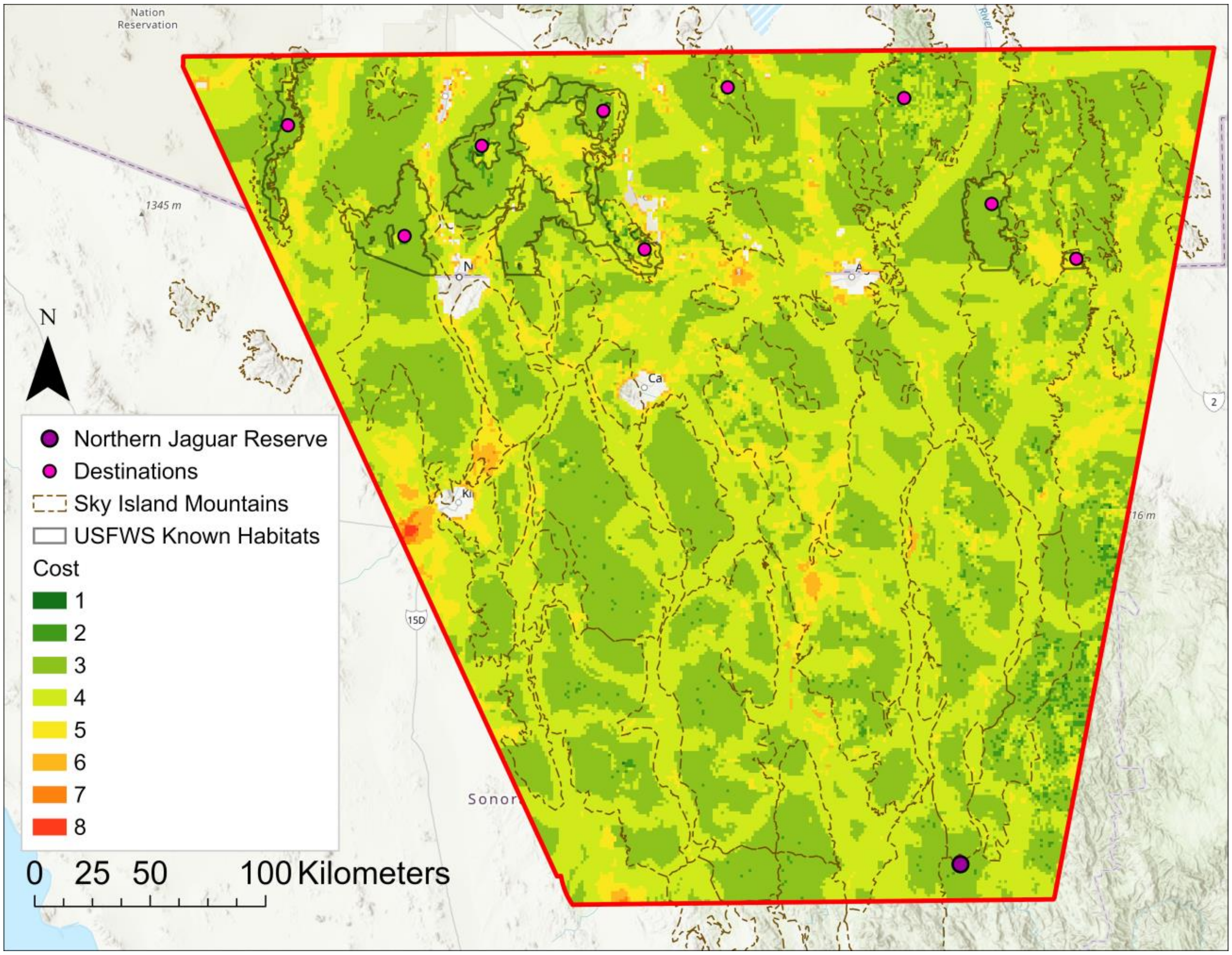

Figure 6. The study area, starting and ending points, and the habitable areas of the study area based on lowest cost and USFWS known habitats layer

3.1. Data and Preliminary Analysis

This chapter outlines the most integral parts of the analysis. Cost values were assigned according to Rabinowitz and Zeller (2010) with small changes to the elevation costs due to a change in environment. The data sets were readied for raster calculation by use of raster transformations, clipping, resampling, multi-layer ring buffers, and projecting to North American Datum (NAD) 1983 (2011) Universal Transverse Mercator (UTM) Zone 12. UTM Zone 12N is a projection that is ideal for measuring distance and is excellent for the study area. After the cost surface was produced, LCP analyses were created with different border scenarios resulting in fifty-four different paths. The resulting cost paths were analyzed for their total cost, length, and the number of roads crossed. The results of these analyses and procedures are discussed in Chapter 4.

The main objective of this research is to determine what the change in cost to jaguars would be if the border structures expanded. The workflow started with research into the subject matter and acquisition of the data. Then the preliminary and primary analyses were conducted (Figure 7).

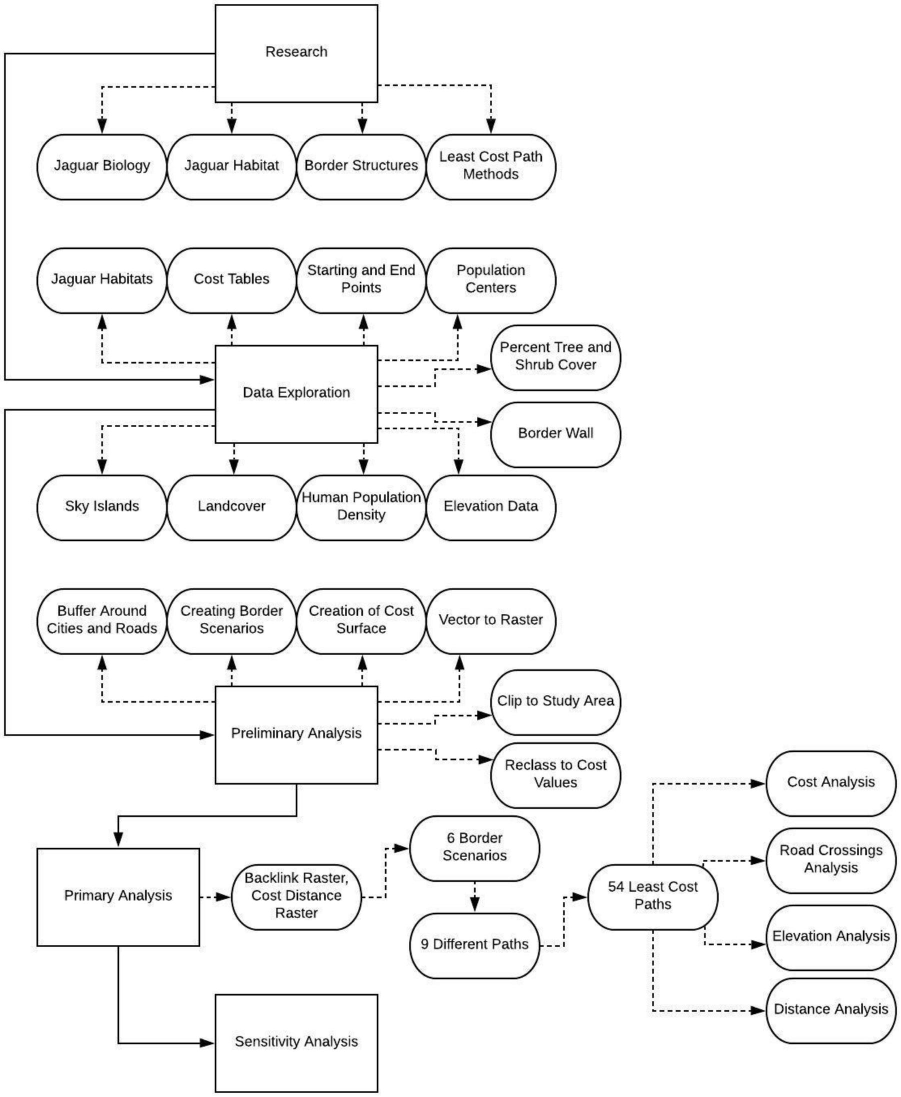

Figure 7. Study workflow

3.1.1. Study Area

The study area was determined by several factors, including distance from the border, known jaguar habitats, and the Sky Island Complexes (Figure 8). First, the study area was limited to land within 24 km of the Sky Islands boundaries, since it is the jaguar’s known route into the U.S. Then, the northern limit of the study area was determined to be 72 km from the border in order to include all the destinations. The southern bounds of the study area was 24 km south of the starting point, the Northern Jaguar Reserve. The study area was designed to stay close to the starting point and the destinations while enclosing most of the Sky Islands.

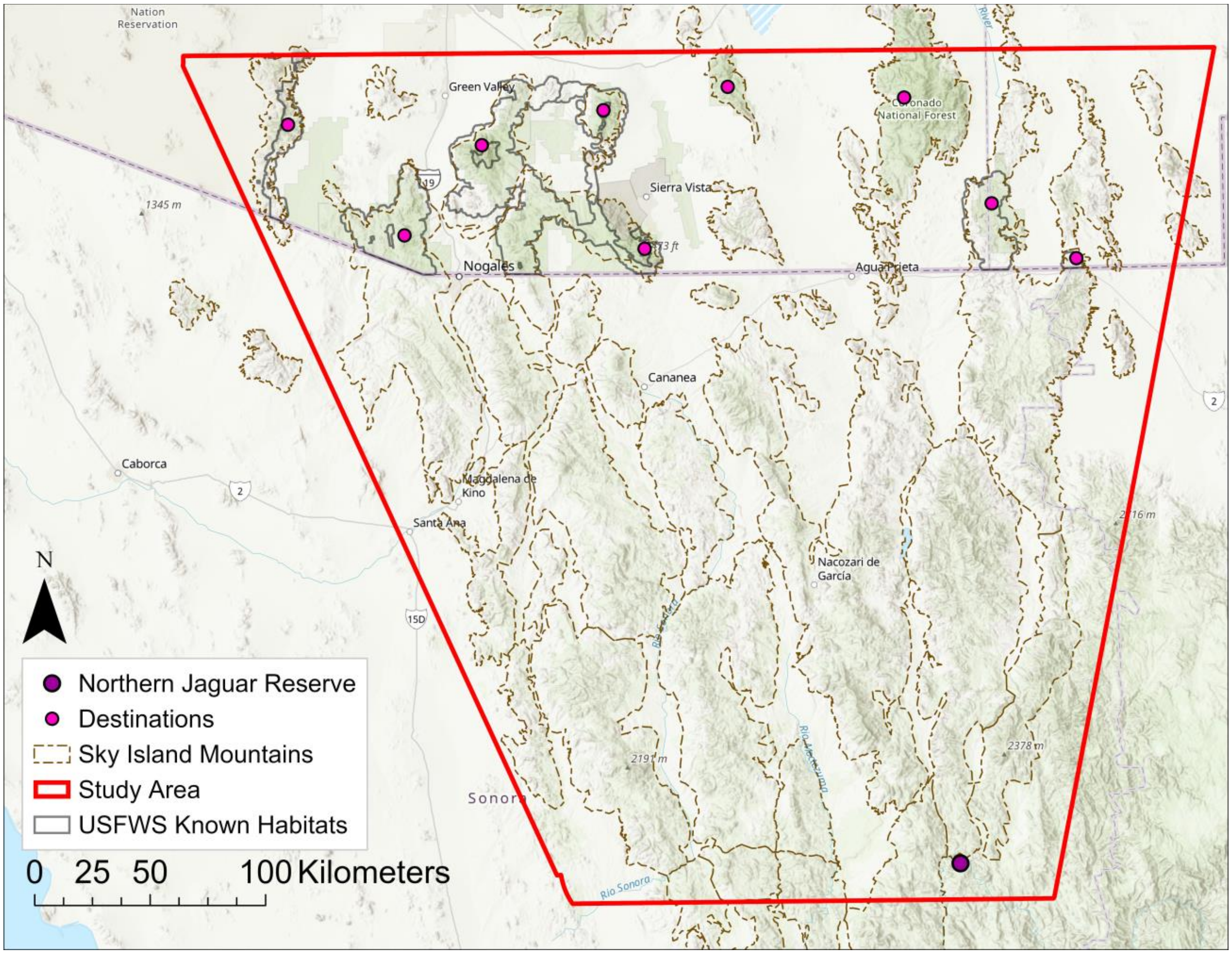

Figure 8. Study area including the known habitats and the Sky Islands

3.1.2. Starting Point

The starting point was determined using several components. All jaguars dispersing north do not start from the same point. However, there is only one place jaguars are known to live in the northernmost point in Mexico- the Northern Jaguar Reserve in Chihuahua, Mexico. Before the sanctuary was built, jaguars would most likely have multiple starting locations before dispersing into the U.S. However, due to habitat reduction and the threat of human interference, it makes the most sense to only have one starting point for this analysis as it boasts the highest number of jaguars and can be trusted to keep them alive. Any small deviation from the one starting location would not have a noticeable impact on the success of the analysis if the deviation is within a couple of kilometers, such as starting from a different section of the sanctuary. Therefore, only one starting point was used, which helps reduce the number of variables in the analysis.

3.1.3. Border Structures

The border data sets include information on all structures along the U.S.-Mexico border. The data set has information on the type of structure, year built, project, and the length of the structure. These datasets were compiled by Reveal from The Center for Investigative Reporting (2017). This is an open source citizen's report and was visually checked for accuracy using Google Earth. The three main border structure types are gates, pedestrian barriers, and vehicle barriers. The gates and pedestrian barriers are made of cement or metal that are up to five meters high and built to deter humans from crossing the border. These barriers were determined to be non-accessible to jaguars and considered the highest cost to cross, so much so as they were input as "no data" for cost so that the jaguars could not even attempt to cross them in the LCP analysis. Vehicle barriers, which are fences designed to prevent vehicle but not pedestrian entry, are generally permeable enough to allow for the passage of jaguars (U.S. Fish and Wildlife Service 2016). The vehicle barrier was considered a moderate cost for the jaguars and was input as a five out of nine for cost.

3.1.3.1. Border Structure Creation

This analysis had six different border structure scenarios that were studied in the analysis: no border (NB), current border (CB), vehicle barriers (VB) which is the current border scenario with all gaps replaced with vehicle barriers, expanded pedestrian barrier/wall one (EPW1) which is VB scenario except any pedestrian barriers were expanded 9.6 km on either side, expanded pedestrian barrier/wall two (EPW2) which is the EPW1 scenario but with another 9.6 kilometer expansion, and expanded pedestrian barrier/wall three (EPW3) which is the EPW2 scenario but with another 9.6 kilometer expansion (Figure 9). A scenario with no border was analyzed to determine the cost change of transitioning from an open border to the current border. This way, it could be observed if removing current border structures benefitted the jaguar's dispersal cost. To create the four expanded border scenarios from the current border, the original polyline vector layer was edited using the editing tools in ArcGIS Pro 2.3. The vertices of the polylines were moved to create vehicle barriers that covered the entire border. This scenario was to simulate a continuous barrier, but with the less expensive method of using vehicle barriers. This method is continuous, but it is porous. Therefore, pedestrian barriers were expanded in units of 9.6 km for each EPW scenario.

With each EPW scenario, 9.6 km of pedestrian barriers were added to either side of current pedestrian barriers. With 3 major pedestrian barrier sections present in the study area, there were six expansions of 9.6 km for each EPW scenario. Two expansions, on either side of three pedestrian barrier sections. This is a total of 57.6 km of pedestrian barrier added in each scenario. After three scenarios of EPW, there is approximately 172.8 km of added pedestrian barriers. When each EPW scenario expands, the 9.6 km of pedestrian barriers replace the vehicle barriers from the scenario before it. Choosing 9.6 km as the expansion rate was to eliminate gaps systematically and consistently between the cities of Sasabe, Nogales, and Agua Prieta, the three border towns in the study area. The six border structure scenarios were designed to realistically analyze the border in manageable way while indicating which sections of the border are sensitive to being impermeable to jaguar dispersal. When the six border scenarios were finished, they were prepared for analysis using a polyline to raster tool transformation. Then, they were conformed to the standard cell size using the resampling tool. After that, they were fit to the study area using the clip tool. Finally, they were projected to NAD 1983 (2011) UTM Zone 12N using the project tool. All raster layers need to be the same cell size and projection as the landcover raster as well as the same extent as the study area.

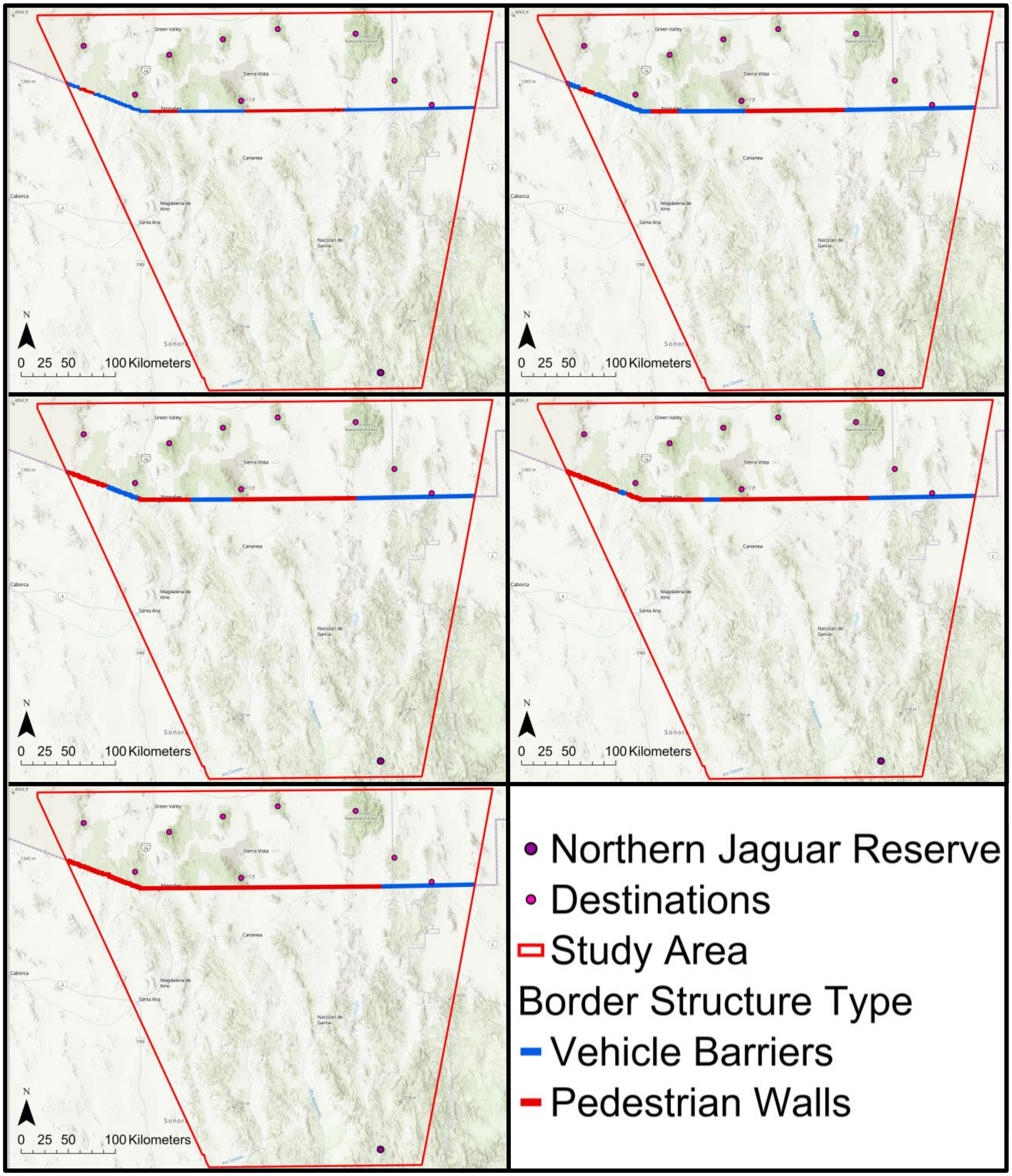

Figure 9. *Above left*, CB scenario; *above right*, VB Scenario; *middle left*, EPW1 scenario; *middle right*, EPW2 scenario; *bottom left*, EPW3 scenario

3.1.4. Landcover Type

The landcover type dataset was obtained from Global Landcover 2000 (Figure 10). Its resolution is 1 km by 1 km and is the lowest resolution in the analysis. This is the same layer that Rabinowitz and Zeller (2010) used in their study and, therefore, had the same cost values and landcover types associated with it. Since Rabinowitz and Zeller (2010) have the cost values associated with this particular landcover raster, it was critical to use the same raster to ensure that the cost values matched. This layer was projected into NAD 1983 (2011) UTM Zone 12N. Due to this layer having the lowest resolution of all the rasters, it became the template for all other layers to resample to in order to avoid the false accuracy of resampling to a higher resolution. From the cost values supplied by Rabinowitz and Zeller (2010), cost values were applied to the landcover types found in the study area. The layer was also clipped to the size of the study area.

3.1.5. Digital Elevation Model

The elevation cost layer required a Digital Elevation Model (DEM) to determine the elevation of this project’s study area at a high resolution. The DEM was created from Light Detection and Ranging (LiDAR) data received from the USGS website. When the DEM was downloaded, it arrived in parcels that together made up the study area but were not originally one complete raster. To stitch them together, the Mosaic tool was utilized to create one DEM raster out of the twelve that were downloaded to cover the study area (Figure 11). The DEM had a maximum elevation of 2983 meters and a minimum elevation of 357m. The average elevation was 1257 meters across the study area. The cell size for the DEM raster was 10 meters by 10 meters and needed to be clipped, projected, and resampled to the extent, projection, and cell size used throughout this study. The resampling tool was used on the raster to change the size of the cell to match that of the landcover type raster.

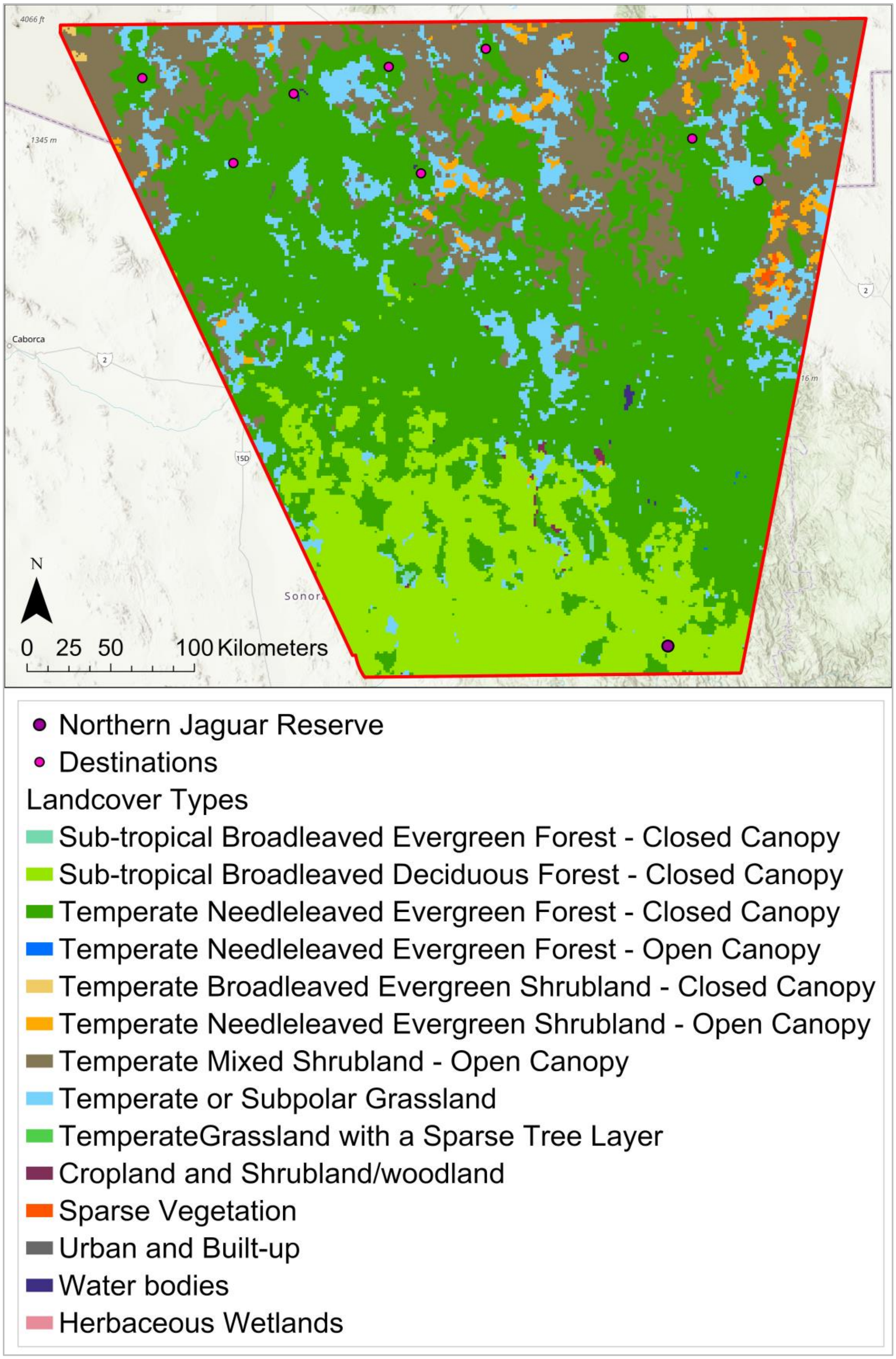

Figure 10. Landcover raster from Global Landcover 2000 within the study area

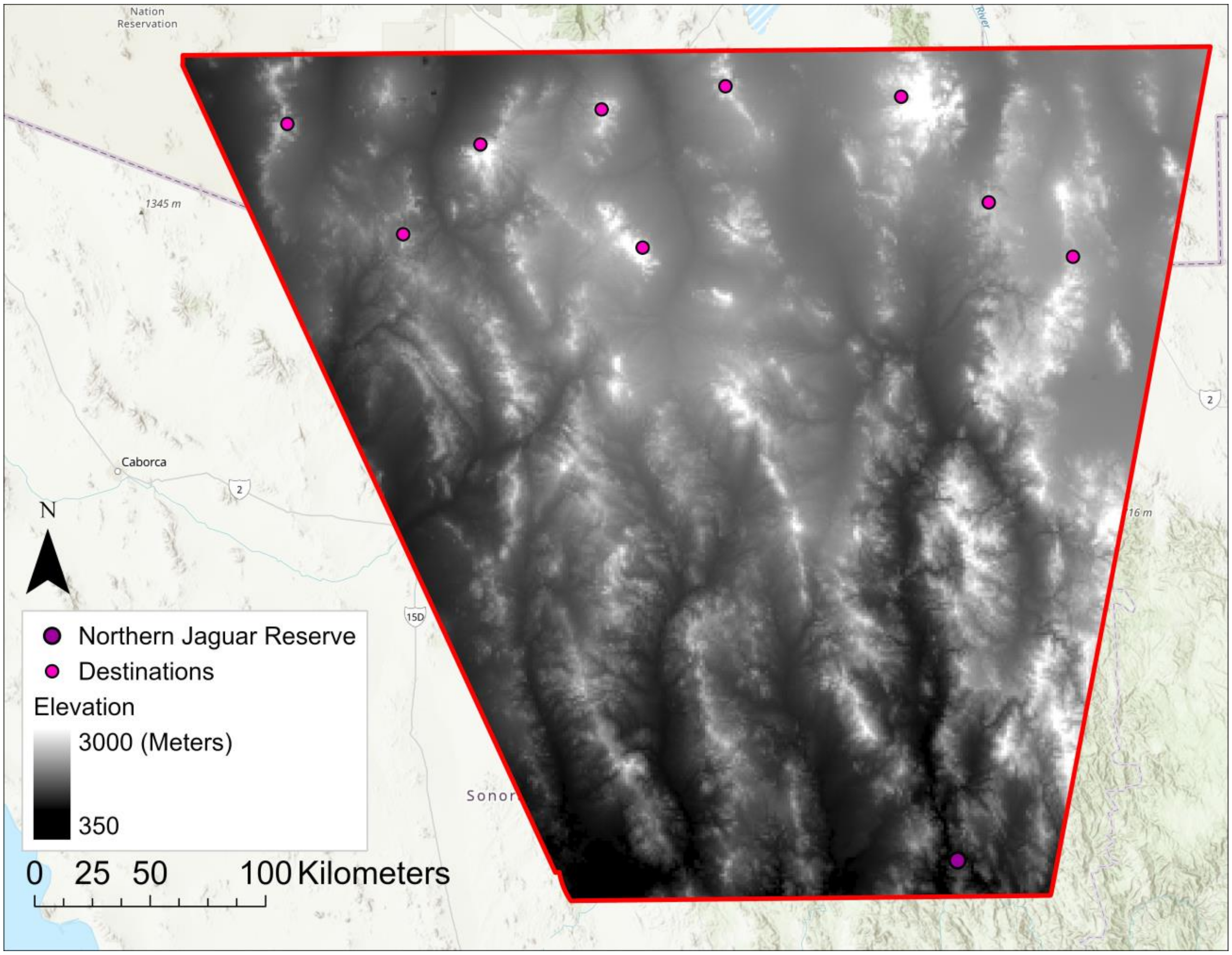

Figure 11. DEM raster from USGS within the study area

3.1.6. Percent Tree Cover

The percent tree cover dataset was obtained from the Global Land Analysis and Discover (GLAD) website. The raster describes what percentage of a cell is covered by trees and shrubs (Figure 12). Jaguars prefer to hunt and live where they can hide and ambush, favoring areas featuring high tree and shrub cover. The tree cover is generally reserved to the Sky Islands territories of the study area where there is a climate that can produce forests that provide tree cover (Figure 12). The cost values for this layer were obtained from Rabinowitz and Zeller (2010) (Table 1). This layer complements the landcover type layer because it takes the landcover type and calculates what percentage of said landcover type is tree and shrub cover. The cell size for the percent tree cover raster was 30 meters by 30 meters and needed to be clipped, projected, and resampled to the extent, projection, and cell size used throughout this study. Raster resampling changed the size of the cell to match that of the landcover type raster.

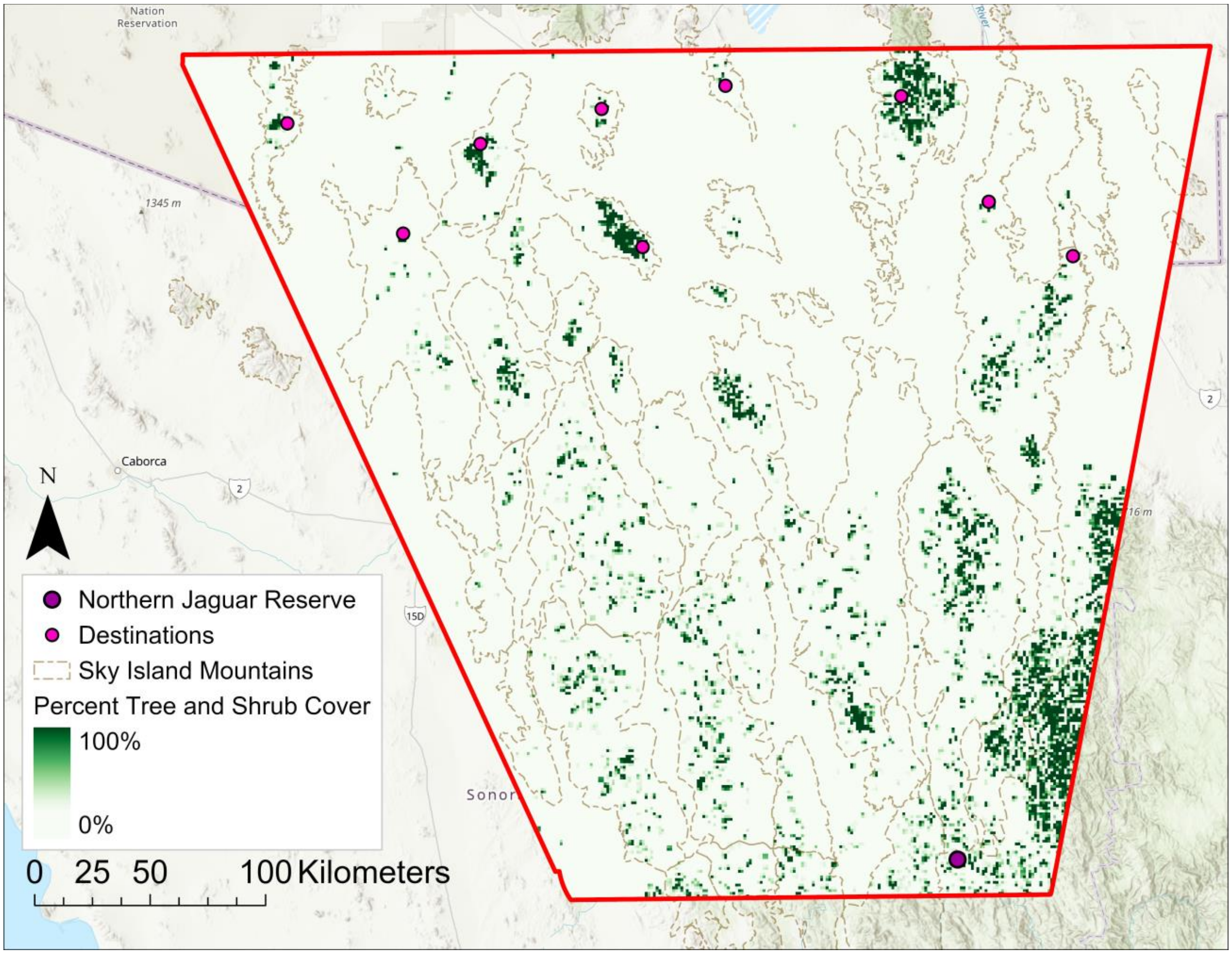

Figure 12. Percent tree and shrub cover from Global Land Analysis within the study area

3.1.7. Population Centers

The population centers vector data layer was obtained from the World Bank website and identifies cities and towns within the study area. In Rabinowitz and Zeller (2010), population centers are included to add the cost of proximity to human settlements to jaguar habitat. In order to create the cost layer, a multilayer ring of two, four, eight, and sixteen kilometers was implemented around each city center using the multiple ring buffer tool in ArcGIS Pro (Figure 13). The closer to the city center, the higher the cost for the jaguar. The distances for the rings as well as the costs associated with them were obtained through Rabinowitz and Zeller (2010) (Table 1). The polygon to raster tool was used to convert the multiple ring buffer layer into a raster, then it was clipped, projected, and resampled to the extent, projection, and cell size used throughout this study. The resampling tool changed the size of the cell to match that of the landcover type raster.

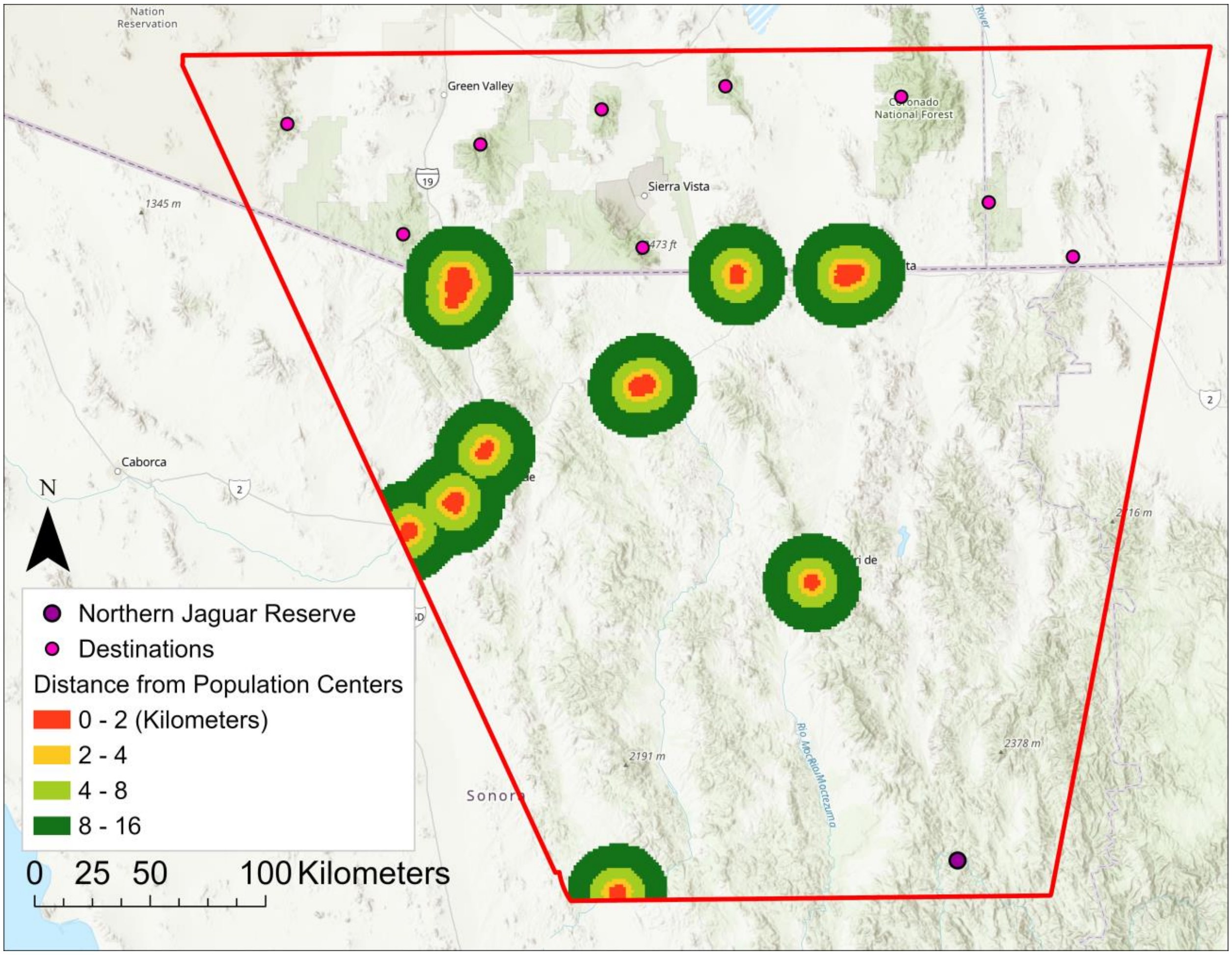

Figure 13. Population centers from the World Bank with accompanying ringed buffers for cost

3.1.8. Population Density

The population density raster was obtained from the Oak Ridge National Laboratory website and it was the only cost layer not originally used by Rabinowitz and Zeller (2010). This layer was chosen because it is more up to date, higher resolution, and the population density map that Rabinowitz and Zeller (2010) used was no longer available. The resolution of the data is higher on the U.S. side of the study area than the Mexico side of the study area. This is most likely due to disproportionate funding for census data between the two countries. The population density raster describes the number of people per square kilometer according to the ranges for cost values laid out by Rabinowitz and Zeller (2010) (Figure 14). The population density of humans in the study area complements the population centers layer for this project. Humans do not always reside in cities but are distributed into smaller communities. Therefore, population centers were not adequate by itself for measuring the cost of human presence in this study region. A population density map allows the ability to add a cost to the human presence throughout the study area outside urban areas. The cost values needed for this raster were obtained from Rabinowitz and Zeller (2010) (Table 1). The cell size for the population density raster was 50 meters by 50 meters for the U.S. and 1 km by 1 km for Mexico. The layer needed to be clipped, projected, and resampled to the extent, projection, and cell size used throughout this study. The resampling tool changed the size of the cell to match that of the landcover type raster.

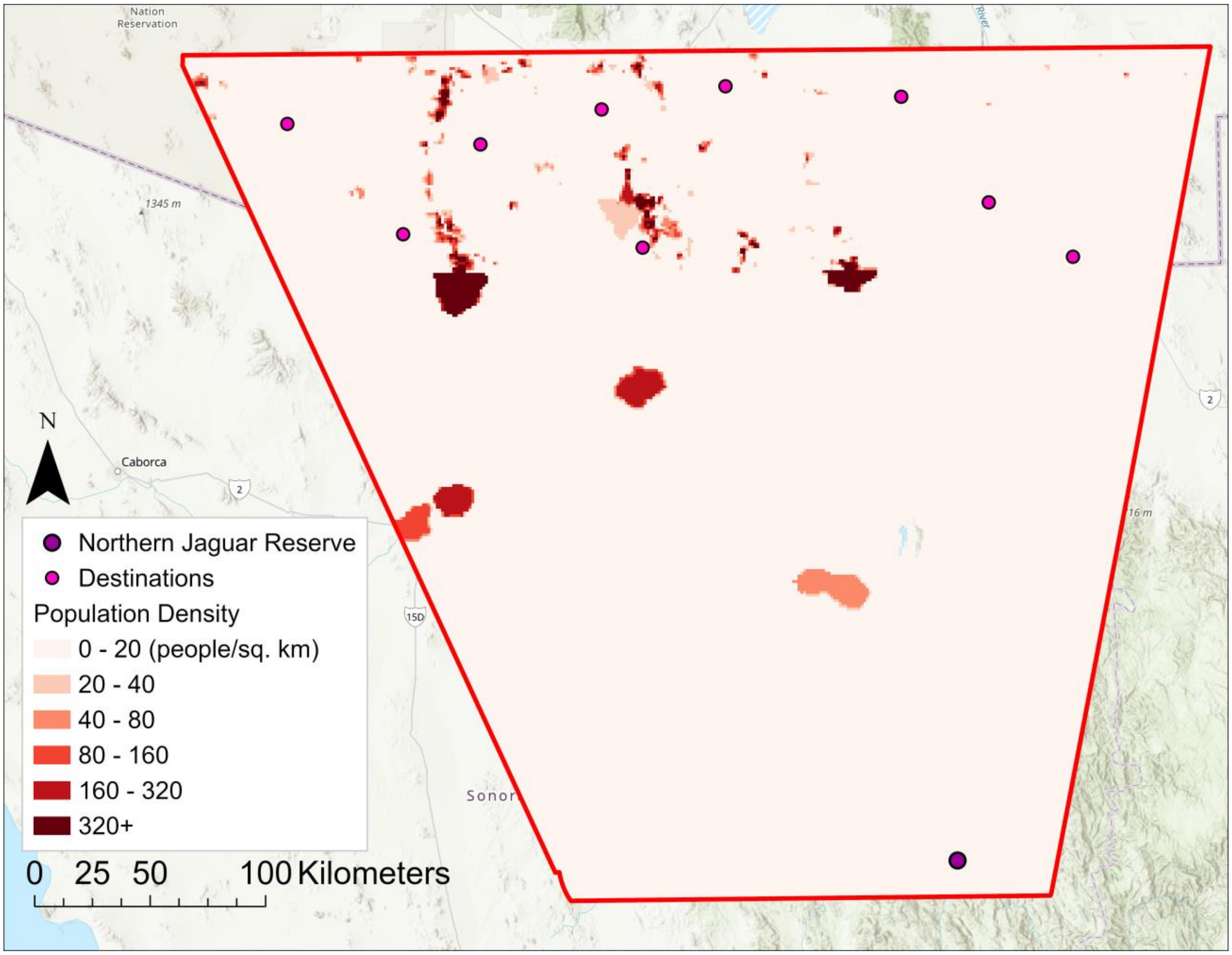

Figure 14. Population density raster from Oak Ridge National Laboratory within the study area

3.1.9. Roads

The roads layer was obtained through the Socioeconomic Data and Applications Center (SEDAC), the same layer that Rabinowitz and Zeller (2010) used in their study. The layer represents all the major roads in North America. This layer was included to simulate the threat of crossing roads and being in proximity with roads and humans. The polyline vector layer used the multiple ring buffer tool to create a multi-ring buffer of two, four, eight, and sixteen kilometers around the major roads in the study area much like the population centers to create a cost for proximity to roads (Figure 15). The cost values for the road proximity and data ranges were obtained from Rabinowitz and Zeller (2010) (Table 1). The multi-ring buffer was converted into a raster using the polygon to raster tool was then clipped, projected, and resampled to the extent, projection, and cell size used throughout this study. The resampling tool changed the size of the cell to match that of the landcover type raster.

Figure 15. Roads raster from SEDAC with multi-ring biffers within the study area

3.1.10. Destinations

The destinations points for the end of the LCPs were the most difficult to define. The USFWS has areas defined as the current extent of the jaguar’s potential habitat in the U.S., which gives a good indication of where to place the destinations. An equally weighted combined cost layer was created from the landcover, percent tree cover, human population density, elevation, distance from roads, and distance from settlements layers to create a habitability map. This layer combined all those rasters into one raster and combined their weights evenly resulting in a cost layer that represents a suitable habitat for the jaguar (Figure 6). This raster overlapped with the known habitat extent from the USFWS to create points intended to be in the known habitat or in what could potentially be habitat. Nine points were created based on the following five criteria to act as the destinations for the jaguars in order of importance. First, the destination point needed to be within the known habitat for the jaguars in the U.S. Second, within the known habitat layer, the destination needed to be around cells with a highest habitability or lowest cost in the habitability raster. Third, the destinations need to be widespread to ensure all the possible locations are tested. Fourth, if the destination could not be within a known habitat, the destination could be in a location with low cost cells and within the Sky Islands. Finally, fifth, the destinations should not be too close longitudinally to reduce path overlap. Overlap occurred when two destinations used the same LCP to cross the border and get to the closer destination, then branch off and arrive at the second destination. Since the intent was to analyze the change in cost of crossing the border, the branched off path was irrelevant, since the LCP already crossed the border, and the continued LCP to the further destination was unnecessary.

Determining which paths needed to be eliminated due to overlap was a methodic process. Originally, seventeen points were chosen based on the first four criteria. Initial tests of the model were run to assess the effectiveness of the destinations and where the paths may occur. Results from the tests showed that any destinations more than seventy-two kilometers north of the border produced considerable overlap and were removed. This resulted in five destinations being removed. Next, points were evaluated for their vertical or longitudinal closeness. Any points that had very similar longitudes and were stacked on top of each other had more LCP overlap than others. These points were either moved to another suitable location or removed which was the case for three more points. This in total removed eight points from the original seventeen destinations resulting in nine final points for destinations. These destinations are designed to represent the most habitable locations known or otherwise to the jaguar in the U.S. Including points not in the known habitats was intended to reduce potential bias that the current border structures might impose on known habitable areas.

3.2. Construction of the Cost Layer

To implement the cost surface, the reclassified rasters had to be inputted into a weighted cost table. To start, all the rasters except the border rasters were input in an equally weighted cost overlay table to create the combined cost layer. All costs were adjusted to fit a 1-10 classed system, as a 0-9 class system wasn’t available as an option in the Weighted Overlay tool. All costs were increased by 1 and if a cost increased from a 9 to a 10, it was input as “no data” instead of 10, which would remove it from the resulting cost layer. This way, all costs are increased by the same amount, generating the same output. A cost of “no data” was input in the analysis because some locations of high cost were deemed impassable for jaguars. These locations include pedestrian barriers, border gates, and any area with a population density higher than 320 people per square kilometer. By inputting the cost as “no data” the cells are removed from the cost layer forcing the LCPs to avoid these cells which is more realistic. This new cost raster was used as the base cost for the NB scenario. When a new border scenario was introduced, the NB cost layer would be put into a weighted cost table with an 80 percent weight while the border scenario layer would be given a 20 percent weight. The values of 80 and 20 were chosen so that the border would have a higher impact on the overall cost and would not be lost in the other layers. This method also allowed a faster running time for the model to create the LCPs. The border structure’s values for the border scenario layers are “no data” for the pedestrian barriers and five for the vehicle barriers. Ensuring the vehicle barriers had meaningful impact on the resulting cost layer was chosen purposely as they represent a small percentage of the map and could be lost in the analysis otherwise.

3.2.1. Integrity check

Once the cost layer was created, an integrity test was conducted. This consisted of picking cells at random in the study area to determine if the cost values applied to those cells made sense for their location. Peaks of mountains and hot desert valleys were found to have high cost while mid-elevation forested areas in the Sky Islands returned low cost values. The highest value was found to be 8 where the lowest value was 1. The integrity test was implemented to ensure that the cost raster was created correctly and that any resulting LCPs would be reliable and realistic.

3.3. Least Cost Path Analysis

LCP analysis creates a path from one point to another along a cost surface using the lowest cost possible between the two points. The tool calculates the shortest route between two points while maintaining the lowest total cost along the path. The model begins with the creation of the cost surface which is created by combining the NB cost layer with the border layer of the selected scenario in the weighted overlay tool (Figure 16). That resulting cost layer is then used in the cost distance tool with the Northern Jaguar Reserve starting point to create a cost distance raster (Figure 17) which describes the accumulative cost distance for each cell to the nearest source over the cost layer and a backlink raster (Figure 18) that describes the direction for the LCP.

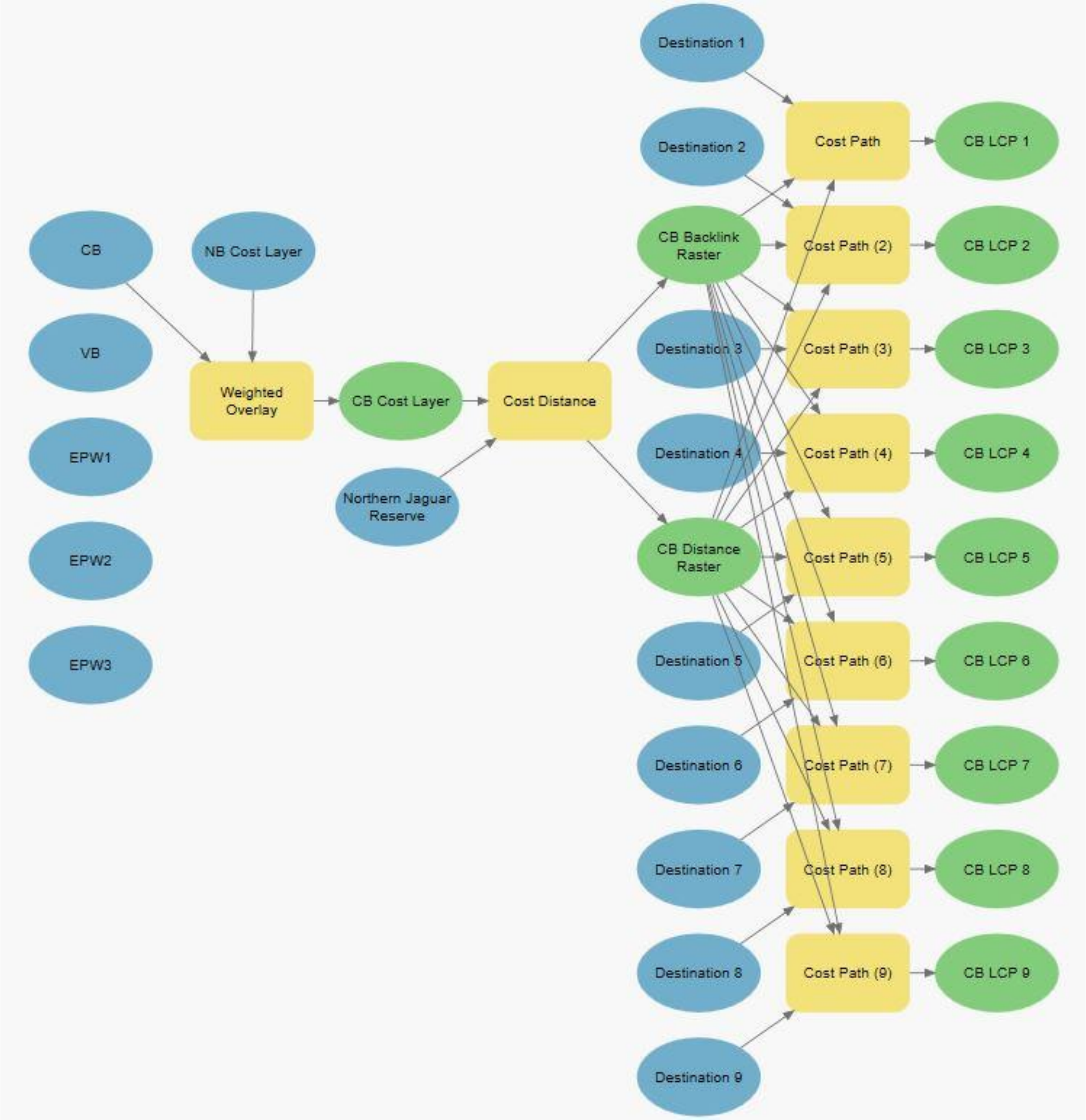

Figure 16. Model for the creation of the LCPs. This iteration shows the CB scenario being run

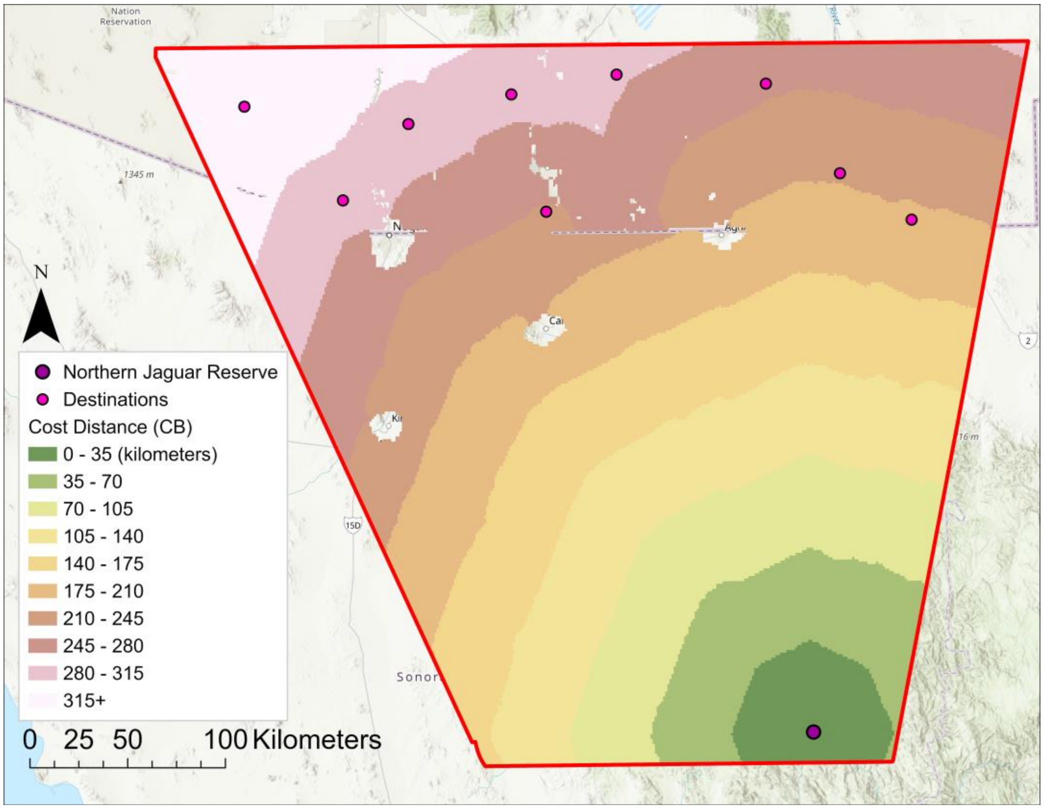

Figure 17. Cost distance raster for the CB scenario

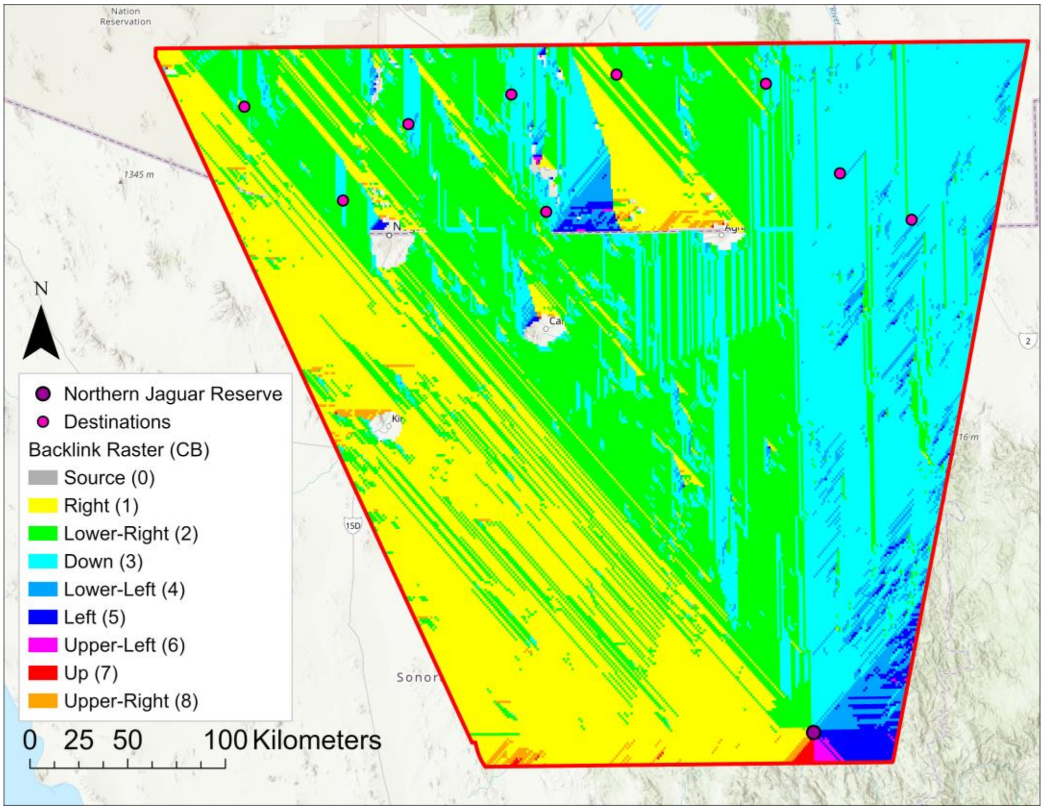

Figure 18. Cost backlink raster for the CB scenario

The backlink raster contains values 0 through 8, which identify the next neighboring cell along the LCP from a cell to reach its least-cost source. Each number describes a direction that the LCP would take for example, moving left has a value of five and moving up has a value of seven. The distance and backlink rasters are then input into nine cost path tools for each of the nine destinations to create the nine LCPs for the given scenario. For each model that was run, a different border scenario was used that increasingly made the border impassable with pedestrian barriers. Running the model can take up to ten minutes and needed to be run six times to create the fifty-four LCPs.

3.4. Path Analysis

After all the paths were created, analysis was completed on each path to determine the change in cost that the border scenarios caused. Determining the change of cost was accomplished by analyzing the overall cost, the number of roads crossed, and the number of days travelled. The overall cost of the path was determined by multiplying the number of cells in the path by the average cost of the path, which was detailed in the attribute table of each LCP. Quantifying the number of roads crossed was achieved by overlaying each LCP on the original roads layer, and manually counting how many times the LCP intersected a road. Calculating the number of days travelled for each LCP was completed by first transforming the LCPs into polylines using the raster to polyline tool, and then using the add geometry tool which can add the length of the polyline in kilometers. Then, the length of the LCP was divided by the average dispersing speed to give the travel time in days. These three ways of analyzing the results give a robust picture of the stress that the jaguars might have to face when dispersing north.

3.5. Sensitivity Analysis

To explore whether uncertainty in underlying cost rasters affected results, a sensitivity test was performed. The sensitivity test was done by creating a new cost surface with different weights assigned in the weighted overlay tool. In the test, one cost surface was given a weight of 40 percent while the rest were given weights of 12 percent instead of the equal weights used in this study and in Rabinowitz and Zeller (2010). This gave a higher priority to the variable to test how sensitive the analysis was to the variable. The variable chosen for the sensitivity analysis was the percent tree and shrub cover layer. The reasoning behind choosing this variable was that the environment in Central and South America has considerably more tree cover in their jungles than the study area has in the Sky Islands. Tree cover is a very important variable to the jaguar and so giving an increased weight to tree cover would prioritize the LCPs to stay in the mountains and tree cover which would be more realistic to a real jaguar's preferences. In addition, there was some uncertainty in five cost paths being partly produced in desert valleys instead of nearby mountainous tree cover, which prompts concern of the measurement of this variable. The cost layer created for the sensitivity analysis had lower costs in the mountains where there is increased tree cover and higher costs in the valleys (Figure 19). The sensitivity analysis will reveal any discrepancies in the percent tree and shrub cover layer.

Using this new cost layer, the CB scenario model was run to create new LCPs for the sensitivity analysis. Once the new LCPs were created, they were matched to the original CB LCPs to identify similarity.

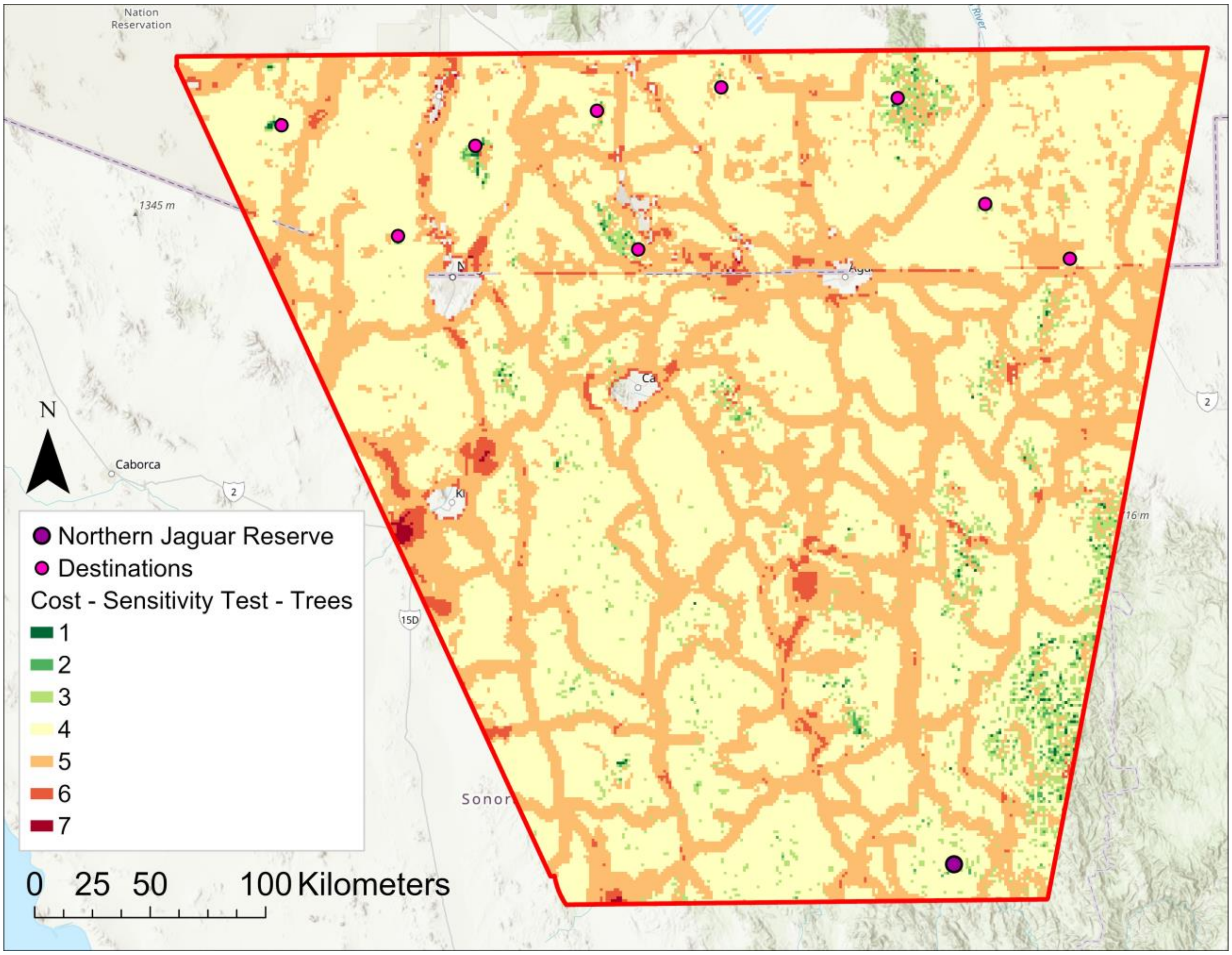

Figure 19. Test cost surface for sensitivity analysis

Chapter 4 Results

This chapter discusses the results from the methods described in chapter 3. The results of the LCPs are analyzed to determine the total change in cost, the number of roads crossed, and the number of days travelled. The resulting map of the NB scenario (Figure 20), CB scenario (Figure 21), and VB Scenario (Figure 22) are nearly identical aside from Cost Path (CP) 6 which was the only LCP to divert due to the current border structures. The resulting maps of the EPW1 scenario (Figure 23), EPW2 scenario (Figure 24), and EPW3 (Figure 25) showed gradual and then sudden change as the pedestrian barriers closed off the gaps in the border with each scenario until the border was closed by EPW3.

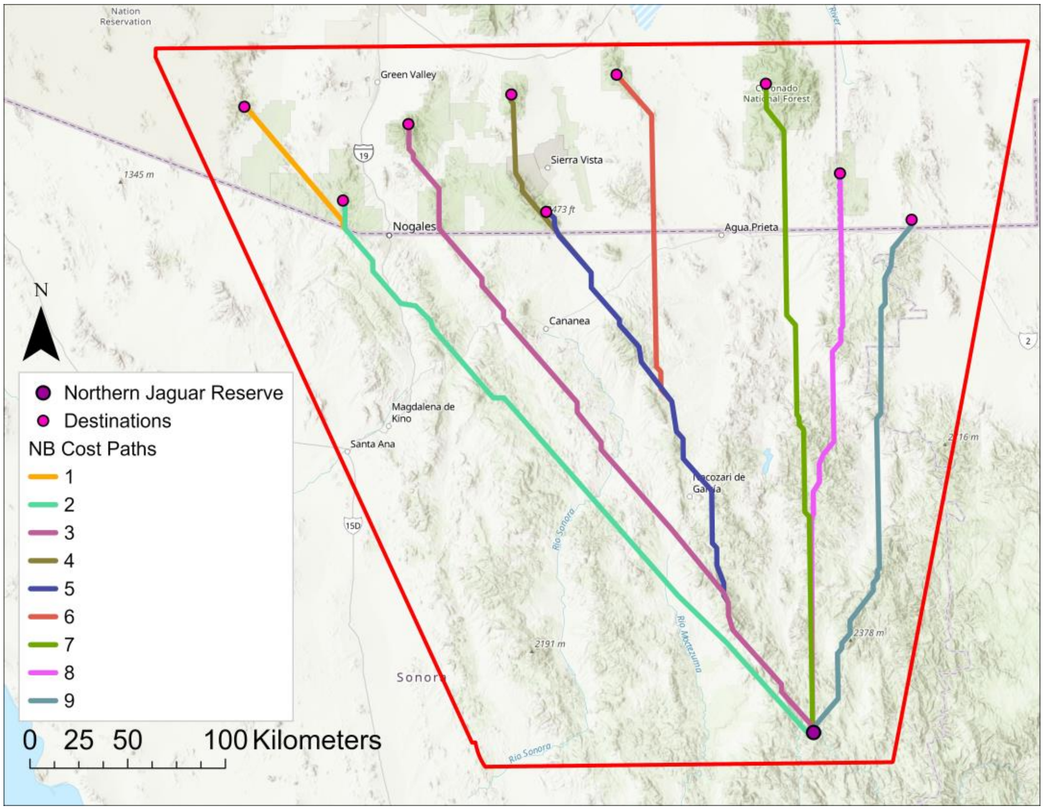

Figure 20. The LCPs generated for the NB scenario

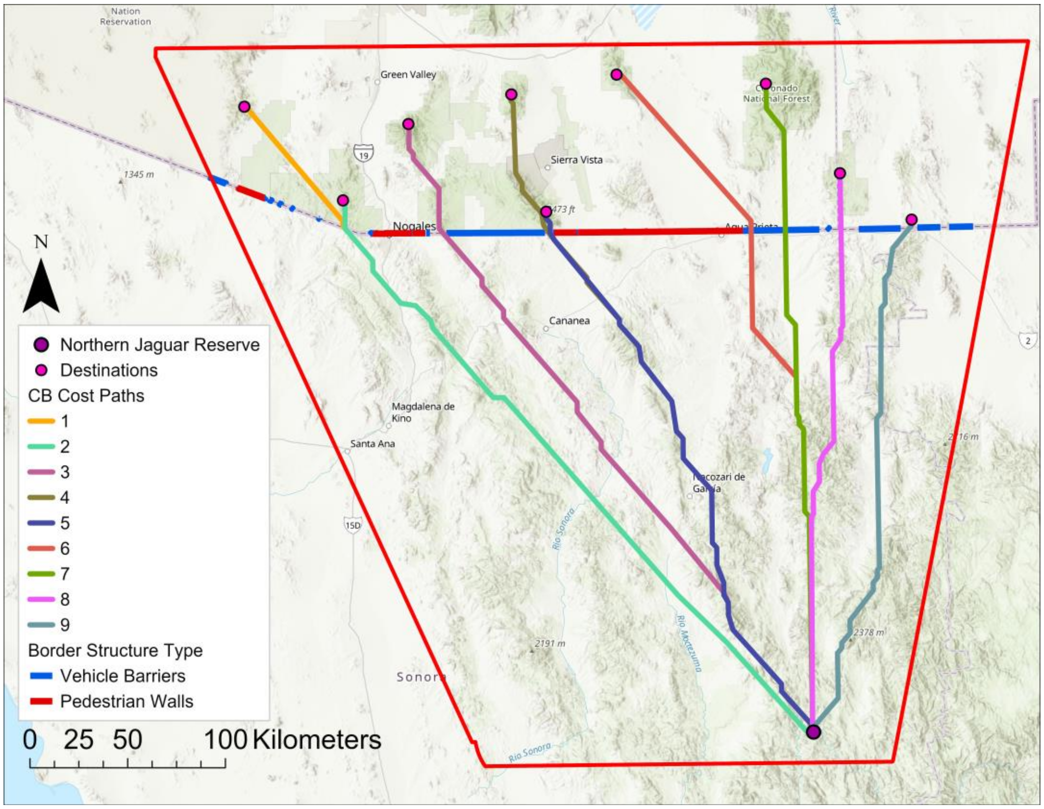

Figure 21. The LCPs generated for the CB scenario

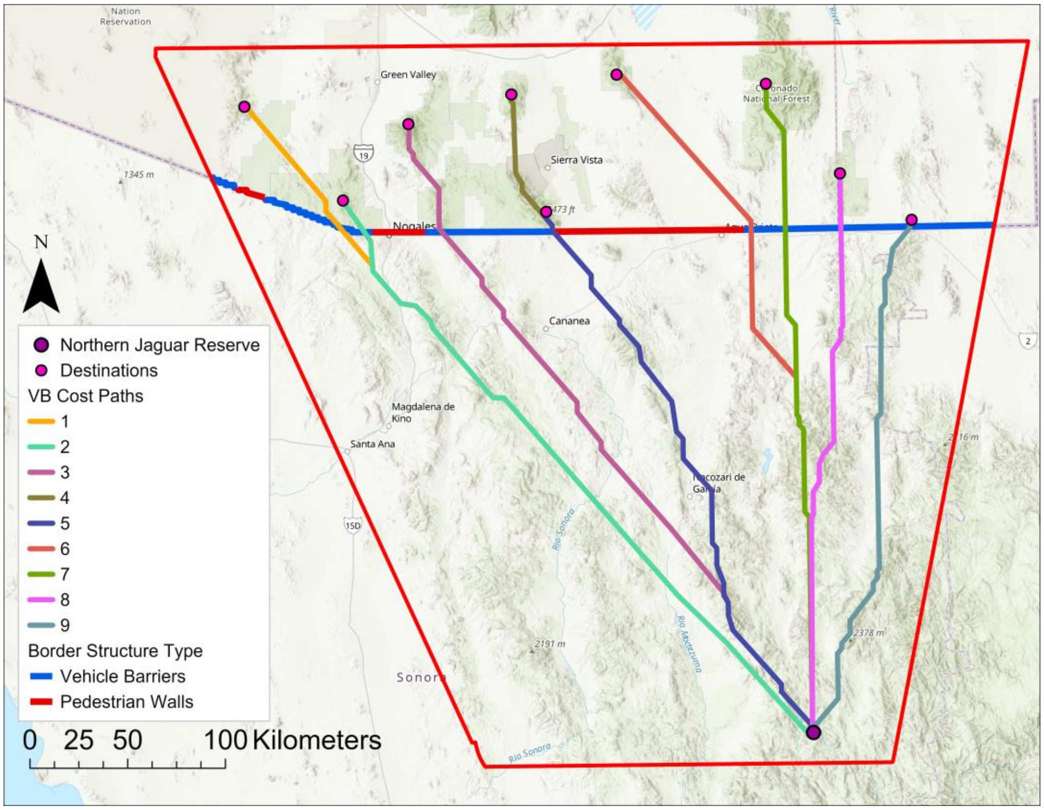

Figure 22. The LCPs generated for the VB scenario

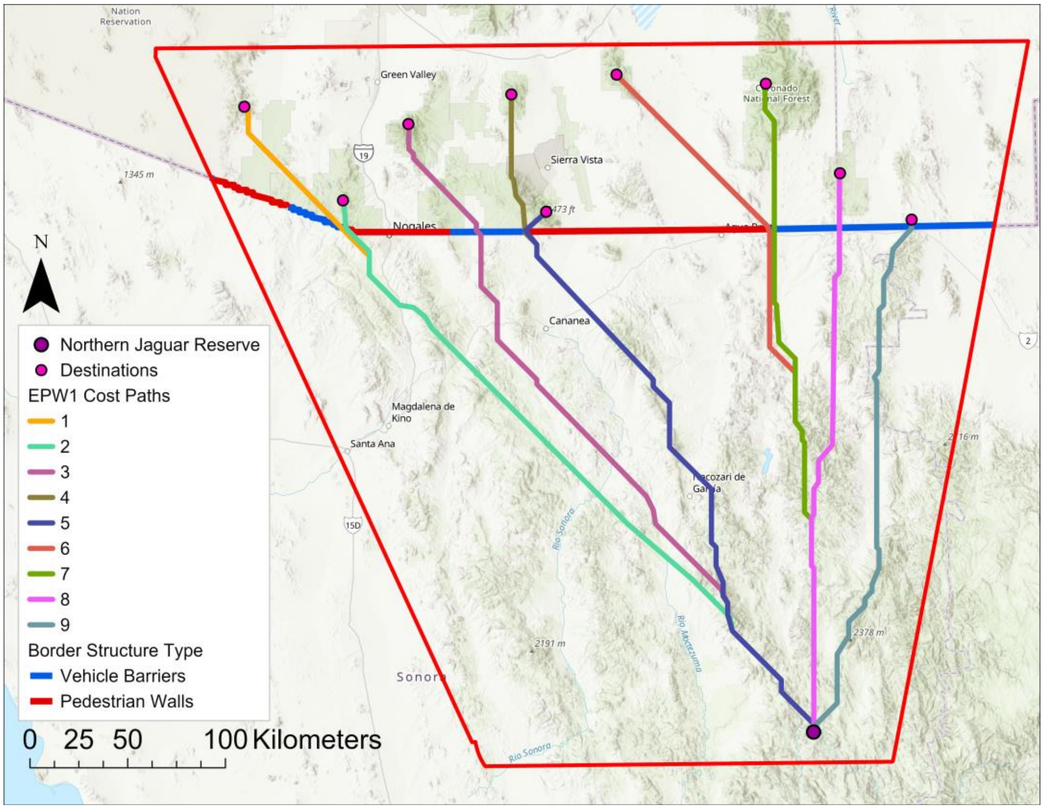

Figure 23. The LCPs generated for the EPW1 scenario

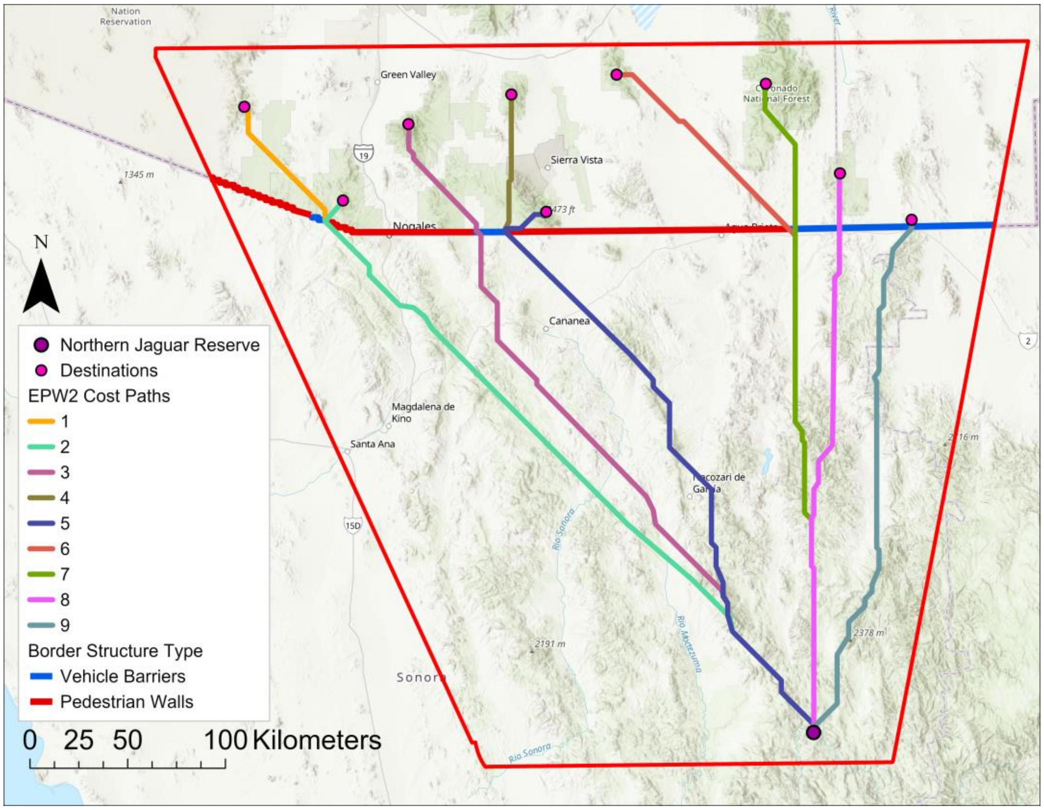

Figure 24. The LCPs generated for the EPW2 scenario

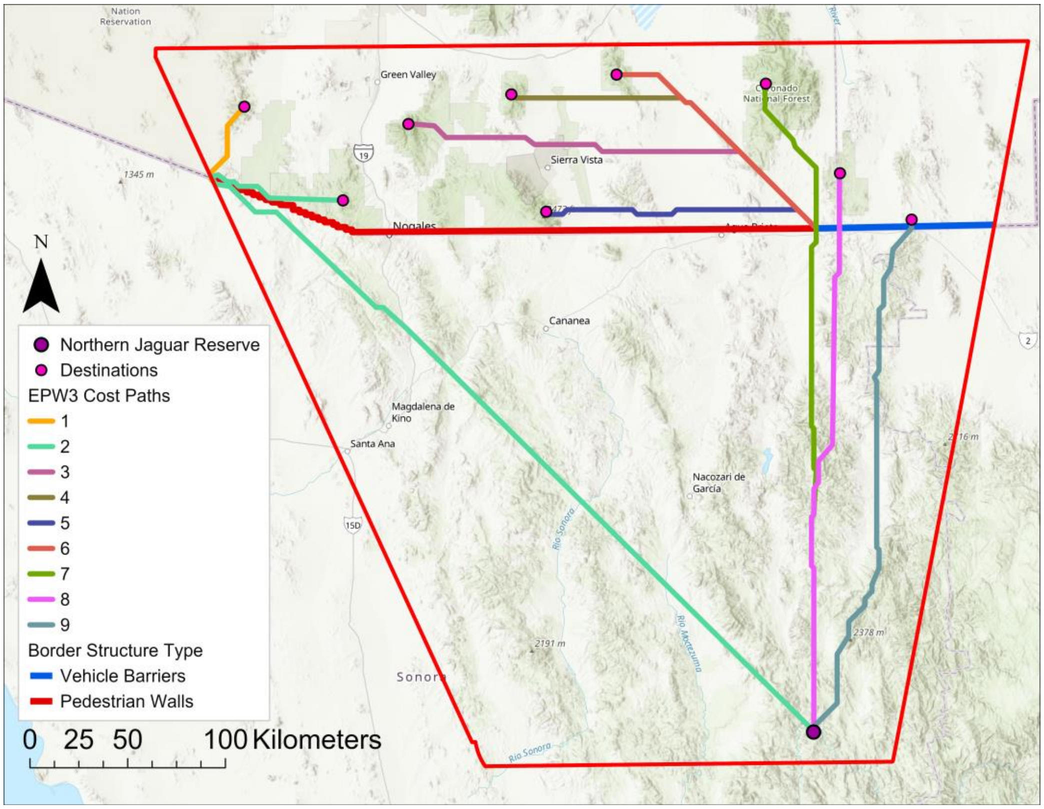

Figure 25. The LCPs generated for the EPW3 scenario

4.1. Total Costs

The results of the total cost calculations were revealing. There was an expectation that with every new border scenario, there would be a gradual change in cost with jumps in cost when gaps in border were closed off. This was not the case. The first three border scenarios were virtually identical except for one path, and the last three scenarios had gradual but less than expected increase in cost until the expected significant increase in cost when the gaps between the pedestrian barriers were blocked off.

4.1.1. No Border and Current Border Scenarios

The change in cost between NB and CB was expected to be substantial with revealing information of how the current border affects jaguar dispersal presently. However, there was little to no change in total cost when transitioning between the NB and CB scenarios. CP5 and

CP6 were the only paths that increased in length between the two scenarios (Table 3). The percent increase change in cost for CP6 was 3.02% where the other cost paths only increased by 0.43% or lower (Table 4). This increase in cost was much lower than expected. There was almost no change in cost for jaguar dispersal between having the current border structures and having no border structures. The average increase in total cost for the CB scenario was 0.37%.

Table 3. Total cost results for each path and scenario. Total cost was calculated by multiplying the average cost and cell length found in the attribute table of each LCP.

Total Cost										
	CP1	CP2	CP3	CP4	CP5	CP6	CP7	CP8	CP9	Average
NB	2693.16	1949.39	2097.71	2144.77	1465.04	2123.35	1869.35	1363.96	1185.45	1876.91
CB	2693.16	1949.39	2097.71	2144.77	1469.73	2187.44	1869.35	1363.96	1185.45	1884.55
VB	2694.60	1951.49	2100.84	2149.92	1471.28	2189.56	1871.37	1365.98	1187.30	1886.93
EPW1	2857.76	2062.47	2374.56	2433.96	1711.37	2494.46	2114.56	1365.98	1187.30	2066.94
EPW2	2861.44	2103.13	2374.56	2483.02	1872.56	2613.84	2154.16	1365.98	1187.30	2112.89
EPW3	3202.57	3752.72	4492.96	3602.42	3163.86	2790.28	2222.87	1365.98	1187.30	2864.55

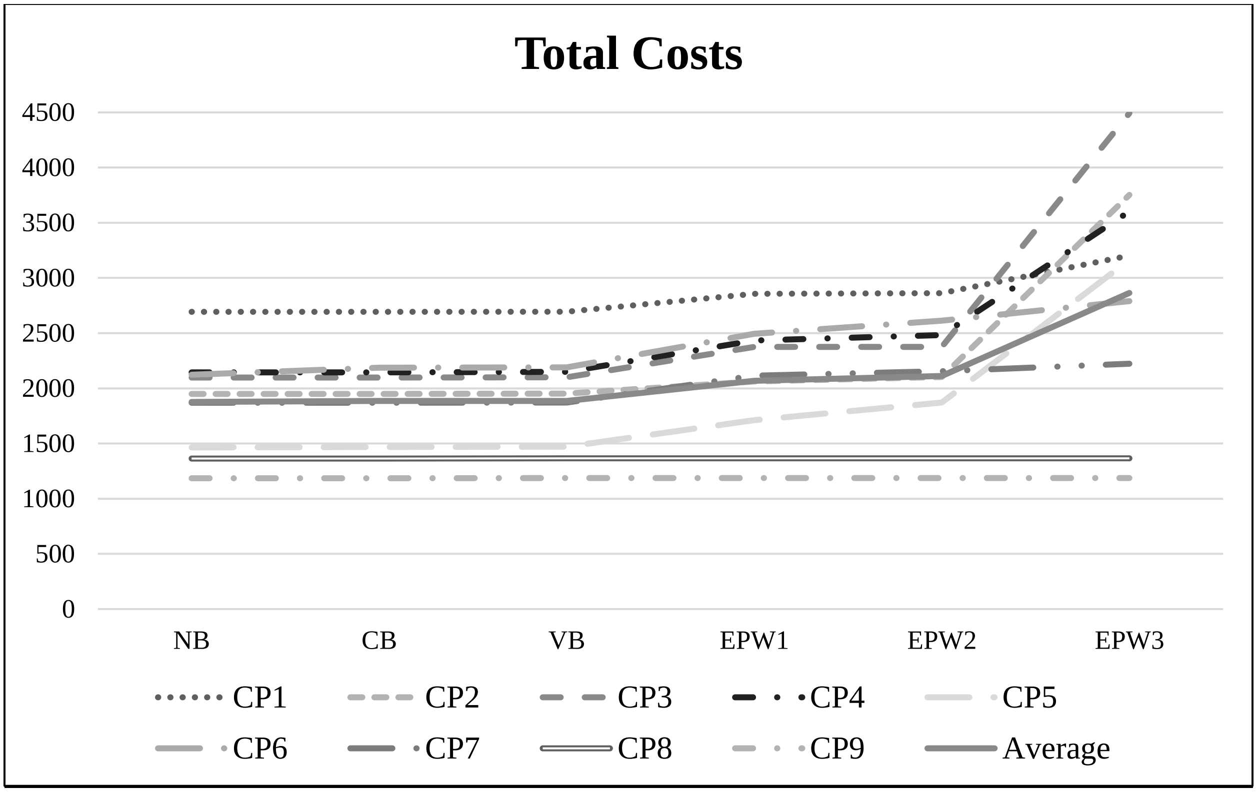

Figure 26. Line graph of the total cost values of each LCP under each scenario

Table 4. Percent change in cost for each path and scenario. Percent change was calculated by finding the difference between the total cost value and the cost value of NB for that scenario, then dividing it by the NB cost.

Percent Change in Cost										
	CP1	CP2	CP3	CP4	CP5	CP6	CP7	CP8	CP9	Average
NB	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CB	0.00%	0.00%	0.00%	0.00%	0.32%	3.02%	0.00%	0.00%	0.00%	0.37%
VB	0.05%	0.11%	0.15%	0.24%	0.43%	3.12%	0.11%	0.15%	0.16%	0.50%
EPW1	6.11%	5.80%	13.20%	13.48%	16.81%	17.48%	13.12%	0.15%	0.16%	9.59%
EPW2	6.25%	7.89%	13.20%	15.77%	27.82%	23.10%	15.24%	0.15%	0.16%	12.17%
EPW3	18.91%	92.51%	114.18%	45.08%	115.96%	31.41%	18.91%	0.15%	0.16%	48.59%

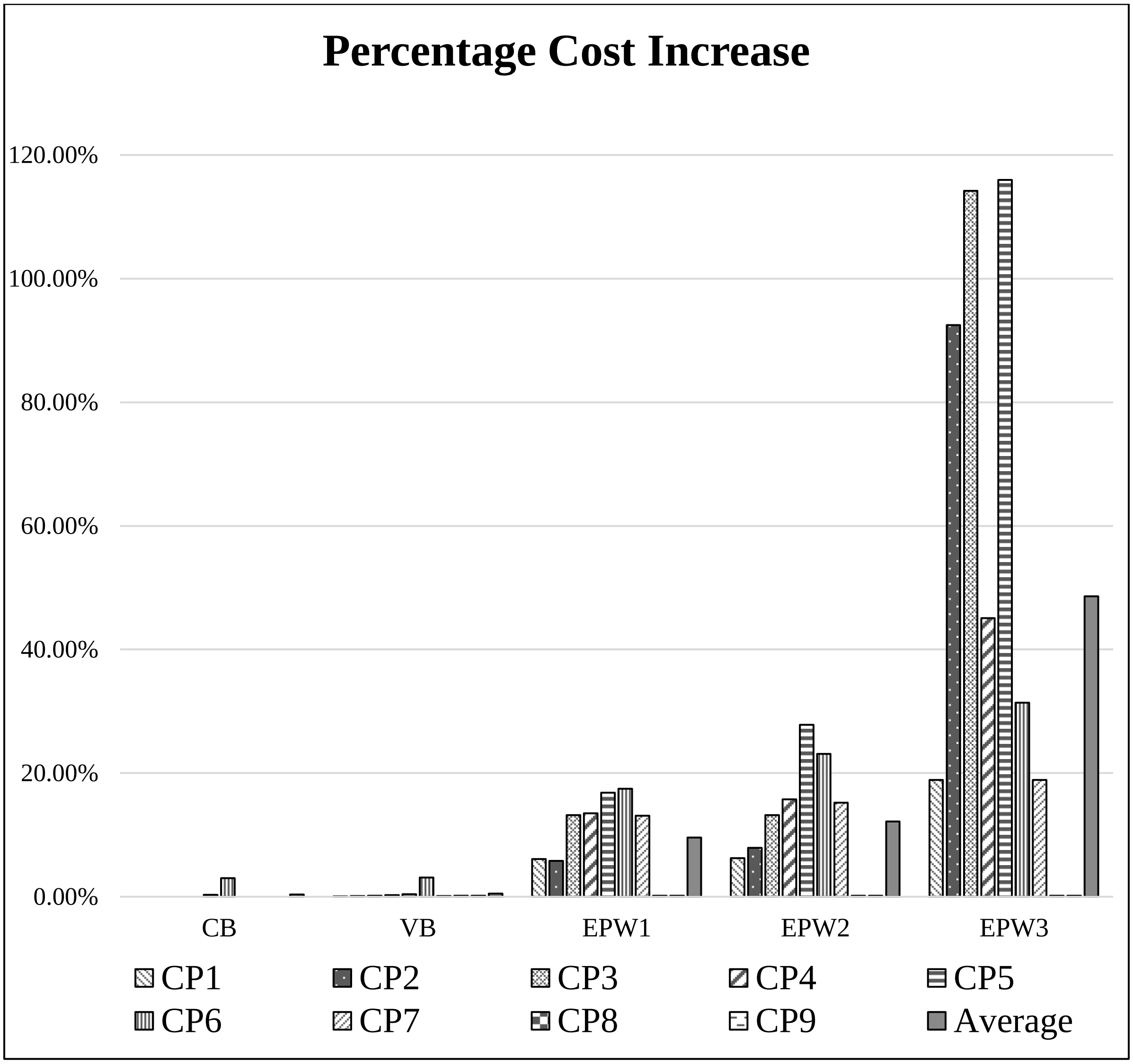

Figure 27. Bar graph of the percent change in cost of each LCP under each scenario

4.1.2. Vehicle Barrier Scenario

There was also slight change between the CB and VB scenarios. The VB scenario, although it created a less expensive continuous barrier, it was permeable, and therefore had little effect on the jaguar's total dispersal cost. The average increase in total cost for the VB scenario was 0.50% from the NB scenario meaning the addition of the vehicle barriers only had a 0.13% difference in cost for the jaguar's dispersal between the CB and VB scenarios. This was not the expected result from this scenario.

4.1.3. Expanded Pedestrian Barrier Scenarios

Expanding pedestrian barriers affected the total cost for the jaguars in the EPW scenarios much more significantly than the NB, CB, and VB scenarios. Expanding barriers that force the jaguar to alter its path, changes the distance of the path as well as the terrain that was encountered along the path. Changing both distance and terrain can have a strong effect on the total cost.

EPW1 experienced a more robust increase in total cost than the previous scenarios with the highest increase found in CP6 where there was a total cost increase of 17.48% (Table 3). The average increase of all the paths for EPW1 was 9.59% which was much higher than the average increase in cost for the CB or VB scenario. Most LCPs were diverted 9.6 km to the east or west but the corridors between the border structures were still at wide enough to cross the border.

EPW2 saw a larger increase in cost for most of the paths compared to EPW1. The average increase in total cost for the EPW2 scenario was 12.17% which is a slight increase from EPW1 but was less of an increase than expected. This scenario adds approximately 115 km of pedestrian barriers to the 257.5 km of pedestrian barrier already constructed, and only increases the average cost of dispersal by 12.17%. The highest increase was found in CP5 at 27.82%. CP6 saw an increase of 23.10%.

EPW3 saw the most significant increase in cost of any scenario. EPW3 closed the open border between Sasabe, Nogales, and Agua Prieta. With the corridors closed, CP2, CP3, and CP5 experienced cost increases of over 90% which was a more significant increase than EPW2. Most paths were diverted during this scenario, increasing total costs by an average of 48.59%. Without the open border sections between the pedestrian barriers, the LCPs experienced higher cost cells and longer paths resulting in considerable cost increase across most paths.

4.1.4. Unaffected Paths

Some paths did not intersect with the border structure expansions. Notably, CP8 and CP9 increased by 0.15%, and 0.16% respectably starting in the VB scenario (Table 4). In fact, CP8 and CP9 were only affected by the vehicle barriers as the pedestrian barriers never intersected their paths. If the pedestrian barriers do not expand more than the approximately 172 km expressed in EPW3, both paths should be unaffected.

4.2. Roads

Road crossing counts was done manually by imposing each LCP over the roads layer and manually counting every intersection (Figure 28). Unlike the total cost change, the number of road crossings fluctuated. Instead of persistent increase, there were increases and decreases in the number of roads crossed by each path over the six scenarios. On average, the number of roads crossed increased from 11 roads to 12.9 roads (Table 5). This was an increase of 17.3%, or 1.9 more roads crossed on average. Due to border structure expansions, the LCPs occasionally will transition from crossing two parallel roads to crossing the road that they merge into. This was the most common reason behind the fluctuations in the number of road crossings for each LCP. While there are fluctuations in the data, the overall trend was an increase in road crossings as the pedestrian barriers expand over each scenario.

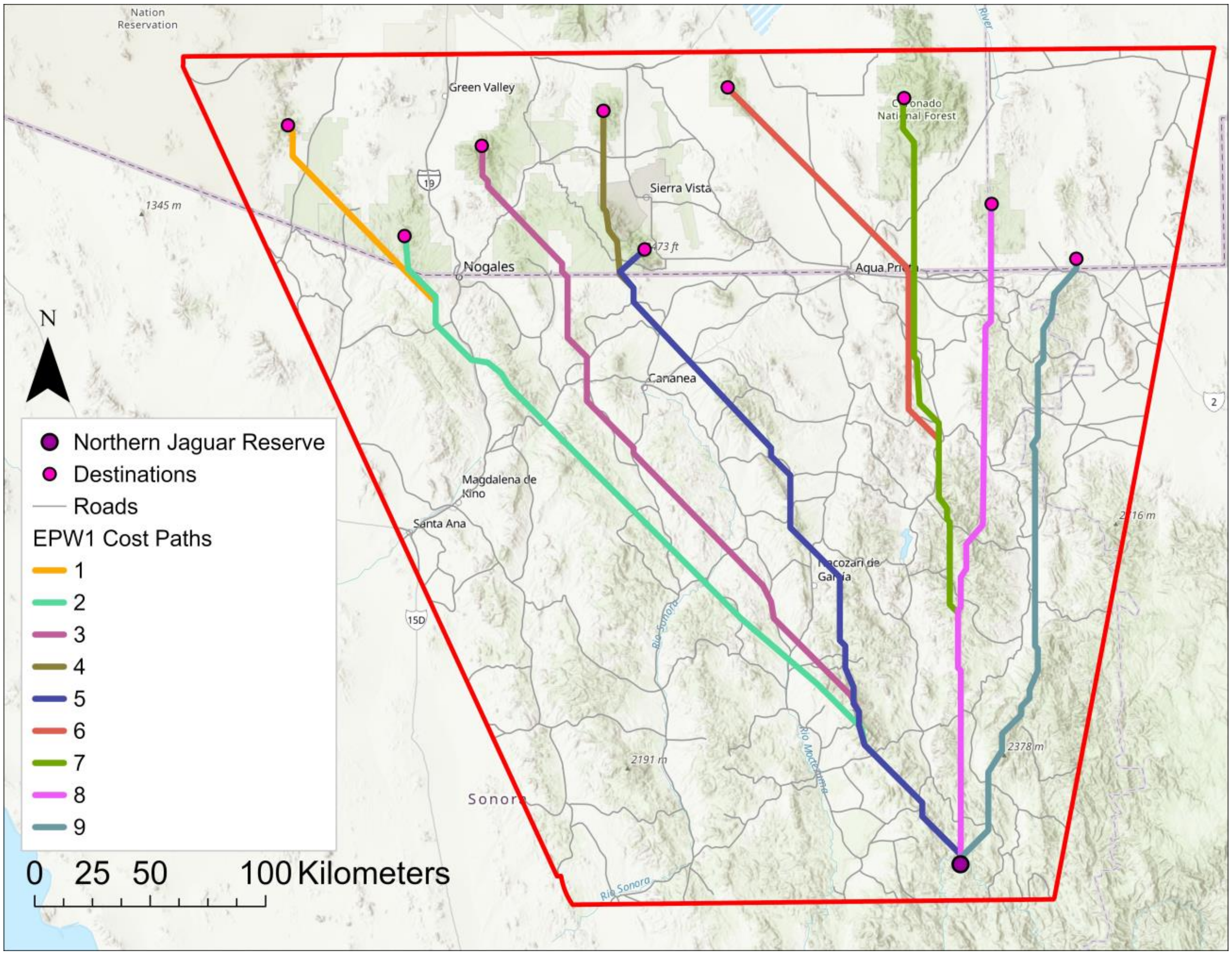

Figure 28. The EPW2 scenario with the roads layer in order to count the number of roads each LCP passes

Table 5. Number of road crossings each LCP makes under each scenario.

Roads Crossed										
	CP1	CP2	CP3	CP4	CP5	CP6	CP7	CP8	CP9	Average
NB	13	12	12	12	11	10	12	8	9	11.0
CB	13	12	12	12	11	10	12	8	9	11.0
VB	13	12	12	12	11	10	12	8	9	11.0
EPW1	14	12	12	12	11	11	10	8	9	11.0
EPW2	14	12	12	12	11	12	11	8	9	11.2
EPW3	17	19	15	13	14	11	10	8	9	12.9

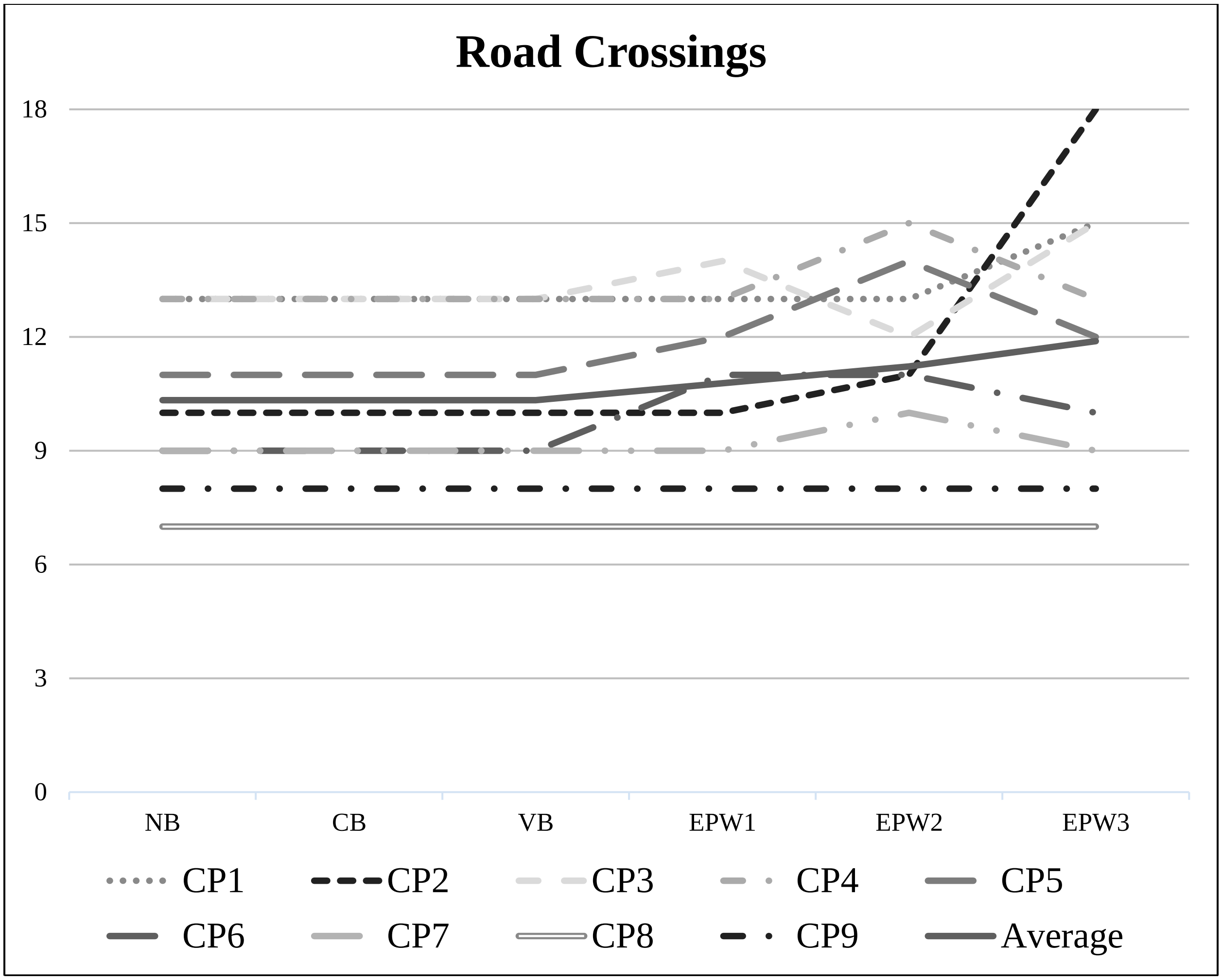

Figure 29. Line graph of the total number of road crossings of each LCP under each scenario

4.3. Days Travelled

For this analysis, the jaguar was assumed to move an average of 9.19 km a day when dispersing. This study analyzed the number of days it would take for a jaguar to complete each path. The number of days travelled was calculated by dividing the length of each LCP and dividing it by the speed of the dispersing jaguar. The range across all paths ranged from 23.9 days to 42.4 days. The average number of days travelled increased from 30.1 days to 34.3 days (Table 6). That was an increase of 13% or 3.2 days. There was not a significant increase in average number of days travelled until EPW3 as the total increase up until EPW2 was only a 0.7-

day difference. The greatest increase in days was 10.7 days, which occurred in CP2 when it increased from 31.7 days to 42.4 days. This was a total change of 33.47% and is over a week of added travel time.

Table 6. Number of days travelled for each LCP under each scenario.

Days Travelled										
	CP1	CP2	CP3	CP4	CP5	CP6	CP7	CP8	CP9	Average
NB	37.5	31.7	33.1	32.5	26.9	31.7	28.9	24.9	23.9	30.1
CB	37.5	31.7	33.1	32.5	26.9	31.7	28.9	24.9	23.9	30.1
VB	37.5	31.7	33.1	32.5	26.9	31.7	28.9	24.9	23.9	30.1
EPW1	37.9	32.0	33.7	32.9	28.0	32.2	29.0	24.9	23.9	30.5
EPW2	37.9	32.7	33.7	33.3	29.5	32.7	29.1	24.9	23.9	30.8
EPW3	39.8	42.4	41.8	37.9	34.6	33.7	29.4	24.9	23.9	34.3
%	6.27%	33.61%	26.44%	16.55%	28.58%	6.50%	1.48%	0.00%	0.00%	13%

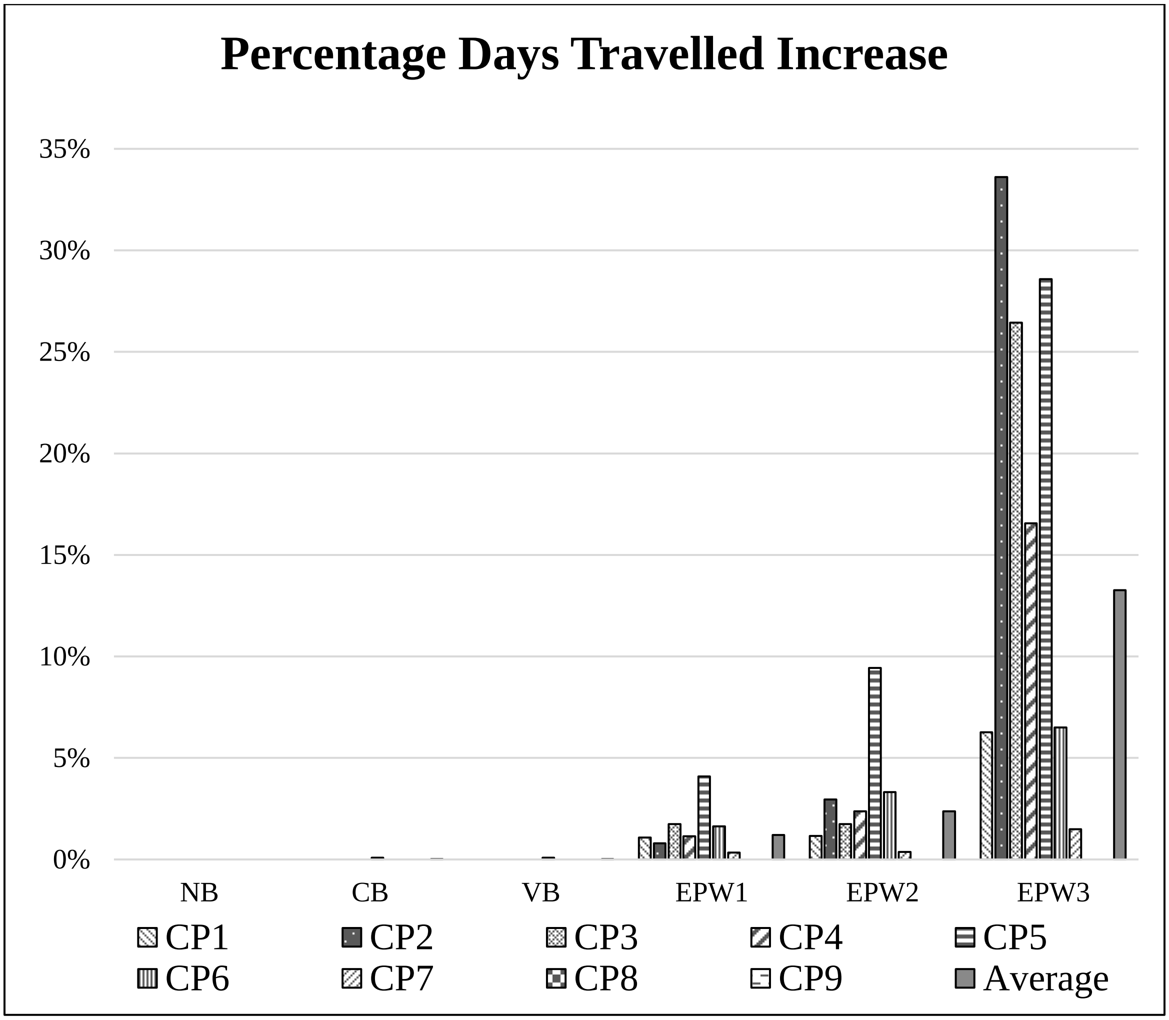

Figure 30. Line graph of the number of days travelled by each LCP under each scenario

4.4. Sensitivity Analysis

The purpose of the sensitivity testing was to analyze how altering the weights of the cost layers could result in differ outcomes than the original results. The test altered the equal weights used from this study and from Rabinowitz and Zeller's (2010) analysis by increasing the weight of the percent tree and shrub layer to be much more prominent in the cost layer. The sensitivity analysis revealed that when increasing the weight of the percent tree and shrub cost layer in the CB scenario, the LCPs generated closely match the original results from original CB scenario LCPs (Figure 31). There are minimal differences of the LCPs between the sensitivity and primary analysis. CP3, CP4, CP5, CP8, and CP9 all have similar paths compared to the original LCPs. CP1, CP2, CP6, and CP7 have overall similar paths as the primary analysis but have small discrepancies for portions of the LCPs. The discrepancies are minor, altering of paths stay within the same mountain regions and they share the same direction and overall route. These results suggest that the percent tree and shrub cover layer is at an acceptable weight for the analysis and that any changes would not affect the overall model results.

4.5. Results Summary

In this chapter, the immediate results of the cost path analysis- including total cost, roads crossed, and days travelled- were discussed. Cost and path length changed as the border structures increased depending on the scenarios. NB, CB, and VB had very little to no change between them. When the pedestrian barriers were expanded, there was measurable change that increased with each scenario. The average number of roads crossed increased despite some fluctuation on several LCPs. The number of days travelled increased similarly to the total cost with very little increase in the first three scenarios to increased exponential change in the latter three scenarios. These and other conclusions are discussed in Chapter 5.

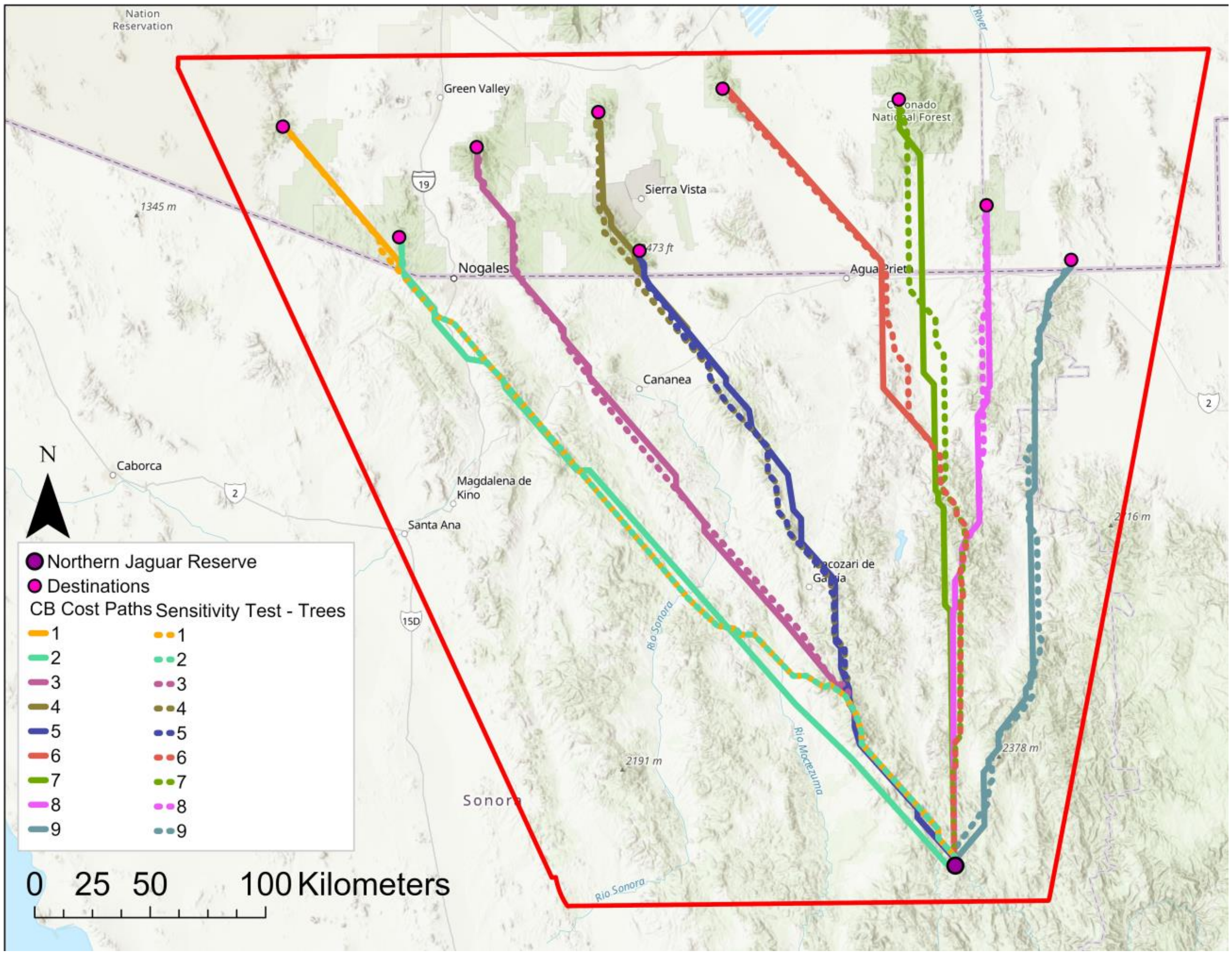

Figure 31. Sensitivity Test Results

Chapter 5 Discussion and Conclusions

The objective of this study was to determine the change to total cost of jaguar dispersal if there was an expansion of border structures along the U.S.-Mexican border. By analyzing LCPs, the most sensitive border crossings to jaguars were identified. Further, it was determined where expanding border structures would be most damaging to their dispersal success.

In this chapter, conclusions are discussed as to the empirical results presented in Chapter 4. Limitations of the project are addressed, as well as areas in which the project was successful. Lastly, recommendations for use of the results and further research was explored.

5.1. Study Observations

The LCPs generated were as expected for the EPW scenarios but not for the NB, CB, or VB scenarios. Observing an average of 0.50% cost change between the first three scenarios was not the expected result. One might assume that implementing impassable structures along a border would inhibit wildlife from crossing. However, there are other variables that affected the minimum effect that the CB scenario had on the jaguar's dispersal. First, the border structures are designed to keep people out of the U.S. The border structures are located near the border towns and across the more accessible lowland deserts. The Sky Islands are more difficult for humans to climb and historically have been used as natural barriers to deter illegal immigration. The jaguar prefers the habitat in the Sky Islands versus hot desert valleys and urban areas that humans tend to prefer. The favored habitats for humans and jaguars are therefore opposite in the study area. When border structures are designed to deter humans, they are much less necessary in the Sky Islands where the jaguar's dispersal routes reside. As a result of this phenomenon, the current border, according to this study, has minimal negative effect on the cost of dispersal of the jaguar into the U.S.

The VB scenario had a minimal effect on the cost paths as well. When creating a line of barriers that universally increase cost by five for one-cell width will only change the total cost of the path marginally. Expanding the pedestrian barriers was the only phenomenon that affected the jaguar's LCP markedly on the grounds that it was impassable and caused the LCPs to divert into longer routes and over higher cost cells. By closing off gaps in the border with vehicle barriers that the jaguars couldn't avoid but could still pass through, the cost only increased slightly, and the LCP length and shape remained the same.

The scenarios that expanded the pedestrian barriers were the only scenarios with substantive results in cost change. Each expansion saw an increase in total cost, roads crossed, and days travelled. It was surprising the rate at which the changes occurred between scenarios. EPW1 and EPW2 saw small increases with slight diversions of LCPs where EPW3 saw large increases and extreme diversions. This shows the impact of completely closing off the border with pedestrian barriers. Reducing the corridor between Sasabe and Nogales to 30% of its original size only increased the total cost of dispersal in that region by an average of 7.07% where closing it off completely saw the average cost increase to 55.71%. This shows the minimal influence that the EPW2 scenario has on CP1 and CP2, the paths in that region, and how much impact the EPW3 scenario has when the gaps in the border are blocked off. With the corridors closed, CP2, CP3, and CP5 experienced cost increases of over 90% which was a much more significant increase from EPW2 where no path increased more than 28%. If the EPW3 scenario were to occur, the northwestern part of the study area would be almost unreachable to the jaguar. The dispersal cost would most likely be too great to see the jaguars dispersing there soon. The northwestern region of the study area holds the lowest cost and most habitable cells in the whole study area. Being unable to inhabit the area would dramatically reduce the total number of jaguars who could stay in the U.S. permanently.

Paths CP8 and CP9 changed very little change and did not get diverted much- if at all- by the pedestrian barrier expansions. These paths were far enough to the east that they were not affected by the pedestrian barriers as the expansions were designed to not cover the entire border. This analysis did not to use a scenario that creates a continuous pedestrian barrier, as the expected result would be that the jaguars would be unable to disperse into the U.S. Therefore, despite 172 km of added pedestrian fencing to the study area, there are some LCPs that do not increase in cost, roads crossed, or days travelled. The unaffected LCPs bring confidence that the jaguars could still disperse into the U.S. in the face of substantial barrier expansions. CP8 and CP9 are the furthest from human settlements which may deter the construction of pedestrian barriers in this region. Thus, in extreme cases of border expansion in the study area, there are still destinations that remain low cost for the jaguar to reach for dispersal.

5.1.1. Road Crossings

The number of road crossings increased slightly over the six scenarios. Much like the total cost, the number of roads crossed started to increase noticeably in EPW1 and EPW2, but it did not substantially increase in EPW3 like total cost did. The average road crossings increase from 11.0 roads crossed for NB, CB, and VB to 12.9 roads for EPW3. That is an increase of 1.9 road crossings or a 17.3% increase. What is interesting is that although the LCPs change so drastically in EPW3, the number of roads stay relatively the same. When a LCP diverts, it changes which roads it crosses, it can leave roads behind and cross new ones. So, as old roads get replaced with new ones, the number of roads can stay the same. In total cost, the further you travel usually increases cost, but different paths cross different roads as they divert around border structures. This demonstrates the minor increase in roads crossed, but the increase is still significant. If each road crossing is a life-threatening event, an increase of 17.3% more life threatening events can be dangerous and will reduce potential dispersal of jaguars.

5.1.2. Days Travelled

Much like the number of roads crossed, the number of days travelled started to increase noticeably in EPW1 and EPW2, however it did increase slightly more significantly in EPW3. The average number of days travelled increases from 30.1 days for NB, CB, and VB to 34.3 days for EPW3 which was an increase of 3.2 days or 13%. The total cost takes the length and the average cost of each LCP, thus both variables increase simultaneously. The days travelled only takes the length into consideration. Therefore, the increase to total cost that was contributed from just the length was 13%. Meaning the cost played a large role in the total cost of the LCP. An extra 3 days of travel to get to the U.S. habitats may have negative effects on jaguar dispersal. Further, a species will need to find more prey and water during the dispersal. Some LCPs saw no increase in days travelled but CP2, CP3, and CP5 experienced an increase in days travelled over 25%. That is over a week of travel. That amount of increase after certain gaps in the border were closed could mean a much lower chance of jaguars' dispersal to those potential habitats. If some jaguars do disperse there, it would be very difficult for them to have connectivity with Mexico, meaning that they could become genetically isolated. A longer path to the U.S. habitats reduces the success of the dispersal and decreases the survivability of the jaguars who may be able to disperse there.

5.2. Wildlife Corridors and Use of Results

One of the goals for this study was to outline where wildlife corridors could be implemented to allow the jaguars to be able to find permanent residence in the U.S. The stark increase in cost between EPW2 and EPW3 makes it very clear where the wildlife corridors need to be constructed (Figure 32). Closing off the gaps between the border towns of Sasabe, Nogales, and Agua Prieta becomes increasingly difficult in terms of cost, roads crossed, and days travelled for the jaguar to be able to reach those habitats. Keeping gaps in the Sky Islands allows the jaguars to be able to move freely between the two countries and successfully create permanent habitats in the U.S. while maintaining connectivity with Mexico. The suggested wildlife corridors are far from human activity and use the Sky Islands as natural barriers against illegal immigration which keeps current border structures intact and proponents of a border wall content. Each suggested wildlife corridor is at least 1 kilometer wide, making it usable to the jaguar. None of the suggested wildlife corridors are where current pedestrian barriers are, therefore, no action is needed at this point with reference to removal of pedestrian barriers.

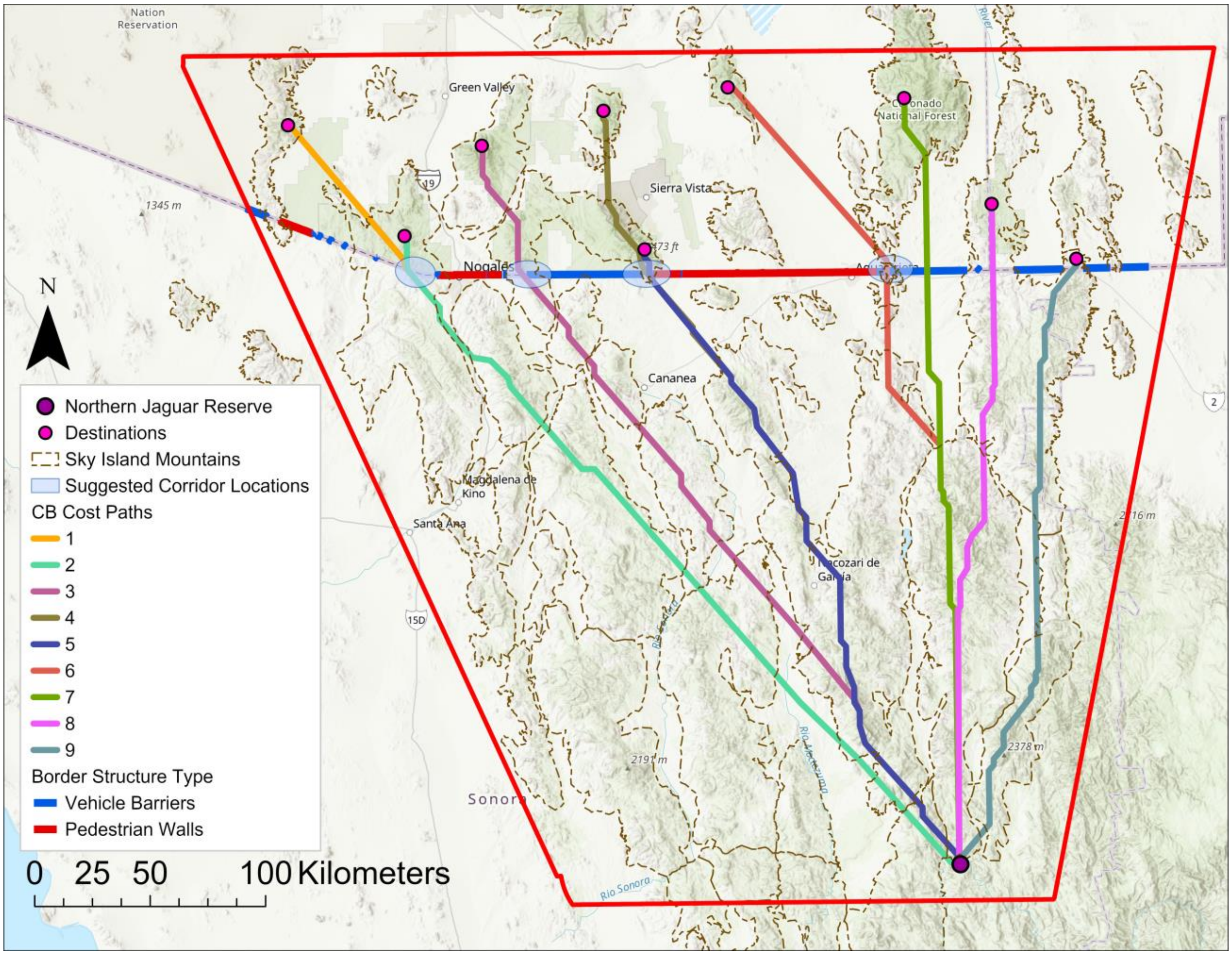

Figure 32. Suggested wildlife corridor locations in the event of border structure expansion

The lack of cost change between NB and CB means that without any expansion of border structures, there is little threat to jaguar dispersal. According to these results, there is limited disruption to jaguar dispersal by the current border structures in place. The expectation of this study was that there would be a suggested location within the current border structures that a wildlife corridor would currently need to be built to benefit the jaguars but there is none. More border structures will only disrupt the jaguars marginally but there is a tipping point evident by EPW3. If the border structures expand past the EPW2 mark, there can be troubling consequences for the jaguars and other wildlife. Finding the balance between the government policy making and conservation is key. In the event that the EPW3 scenario is implemented, these suggested wildlife corridors should be emplaced to allow jaguar dispersal and habitat connectivity.

Many organizations are interested in bringing the largest cat in the Americas back to the U.S., though many would also anticipate challenges. Knowing the impact of various border scenarios is critical to conservationists and decisionmakers. There is the possibility of balancing increased border security while allowing free movement of jaguars and wildlife across the border.

5.3. Study Limitations

Any LCP analysis can be improved upon in future studies. This study was limited in several ways. First, other studies used cost layers such as terrain ruggedness, water availability, food availability, and temperature (Stoner 2015). This analysis aimed to include only the most critical criteria, but a future study could add more complexity and ideally better mimic the ecological processes taking place on the ground. Second, the resolution of the project was at 1 km by 1 km due to the landcover raster, the lowest resolution layer. All rasters with higher resolutions needed to be reduced to match that layer. A future study could use higher resolution data that could lead to more fine-grained results. Third, information on future border structures is limited and is constantly changing. The scenarios tested in this analysis were based on likely scenarios, including the cost for the VB scenario and expanding pedestrian barriers from existing pedestrian barriers. Knowing the future construction details would reduce the number of scenarios which could enhance the more focused analysis. Not using more variables, low resolution rasters, and limited border structure predictability limited this study. Future work could possibly build on this project to find more accurate results.

5.4. Future work

As more information becomes available as to the specifications of the border structures, future studies could input upcoming barriers into an LCP analysis to understand the impact with more accurate results. This study predicted the future border scenarios based on cost and techniques by the border agencies. The Sky Islands and the study area was only 257 km wide which makes up only 8.1% of the 3,144- kilometer-long border between the U.S. and Mexico. Knowing the plans for future barriers would be beneficial for other studies along the border. If future analyses could know future construction plans, then a more accurate prediction could be ascertained.

Studying how jaguars and other wildlife behave around vehicle barriers could help future research. In this study, the travel distance of the paths was between 200 and 300 cells in the raster. The border structures typically only register along one cell, so the inclusion of continuous vehicle barriers only effects one cell along each path once. There was no avoidance of that one cell due to its universal application, so the LCPs kept the same route. This led to very little change in cost which may not be realistic. Jaguars are known to be able to cross vehicle barriers, but nothing else in known about the effect vehicle barriers have on jaguars. Determining the true effect of vehicle barriers could benefit future research.

This analysis uncovered where in the study area there is a tipping point for cost and where wildlife corridors need to be implemented. Future studies could attempt to better understand how jaguars react to increases in cost. If the cost increases by 15%, what percentage of jaguars would not be able to disperse as a result? How does the increase in cost affect the timeline until permanent residence? Understanding the impact of cost increase would allow for more conclusions about long-term consequences of barrier construction.

5.5. Conclusions

This study looked at how different border scenarios would affect the cost of jaguar dispersal. Looking at the LCPs, this study hoped to identify areas of the border that would be sensitive to an expansion of border structures. The project had expectations of gradual cost increase until the border was completely blocked but instead found minimal increase in cost until the border was blocked off. At that point the cost to jaguar dispersal into the U.S. was significant. A continuous barrier would be impossible for jaguars to cross but building wildlife corridors for the jaguar would allow jaguars to disperse into the U.S. while maintaining connectivity with Mexican habitats.

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