Jaguar Habitat Connectivity and
Identification of Potential Road Mitigation Locations
in the Northwestern Recovery Unit for the Jaguar

A Final Submission to the U.S. Fish and Wildlife Service
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ABSTRACT

The loss and fragmentation of habitat due to anthropogenic activity is a major threat to the persistence of the jaguar (*Panthera onca*) across its range. Range-wide assessments of habitat suitability and connectivity have been performed; however, there is an acknowledged need for regional studies that better reflect the local environment and habitat preferences of this highly adaptable species. A regional connectivity study for the northern part of the jaguar's range is of particular interest given efforts by the U.S. Fish and Wildlife Service to recover the species across its range, with a focus on the Northwestern Recovery Unit (NRU) for the jaguar.

In this report, we aim to identify places where mitigation efforts such as road crossing structures may be used to prevent fragmentation and promote habitat connectivity in the NRU, an area identified in the Recovery Outline for the Jaguar (U.S. Fish and Wildlife Service 2012, updated in Sanderson and Fisher 2013). We used electrical circuit theory to predict important jaguar corridors and locations where jaguar movement may be obstructed by transportation infrastructure. Our analysis revealed 10 locations where road crossing structures would protect and enhance habitat connectivity for jaguars in the NRU. Based on these results, we offer suggestions and considerations for next steps in planning for the incorporation of measures to maintain connectivity and safe passage of jaguar across these landscapes.

INTRODUCTION

Large carnivores such as the jaguar (*Panthera onca*) are in global decline due to the loss, degradation, and fragmentation of their habitat, direct hunting of carnivores and their prey, and persecution for attacks on livestock (Sanderson et al. 2002b, Hilty et al. 2006, Rabinowitz and Zeller 2010, Estes et al. 2011, U.S. Fish and Wildlife Service 2012, Ripple et al. 2014). Anthropogenic land use and modification have reduced the habitat available to jaguars and, in addition to climate change, threatens to continue to do so in the future (e.g., U.S. Fish and Wildlife Service 2012). The direct loss of habitat is exacerbated by fragmentation, which threatens the long-term health and persistence of these wide-ranging, naturally low-density species by preventing gene flow between core populations (Crooks et al. 2011). The resulting isolated subpopulations are vulnerable to local extinction. Maintaining connectivity for carnivores is critical for their conservation and the preservation of their influence on biodiversity and ecosystem processes (Colchero et al. 2011, Rodriguez-Soto et al. 2013, Ripple et al. 2014).

Jaguars are an excellent case study for assessing population connectivity and potential fragmentation. Although jaguars now only persist in 61% of their historical range (Zeller 2007), recent genetic studies indicate that gene flow remains quite high (Eizirik et al. 2001). A number of recent range-wide analyses have prioritized habitats for jaguar (e.g., Sanderson et al. 2002a) and identified potential corridors between these areas (e.g., Rabinowitz and Zeller 2010) across the jaguar's entire range. However, there is a recognized need for regional assessments of connectivity that better reflect the local habitat preferences of this highly adaptable species (Petracca et al. 2013).

Because there are limited regional assessments of habitat connectivity in the northernmost portion of the jaguar's range, studies in other landscapes provide insight as to the effect of habitat fragmentation and road development on jaguar persistence. One study in the Atlantic Forest of Brazil found that recent habitat fragmentation (i.e., occurring in the latter half of the 20^{th} century) measurably reduced genetic diversity in jaguars (Haag et al. 2010). A least-cost path analysis of the Caatinga Biome, also in Brazil, found that the remnant populations of jaguar were disconnected, likely due to growing human land use and limited water availability, despite the fact that suitable xeric habitat seemed to be widely available (Morato et al. 2014). A movement-based model of habitat fragmentation due to roads in the Mayan Forest of the Yucatan Peninsula found that female jaguars are sensitive to the presence of roads and use a much more limited set of crossing sites than male jaguars (Colchero et al. 2011). Collectively these studies suggest that habitat fragmentation and subpopulation isolation is possible in the Northwestern Recovery Unit (NRU; U.S. Fish and Wildlife Service 2012, updated in Sanderson and Fisher 2013).

A regional habitat connectivity assessment is necessary for effective conservation of jaguars in the NRU. This assessment is of particular interest to the U.S. Fish and Wildlife Service (USFWS) and Jaguar Recovery Team given their recovery planning efforts for the species across its range, with a focus on the NRU. Connectivity across all areas of the NRU is a key component in recovering the species within the NRU, as well as range wide, but the nature of this connectivity is currently unknown and requires further investigation (U.S. Fish and Wildlife Service 2012).

The Recovery Outline for the Jaguar identifies preliminary recovery actions, including analysis of habitat and corridor use to maintain and improve connectivity of jaguar habitat throughout the northern extent of the species' range and between populations to increase the long-term survival of subpopulations (U.S. Fish and Wildlife Service 2012). In conjunction, the outline also recommends studying the impacts of highways and vehicle traffic on jaguar movements, as well as the effectiveness of methods for mitigating the impediments that transportation infrastructure and activities impose on jaguar movement. Specifically, the recovery actions call for identifying where and how to incorporate highway under- or over-passes and other design measures into transportation infrastructure to facilitate jaguar movement where needed.

To assess where these mitigation measures may be needed, connectivity modeling can be applied to predict where jaguars are most likely to move and where transportation infrastructure may impede these movements. Electrical circuit theory offers a rigorous approach for predicting ecological connectivity between habitat patches (McRae et al. 2008). The use of circuit theory in ecological connectivity modeling uses underlying algorithms that are simple and efficient enough to be calculated across large datasets allowing for broad-scale analyses over space and/or time.

In this method, habitat patches are treated as nodes within an electrical circuit, connected by edges. The edges are characterized by weights representing the probability that an electron (or individual jaguar) might move through them; these weights may be understood as the conductance or resistance value, which is an amalgamation of variables assumed to influence animal occupancy and movement in and around that location (Shah and McRae 2008). As the individual moves from node to node, the landscape features change and so, too, does the underlying value of each pixel. Circuit theory can then be used to predict the likelihood that wildlife, such as the jaguar, might selectively move across particular pathways on the landscape given the conductance/resistance values (Shah and McRae 2008).

Circuit theory recognizes multiple pathways across the landscape, and the output adapts as additional pathways are added or removed (McRae et al. 2008), making this method particularly valuable for identifying the most important corridors influencing connectivity (Shah and McRae 2008). Pixels with low probabilities of conductance are seated within broad swaths of potential habitat that may be used generally by the target species, while pixels with high probabilities of conductance reflect more specific delineations or pathways that may be important corridors where connectivity may be particularly vulnerable.

At a coarse scale, one can visually assess these outputs to identify where important movement corridors may be bisected by roads, with potential to impede wildlife movements. Wildlife managers and transportation agencies can use this information to conduct localized, on-the-ground assessments on these potentially problematic sections of road to consider incorporating structures such as fences that guide wildlife to under- and over-passes where the animals can safely move under or over the road.

The goal of this report is to identify potential areas where enhancements (e.g., underpasses, overpasses, guiding fences, etc.) would improve the passage of jaguars across different types of roadways that would be effective in a variety of different habitat types in the NRU in Mexico and the southwestern U.S. We applied circuit theory connectivity modeling to predict important jaguar corridors and locations where jaguar movement may be obstructed by transportation infrastructure. Based on these results, we offer suggestions and considerations for next steps in planning for the incorporation of measures to maintain connectivity and safe passage of jaguars across these landscapes. This report is complemented by another report (Matthews et al. 2015) summarizing design recommendations for wildlife crossing structures. Together, these reports are delivered to address the gaps and needs for research identified in the Recovery Outline for the Jaguar (U.S. Fish and Wildlife Service 2012).

METHODS

Study Area

Using the jaguar habitat model developed by Sanderson and Fisher (2013), we modeled jaguar habitat patches and connectivity across the NRU (Figure 1), which encompasses approximately 226,826 square kilometers (km^2) including 196,805 km^2 in Mexico and 29,021 km^2 in the U.S. The NRU extends from the northern border of Colima, Mexico north through the Sierra Madre Occidental mountain range and lowland desert areas in northern Mexico (Polisar et al. 2014), and into areas south of Interstate 10 between the Baboquivari and Animas Mountains in the southern borderlands of Arizona and New Mexico in the U.S. Within the NRU there are 2 "Core Areas," Sonora and Jalisco, with persistent, verified records of jaguars and recent evidence of reproduction; and 2 "Secondary Areas," Sinaloa and Borderlands, with historical and/or recent records of jaguars but no or very few recent records of reproduction (Figure 1; U.S. Fish and Wildlife Service 2012, Sanderson and Fisher 2013). Elevation in the NRU ranges from sea level along the coast up to 3,300 meters above sea level. The habitat in the study area ranges from tropical dry deciduous and pine-oak forests in the Jalisco Core and Sinaloa Secondary Areas at the southern end of the NRU, to sub-tropical dry deciduous forest and thorn scrub in the Sonora Core Area, to a mix of scrub grasslands, pine-oak woodlands, and montane conifer forests in the Borderlands Secondary Area (U.S. Fish and Wildlife Service 2012) at the northern end of the NRU.

Human land use and ownership varies across the NRU. Within the Borderlands Secondary Area in the U.S., the majority of land is publically owned and managed by tribal entities (the Tohono O'odham Nation) and federal and state agencies, including the U.S. Forest Service, U.S. Bureau of Land Management, U.S. National Park Service, U.S. Fish and Wildlife Service, and Arizona State Land Department (U.S. Fish and Wildlife Service 2012). Much of this land carries some level of protection for habitat and wildlife, although some lands are mixed-use, such as Forest Service, Bureau of Land Management, and State lands. Generally, the mountainous parts of the terrain are under some form of protection, whereas valley bottoms tend to be the location of transportation and other infrastructure. There are also mining activities occurring and proposed at several locations in the U.S. portion of the Borderlands Secondary Area. In Mexico, land ownership is primarily a mix of private, communal, and indigenous lands. Additionally, many protected areas (at federal, state, and municipal levels) exist in the NRU (U.S. Fish and Wildlife Service 2015, in prep.). Similarly, land is used for a variety of purposes: in the Sonora Core Area cattle ranching is the predominant economic activity, while in the Sinaloa Secondary Area, the coastal plains (representing some 35% of this Secondary Area) are being transformed for agriculture, aquaculture, and human settlement (Polisar et al. 2014). In the Jalisco Core Area, cattle ranching and agriculture are common, as is tourism development along the coast (Polisar et al. 2014).

In 2014, the USFWS delineated critical habitat for the jaguar in Arizona and New Mexico (U.S. Fish and Wildlife Service 2014). Critical habitat does not establish a conservation area; however, it does receive some protection under the Endangered Species Act. In total, the critical habitat is comprised of 6 units amounting to 3,093 km^2 (U.S. Fish and Wildlife Service 2014), of which approximately 67% is federally-owned, 16% is state-owned, and 17% is privately owned. The critical habitat does not include tribal lands.

Modeling Process Overview

To identify potential locations where enhancements would improve the passage of jaguars across roadways, we first examined habitat connectivity within the NRU. Our overall process used the habitat suitability model created by Sanderson and Fisher (2013) as the conductance surface (representing the ease with which a jaguar might move through each pixel) and habitat patches derived from the habitat suitability model to predict jaguar movements (i.e., the connectivity model). We identified and described corridors with the highest probability of jaguar movements. After creating the connectivity model, we identified intersections between important connective habitat and roadways of interest. These steps are explained in detail below.

Habitat Suitability Modeling and Patch Selection

From 2011 to 2013 the technical subgroup of the Jaguar Recovery Team, with support from the Wildlife Conservation Society, prepared a series of habitat suitability maps for jaguars in the NRU (Sanderson and Fisher 2011, 2013). The subgroup selected 5 environmental variables (tree cover, terrain ruggedness, distance to water, anthropogenic influence, and habitat type) to incorporate in the habitat suitability score. The subgroup examined the relative importance of each variable based on histograms of jaguar observation events to assign relative weights to each variable (see Sanderson and Fisher 2011, 2013 for further discussion). The resulting weighted variables were combined to produce a habitat suitability score for every 1-km^2 pixel within the NRU, ranging from 0.1 (low suitability) to 8.2 (high suitability; Figure 2).

To begin the current project, we derived core habitat patches from version 13 of the habitat suitability model (Sanderson and Fisher 2013). Core habitat patches were defined as high quality habitat in contiguous blocks of more than 100 km^2 with low anthropogenic influence. We removed patches smaller than 100 km^2, and subsequently removed all pixels with a high human influence score (as defined by the technical subgroup; see Sanderson and Fisher 2013). This method resulted in 8 core habitat patches across the southern 3 Areas (Sonora, Sinaloa, and Jalisco; Figure 3). However, this method produced no core habitat patches in the U.S. portion of the Borderlands Secondary Area and only 1 very small patch in the Mexico portion of the Borderlands Secondary Area that met our requirements for quality, size, and degree of human influence. Thus, we created patches in the Borderlands Secondary Area by using all suitable habitat pixels (Sanderson and Fisher 2013; Figure 4), which resulted in 34 suitable habitat patches within this Area. We then merged the 34 suitable habitat patches with the 8 core habitat patches identified in the other 3 Areas to produce a single set of 42 overall habitat patches across the NRU.

Given that the overall habitat patches produced by our model encompassed such a large percentage of the total area of the NRU (Table 1), we selected the smallest percentage of pixels possible to create nodes for the analysis. *Circuitscape* does not assess connectivity within the habitat patches themselves, so using all of the identified patches would not produce a nuanced, qualitative assessment of connectivity across the study area. Rather, we selected 3% of overall habitat pixels nearest the northern and southern borders to represent the focal nodes, or source habitat, for modeling purposes, which amounted to 10,250 km^2 (Figure 5). Using these areas as source habitat allowed us to model connectivity across the NRU without losing specificity in the corridors at the northern and southern ends of the study area.

Habitat Connectivity Modeling

We used *Circuitscape* software (version 4.0; Shah and McRae 2008) to predict connectivity across the entire NRU including all 4 Areas, from its northern border in Arizona and New Mexico to its southern border in Colima. *Circuitscape* required 2 inputs: a set of nodes to be connected and a conductance surface. We used the above-described habitat suitability model as our conductance surface, which represents the ease with which a jaguar might move across the landscape. For the NRU-wide analysis, we used 3% of overall habitat patches nearest the northern and southern borders of the NRU (Figure 5). We used the pair-wise modeling approach, wherein paths were identified between every possible pair of nodes (i.e., a pair is 1 northern and 1 southern node). These paths were assigned a probability value representing the likelihood that a jaguar would move through that pixel versus any other nearby available pixel. The results presented below represent the cumulative jaguar movement probabilities across all pair-wise comparisons (i.e., the connectivity surface).

A visual examination of the connectivity surface allowed for the identification of corridors. We examined the overlap between corridors and roadways of interest across the NRU. We selected the highways in consultation with field experts (Carlos López González, University of Querétaro, personal communication) and the U.S. Fish and Wildlife Service. Generally, the highways selected are 4-lane, heavily-trafficked highways, although 2 highways are currently 2-lane highways of interest because of their location relative to jaguar habitat, and the possibility they may be more heavily-trafficked in the future. This coarse-scale assessment allowed us to identify places where highways intersect with corridors and where additional research may help verify and select the optimal location for road crossing mitigation efforts.

RESULTS

Habitat Suitability and Habitat Patches

The overall set of habitat patches derived by our methods totaled 170,854 km^2 in area, with the total for each Core and Secondary Area summarized in Table 1.

Across the NRU, the core habitat falls into 8 patches. Except for 1 very small patch of core habitat in the Borderlands Secondary Area, these patches are found in the Sonora and Jalisco Core Areas and Sinaloa Secondary Area. One very large contiguous patch spans from the northern end of the Sonora Core Area, across the Sinaloa Secondary Area, and extends almost the full length of the Jalisco Core Area (Figure 3). In terms of the modeling approaches used here, the existence of this main core patch suggests that the 2 Core Areas are well-connected by high quality habitat.

The suitable habitat in the Borderlands Secondary Area falls into 34 patches (Figure 4). Much of the area within the Borderlands is suitable for supporting jaguars and 1 very large contiguous patch spans most of the Mexico portion of the Borderlands and extends north into the U.S. portion as well. A number of smaller patches in the U.S. primarily represent individual mountain ranges, including the Baboquivari, Sierrita, Tucson, Mule, Dragoon, and Parilla Mountains in Arizona and the Animas Mountains in New Mexico.

Connectivity Across the Northwestern Recovery Unit

The results of the *Circuitscape* analysis indicate that connectivity is varied between the southwestern U.S. and Colima, revealing several important corridors across the NRU (Figure 5). Much of the Mexico portion of the Borderlands has low predicted probability values (Figure 6). Low connectivity probability does not mean that the pathway is less suitable for jaguars; rather, the low values indicate that there are many redundant pathways available to dispersing cats and therefore it is difficult to predict which path a jaguar would use. However, there are 2 distinct corridors extending from the northern part of the Sonora Core Area through the Mexico portion of the Borderlands Secondary Area, which split into 3 corridors near the U.S.–Mexico border (Figure 6). Specifically, in the Borderlands Secondary Area, the western corridor diverges around Mexican Federal Highway 15 (Fed. 15) in northern Mexico and crosses the border at the Pajarito, Patagonia, and Huachuca Mountains in southern Arizona (Figure 6). The eastern corridor is quite narrow and crosses the U.S.–Mexico border at the Peloncillo Mountains in Arizona and New Mexico (Figure 6).

Connectivity is quite diffuse in the central part of the Sonora Core Area, but narrows to a more obvious corridor in the southern part of the Area (Figure 7). Connectivity is likewise dispersed across the landscape in the Sinaloa Secondary Area; however, a corridor running from north to south is still apparent in the central part of the Area (Figure 8). In the Jalisco Core Area, connectivity is concentrated near the center of the northern portion of this Area, with corridors running primarily north to south (Figure 9). In the southern portion of the Jalisco Core Area, connectivity is concentrated along several north-south corridors (Figure 10).

Roadways of Interest and Potential Sites for Road Crossing Infrastructure

We assessed 1 U.S. federal highway, 2 U.S. state highways, and 5 Mexican federal highways within the NRU to identify areas along these roads where jaguar movements may be impeded (Figure 11). In the U.S., these highways included Interstate 19 (I-19), which bisects the U.S. portion of the Borderlands Secondary Area (Figure 5), and State Routes 82 (SR 82) and 83 (SR 83), which together also bisect the U.S. portion of the Borderlands Secondary Area (Figure 5). In

Mexico, these highways included Federal Highway 2 (Fed. 2) along the U.S.–Mexico border and its junction with Fed. 15, which bisects the Mexico portion of the Borderlands Secondary Area (Figure 5); Federal Highway 16 (Fed. 16) traversing the Sonora Core Area (Figure 5); and Federal Highways 40 (Fed. 40) and 150 (Fed. 150) crossing the Jalisco Core Area (Figure 5).

We focused on the intersections between these highways and corridors in the jaguar connectivity model to identify, at a coarse scale, locations where transportation infrastructure enhancements might be considered to reduce road impacts on jaguar connectivity in the NRU. We found a total of 10 locations where highways intersected with corridors (Figures 6 through 10).

In the U.S. portion of the Borderlands Secondary Area, I-19 does not intersect with predicted corridors in our results (Figure 6). However, there are records of jaguar presence both east and west of I-19, and, thus, I-19 likely poses a threat to jaguar movements in the U.S. portion of the Borderlands Secondary Area. In contrast, SR 82 and SR 83 intersect significantly with source habitat and connectivity habitat to the southeast of Tucson, Arizona (Figure 6). SR 82, in particular, intersects with 2 corridors (Figure 6).

In the Mexico portion of the Borderlands Secondary Area, Fed. 2 and Fed. 15 bisect 3 identifiable corridors (Figure 6). Fed. 2 stretches across the entire width of the Borderlands Secondary Area and intersects with each of the 2 identifiable corridors (Figure 6). Fed. 15, which diverges from Fed. 2 and extends north to the U.S.–Mexico border, intersects a corridor that our results indicate is critical for maintaining connectivity from the Mexico portion of the western part of the Borderlands Secondary Area (Figure 6). Fed. 16, which bisects the Sonora Core Area, does not intersect any corridors (Figure 7); however, this does not indicate that Fed. 16 has no potential impact on connectivity. Rather, the model indicates that dispersing jaguars are likely to cross this highway at a large number of locations, making it difficult to pinpoint the ideal location for a road crossing structure. Further research is needed to identify the likely place(s) for such infrastructure. No highways of interest were identified in the Sinaloa Secondary Area (Figure 8). Fed. 40, however, intersects with a corridor in the central part of the Jalisco Core Area (Figure 9) and Fed. 150 intersects with 3 corridors near the southern end of the Core Area where the habitat is already fragmented due to anthropogenic activity (Figure 10).

DISCUSSION

The habitat suitability model (Figure 2) concurs with range-wide assessments of habitat availability (for example, Sanderson et al. 2002). This study is the first to model regional jaguar habitat connectivity across the NRU. Other studies of connectivity at the northern end of the jaguar's range have used least-cost pathways (Rodríguez-Soto et al. 2013), occupancy data gathered from interviews with local residents (Petracca et al. 2013), or expert opinion (Grigione et al. 2009) to model connectivity. In contrast, our methods applied electrical circuit theory to a model of habitat suitability to predict the probability of jaguar movement across the landscape. Given that our technique has several advantages compared to the previously-used methods – namely, it accounts for the random behavior of some individuals (McRae et al. 2008) and is not biased by interviewer response – our connectivity model is also the most rigorous produced to date. Based on these results, we then offered a coarse-scale assessment of sites where 8 roadways of interest (3 in the U.S. and 5 in Mexico) bisect corridors and where enhancements such as over- or under-passes with fencing could facilitate the continued dispersal of jaguars despite the presence of the highway.

Our results suggest 10 candidate sites where highway mitigation measures may help maintain jaguar connectivity in the NRU: 6 in the Borderlands Secondary Area (3 in the U.S. and 3 in Mexico; Figure 6) and 4 in the Jalisco Core Area (Figures 9 and 10). These 10 sites are general areas where additional on-the-ground, localized evaluations are needed to assess the feasibility of installing over- and under-passes and fences to accommodate jaguar dispersal (Matthews et al. 2015). These assessments, complemented by empirical field studies of jaguar movement in each region (e.g., using GPS and remotely-triggered cameras to validate the connectivity model results), would help identify the specific sites where passages are most likely to be used by jaguars (see Polisar et al. 2014 for a review of monitoring techniques).

Similarly, additional site-based assessments are needed to identify sites for road crossing mitigation efforts along Fed. 16 in the Sonora Core Area (Figure 7). This highway crosses the entirety of the NRU but does not intersect any distinguishable jaguar movement corridor and, thus, the task of identifying the optimal crossing locations is challenging. Although the predicted connectivity along this highway is diffused, the value of this area for maintaining connectivity should not be underestimated. Connectivity in the Sonora Core Area is still critically important for maintaining gene flow across the entire NRU. Given that our model indicates that jaguars may move across the highway at any point along Highway 16, the challenge of assessing where crossing structure investment may be most effective should be addressed via field studies of jaguar habitat use and movement in this area.

Our consultation with regional jaguar experts and the USFWS did not identify any roadways of interest for assessment in the Sinaloa Secondary Area (Figure 8). It should be noted, however, that possible increases in future traffic could have negative implications for jaguars if dispersing animals are no longer able to move between the Sonora and Jalisco Core Areas. Although this Area currently lacks a roadway of interest and, thus, is of lower concern than the other Areas, empirical landscape and jaguar field data would be useful should future anthropogenic habitat modification occur, particularly for the development of new or enhancement of existing transportation infrastructure.

The impact of the U.S.–Mexico border fence is of interest to wildlife conservationists (e.g., Cordova and de la Parra 2007, McCain and Childs 2008, Sayre and Knight 2009, Lasky et al. 2011). Although a complete assessment of the fence's impact on jaguars is beyond the scope of this report, our results indicate that the border fence has the potential to affect jaguar dispersal across the international border. The U.S.–Mexico border within the Borderlands Secondary Area has a mix of pedestrian fence (not permeable to jaguars), vehicle fence (fence designed to prevent vehicle but not pedestrian entry; it is generally permeable enough to allow for the passage of jaguars), legacy (older) pedestrian and vehicle fence, and unfenced segments (primarily in rugged, mountainous areas). Approximately 83 kilometers of connective habitat crosses the border; of this, approximately 27 kilometers has vehicle fencing (32.5%) and virtually none has pedestrian fencing (Figure 6). While vehicle fencing is generally thought to allow jaguars to pass, the impact of the fencing on jaguar dispersal is not currently well-known, and additional research is necessary to understand jaguar responses to the fence.

We reiterate that the results reported here are model-based and have not yet been validated with empirical data on the actual movement of jaguars in these areas. Jaguar responses to highways are complex and currently not well studied (Matthews et al. 2015). Many studies have assessed the design of wildlife road crossing structures (e.g., Clevenger and Waltho 2000), but the selection of the crossing site is equally as important yet understudied (Clevenger and Huijser 2011). Our coarse-cut analysis, while more specific than previous connectivity assessments (e.g., Rabinowitz and Zeller 2010), is not refined enough to identify precise locations for wildlife crossing structures.

Furthermore, jaguar habitat selection and use is related to more than the 5 variables included in our habitat suitability model. A fine-scale examination and synthesis of the suite of factors that may influence jaguar movement, such as prey availability, local landscape and habitat features, and jaguar behavioral responses to highways and other forms of anthropogenic land use, would help identify the priority locations for mitigation efforts (Rabinowitz and Zeller 2010). For example, camera trap studies to estimate jaguar occupancy within the corridors and the surrounding areas would clarify the extent to which jaguar movement is actually restricted and, therefore, vulnerable to fragmentation at these locations. Similarly, jaguar road mortality data and highway-crossing behavior would also assist in the selection of mitigation techniques. Given the current lack of empirical data on jaguar responses to highways and the fact that road-induced habitat fragmentation is one of the greatest threats to large carnivore populations, such information would be valuable across the jaguar's range.

This information begins to fill research gaps identified in the Recovery Outline for the Jaguar (U.S. Fish and Wildlife Service 2012), and offers guidance for prioritizing where investments in jaguar conservation and recovery may offer the greatest return at the northern extent of their historical range. Understanding the distribution of important corridors within the NRU is crucial for maintaining current connectivity, as well as anticipating the impacts of potential future anthropogenic landscape modifications and climate change that will ultimately affect the recovery of the jaguar in the NRU, as well as throughout its range.

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GLOSSARY

conductance surface

One of 2 inputs for *Circuitscape*, in which the pixel values are a relative representation of the ease with which a jaguar might move across the study area. The conductance surface used in these analyses was the habitat suitability model described in Sanderson and Fisher 2013.

connective habitat

Any pixel of habitat that has a predicted connectivity value greater than zero.

connectivity model

The *Circuitscape* output representing predicted habitat connectivity across the study area. See also *connectivity surface*.

connectivity probability

The likelihood that an individual jaguar will move through a particular pixel versus any other nearby pixel. A low probability value thus indicates many nearby suitable pixels and a high probability value indicates few nearby suitable pixels.

connectivity surface

The *Circuitscape* output representing predicted habitat connectivity across the study area. "Surface" generally refers to the GIS layer. See also *connectivity model*.

core areas

Areas within a recovery unit for the jaguar with the strongest long-term evidence of jaguar population persistence (U.S. Fish and Wildlife Service 2012). Core areas have both persistent, verified records of jaguar occurrence over time and recent evidence of reproduction.

Criteria for core areas:

1) Reliable evidence of long-term historical and current presence of jaguar populations.
2) Recent (within the last 10 years) evidence of reproduction.
3) Contains habitat of the quality and quantity that is known to support jaguar populations and is of sufficient size to contain at least 50 adult jaguars.

core habitat patches

Habitat patches derived from the habitat suitability model described in Sanderson and Fisher (2013). Each pixel was given a score for amount of tree cover, amount of ruggedness, distance to water, elevation, and habitat type, and these scores were combined. Subsequently, patches under 100 km^2 in size and all pixels with high human influence were removed. See Sanderson and Fisher (2013) for a detailed explanation.

corridor

A linear habitat, embedded in a dissimilar matrix, that connects 2 or more larger blocks of habitat and that is proposed for conservation on the grounds that it will enhance or maintain the viability of specific wildlife populations in the habitat blocks (Beier and Noss 1998).

critical habitat

Federally-designated habitat that is critical for the conservation of an endangered species. There are 3,093 km^2 of critical habitat for the jaguar in the U.S.

high quality habitat

Habitat that is highly suitable for jaguars, as defined by the technical subgroup of the Jaguar Recovery Team (U.S. Fish and Wildlife Service 2012, Sanderson and Fisher 2011, 2013).

node(s)

The habitat patches that *Circuitscape* attempts to connect. The modeling equivalent of *source habitat*.

overall habitat patches

The habitat patches created by combining all suitable habitat patches in the Borderlands Secondary Area and all core habitat patches in the Sonora Core, Sinaloa Secondary, and Jalisco Core Areas within the NRU.

secondary areas

Areas containing jaguar habitat with historical and/or recent records of jaguar presence with no recent record or very few records of reproduction (U.S. Fish and Wildlife Service 2012). These areas are of particular interest when they occur between core areas and can be used as transit areas through which dispersing individuals can move, reach adjacent areas, and potentially breed. Jaguars may be at lower densities in secondary areas because of past control efforts, and, if future surveys document reproduction in a secondary area, the area could be considered for elevation to a core area.

Criteria for secondary areas:

1) Compared to core areas, secondary areas are generally smaller, likely contain fewer jaguars, maintain jaguars at lower densities, and contain more sporadic historical and current records. Evidence of occupancy may be weak or low because the area is not well surveyed, resulting in an unknown status of jaguars in these areas.
2) There is little or no evidence of recent (within 10 year) reproduction.
3) Habitat quality and quantity is lower compared to core areas.

source habitat

For the purposes of this modeling exercise, source habitat is the ecological equivalent of *nodes*, indicating the northernmost and southernmost areas of habitat within the NRU between which individual jaguars may move.

suitable habitat

The area with a suitability index greater than 0, based on tree cover, terrain roughness, distance to water, human influence, and ecoregions (Sanderson and Fisher 2013).

suitable habitat patches

All pixels of habitat in the Borderlands Secondary Area with a suitability value greater than zero.

Table 1. Amount of suitable and core habitat and number of habitat patches per Core and Secondary Area in the Northwestern Jaguar Recovery Unit. We calculated the suitable habitat using the method described in Sanderson and Fisher (2013). We created habitat patches in the Borderlands Secondary Area by using all available suitable habitat (suitable habitat patches). We derived habitat patches in the other 3 areas by selecting only high quality habitat in contiguous patches larger than 100 km^2 and with low relative anthropogenic influence (core habitat patches).

<table>
<tr><th></th><th>Borderlands Secondary Area – US</th><th>Borderlands Secondary Area – MX</th><th>Sonora Core Area</th><th>Sinaloa Secondary Area</th><th>Jalisco Core Area</th><th>Total</th></tr>
<tr><td>Total Area (km^2)</td><td>29,021</td><td>33,955</td><td>77,710</td><td>31,191</td><td>54,949</td><td>226,826</td></tr>
<tr><td>Suitable Habitat (km^2)</td><td>6,839</td><td>22,901</td><td>67,931</td><td>28,723</td><td>44,460</td><td>170,854</td></tr>
<tr><td>Number of Suitable Habitat Patches</td><td colspan="2">34</td><td>0</td><td>0</td><td>0</td><td></td></tr>
<tr><td>Core Habitat (km^2)</td><td>0</td><td>423</td><td>28,310</td><td>18,790</td><td>26,267</td><td>73,790</td></tr>
<tr><td>Number of Core Habitat Patches</td><td colspan="2">1</td><td>4</td><td>1</td><td>4</td><td></td></tr>
</table>

Table 2. Roadways of interest assessed in our study and the number of times each highway intersects with predicted corridors in the Northwestern Jaguar Recovery Unit. We selected the highways in consultation with regional jaguar experts and the U.S. Fish and Wildlife Service. I=Interstate (U.S.); SR=State Route (U.S.); Fed.=Federal Highway (Mexico).

Highway	Highway Type	Area	# Intersections with Corridors	Total Intersection Length (km)
I-19	4-lane federal	Borderlands Secondary Area (US)	0	n/a
SR 82	2-lane state	Borderlands Secondary Area (US)	2	30
SR 83	2-lane state	Borderlands Secondary Area (US)	1	15
Fed. 2	4-lane federal	Borderlands Secondary Area (MX)	2	47
Fed. 15	4-lane federal	Borderlands Secondary Area (MX)	1	6
Fed. 16	4-lane federal	Sonora Core Area	0	n/a
Fed. 40	4-lane federal	Jalisco Core Area	1	14
Fed. 150	4-lane federal	Jalisco Core Area	3	10
Total			10	122

Figure 1. Map of the extent of the Northwestern Jaguar Recovery Unit (NRU), as updated by Sanderson and Fisher (2013). The NRU covers 226,826 km^2 extending from southwestern New Mexico and southeastern Arizona in the United States, south into Mexico along the Sierra Madre Occidental mountain range to Colima. Within the NRU there are 2 "Core Areas," with persistent, verified records of jaguar and recent evidence of reproduction, and 2 "Secondary Areas," with historical and/or recent records of jaguar but no or very few recent records of reproduction.

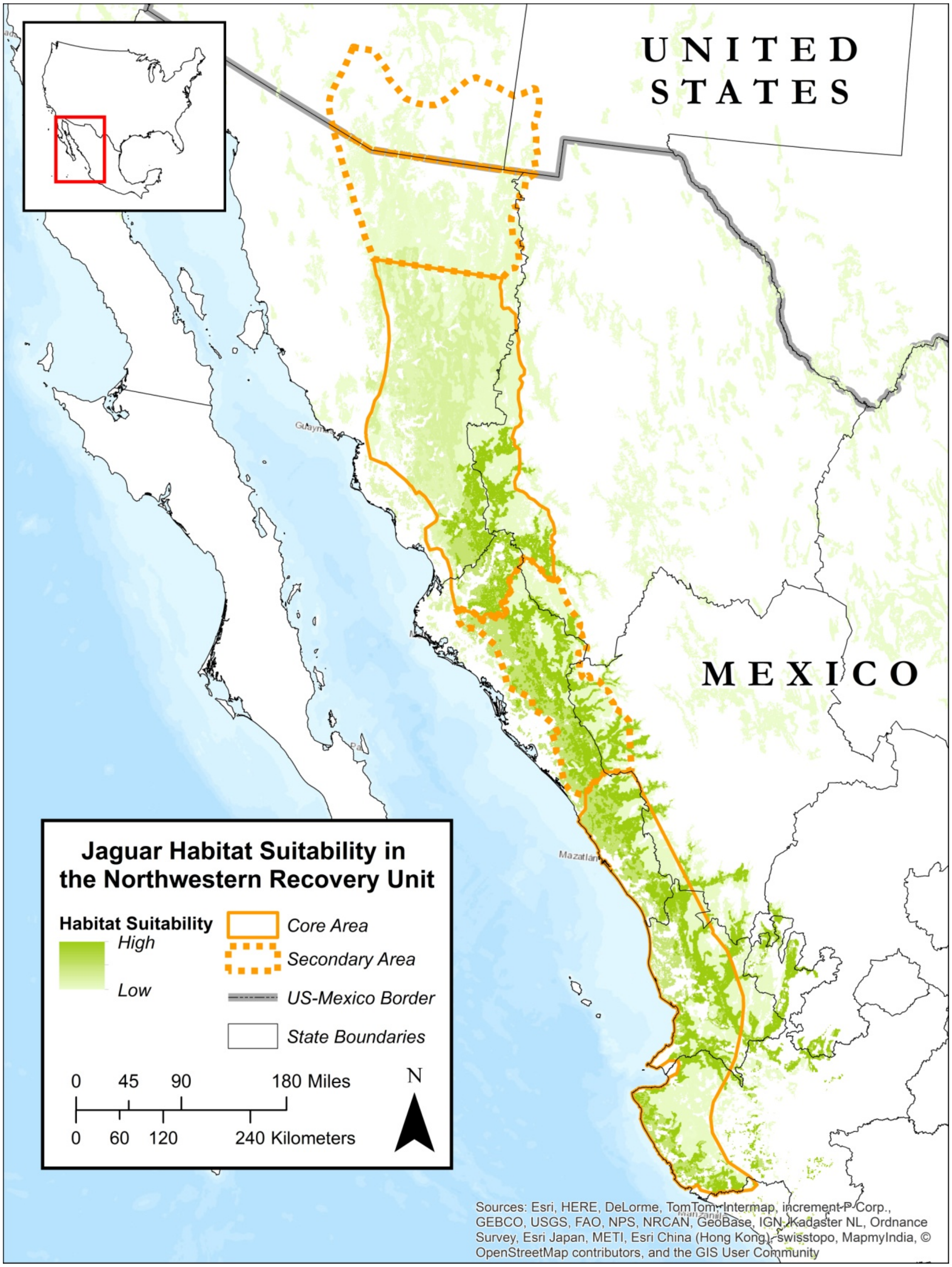

Figure 2. Habitat suitability scores for jaguars across the Northwestern Jaguar Recovery Unit. Five environmental variables – tree cover, ruggedness, distance to water, anthropogenic influence, and ecoregion – were combined to calculate the habitat suitability score. See Figure 1 for further information regarding Core and Secondary Areas (Sanderson and Fisher 2013).

Figure 3. The 8 core habitat patches used to predict jaguar habitat connectivity across the Northwestern Jaguar Recovery Unit. The patches in Mexico were derived from the habitat suitability model by selecting only high quality habitat in contiguous patches larger than 100 km^2 and with low relative anthropogenic influence.

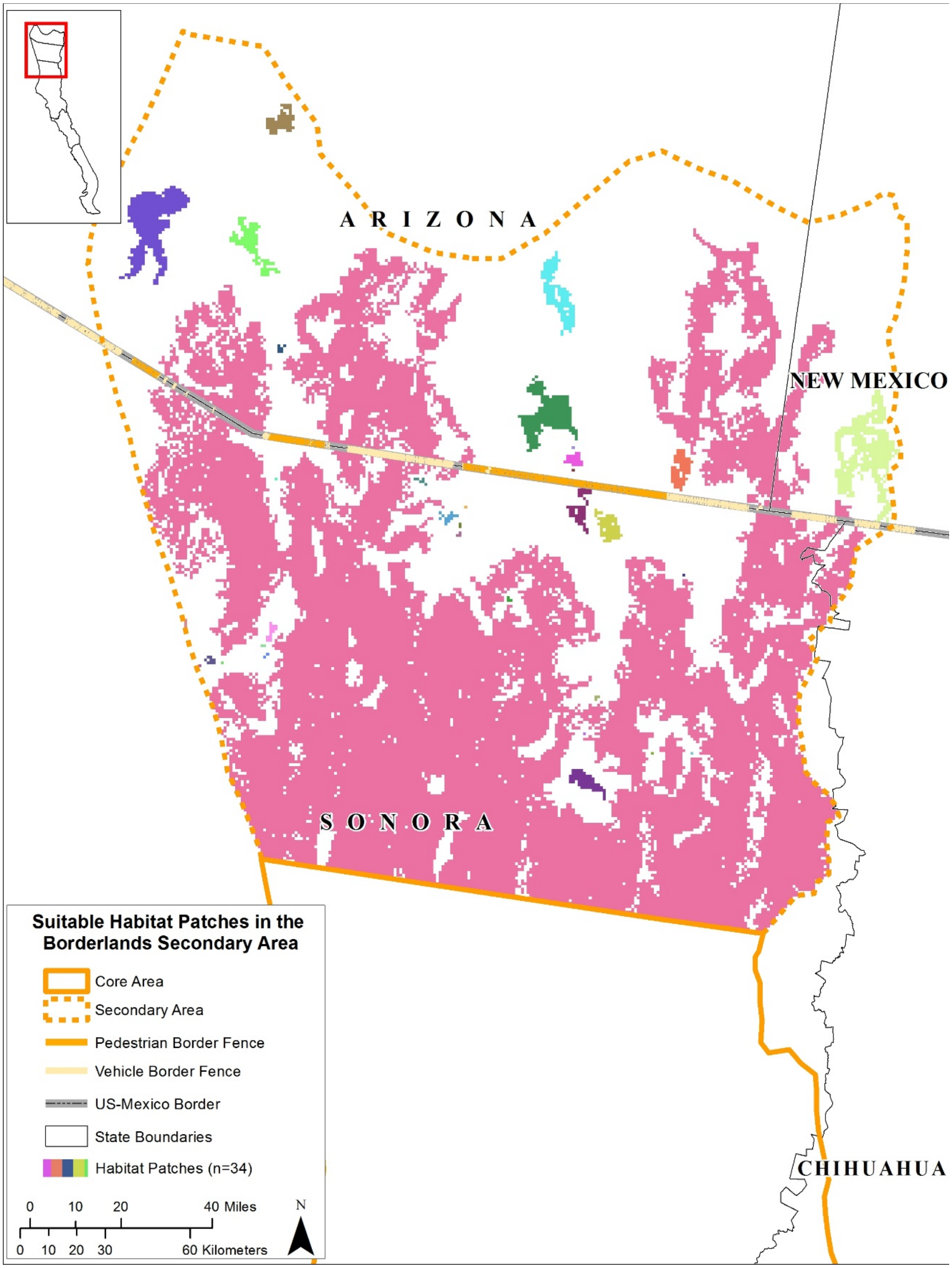

Figure 4. The 34 suitable habitat patches in the Borderlands Secondary Area used to predict jaguar habitat connectivity across the Northwestern Jaguar Recovery Unit. The patches in the Borderlands Secondary Area were comprised of all suitable habitat within the Area, as modeled in Sanderson and Fisher (2013).

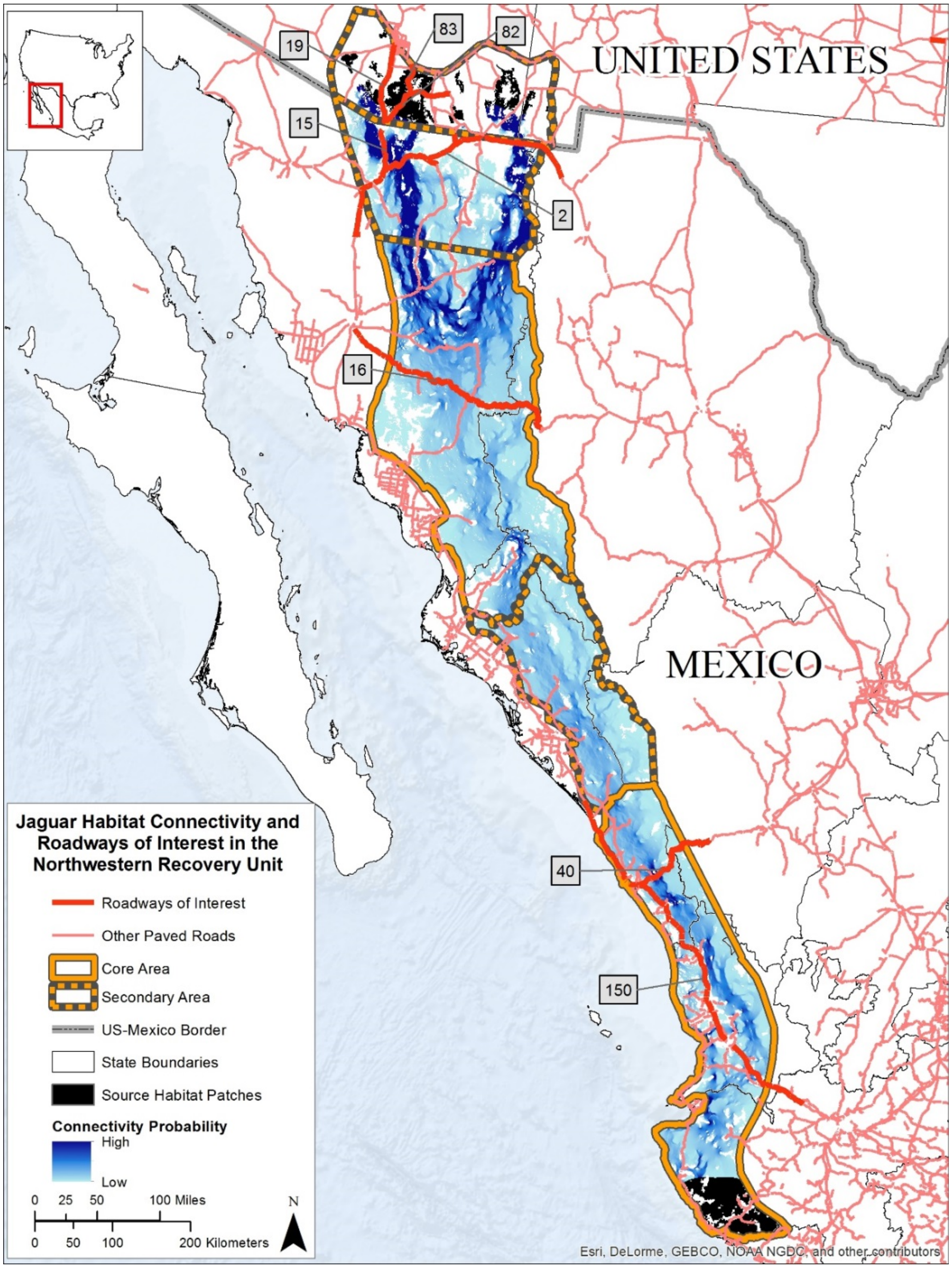

Figure 5. Predicted jaguar habitat connectivity and roadways of interest in the Northwestern Jaguar Recovery Unit (NRU). We created this model using *Circuitscape* software, which predicts connectivity by applying electrical circuit theory to a set of nodes (the source habitat patches) and a conductance surface (the habitat suitability model in Figure 2). Corridors, where connectivity probabilities are high, indicate areas where there are fewer paths available for dispersing jaguars. We assessed the intersection between connectivity and roadways of interest in the U.S. and Mexico, labeled in grey on the map: Interstate 19 and State Routes 82 and 83 in the U.S., and Federal Highways 2, 15, 16, 40, and 150 in Mexico.

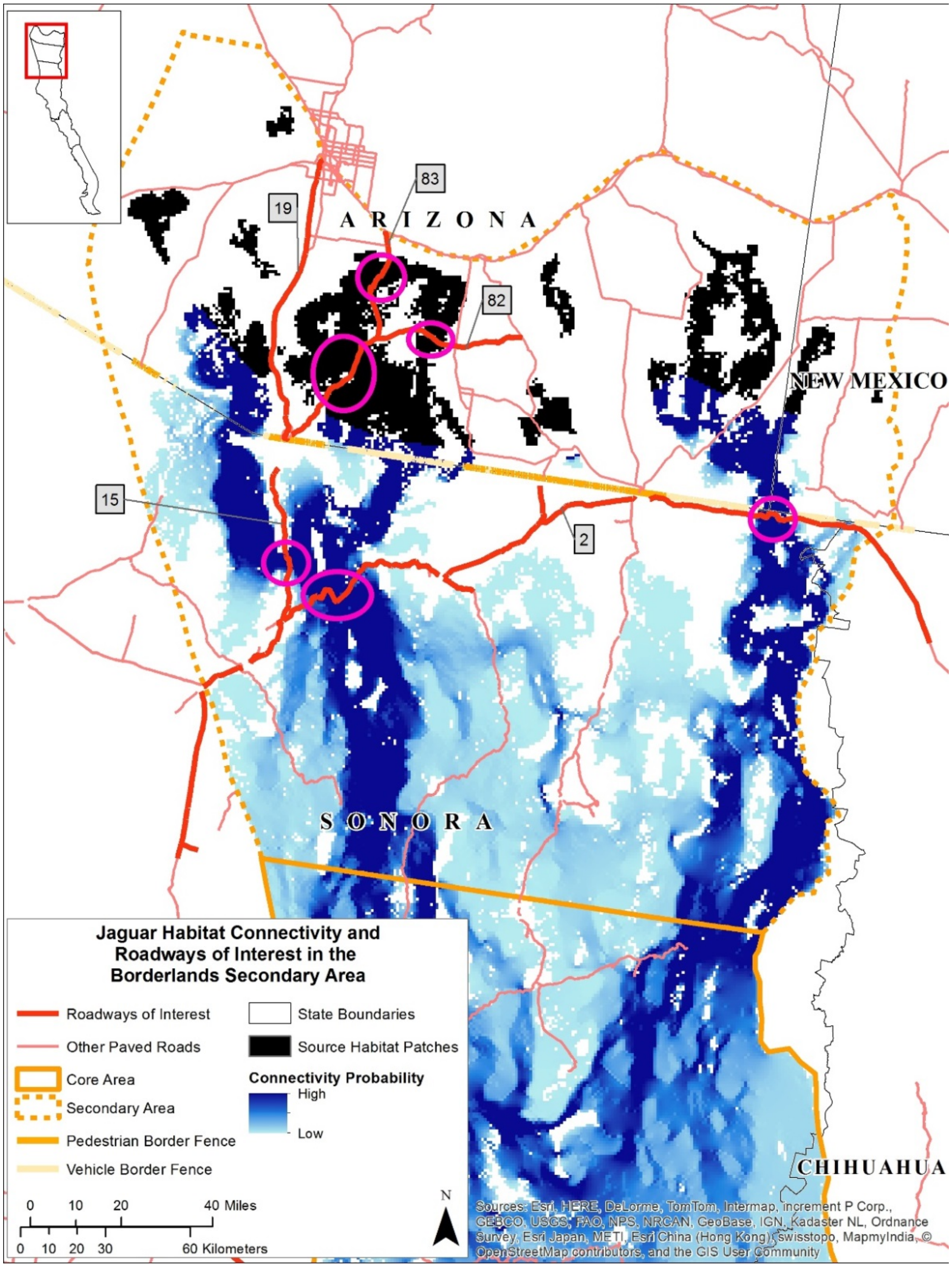

Figure 6. Habitat connectivity and roadways of interest in the Borderlands Secondary Area (some road segments in densely populated areas omitted). A visual examination of this connectivity model, which extends across the entirety of the Northwestern Recovery Unit, reveals 3 corridors that extend across the U.S.–Mexico border. These corridors are intersected by Mexico Federal Highways 2 and 15. U.S. State Routes 82 and 83 also intersect with source habitat patches, which may impact jaguar habitat connectivity. These areas are good candidates for further assessment to determine the potential for road crossing mitigation structures.

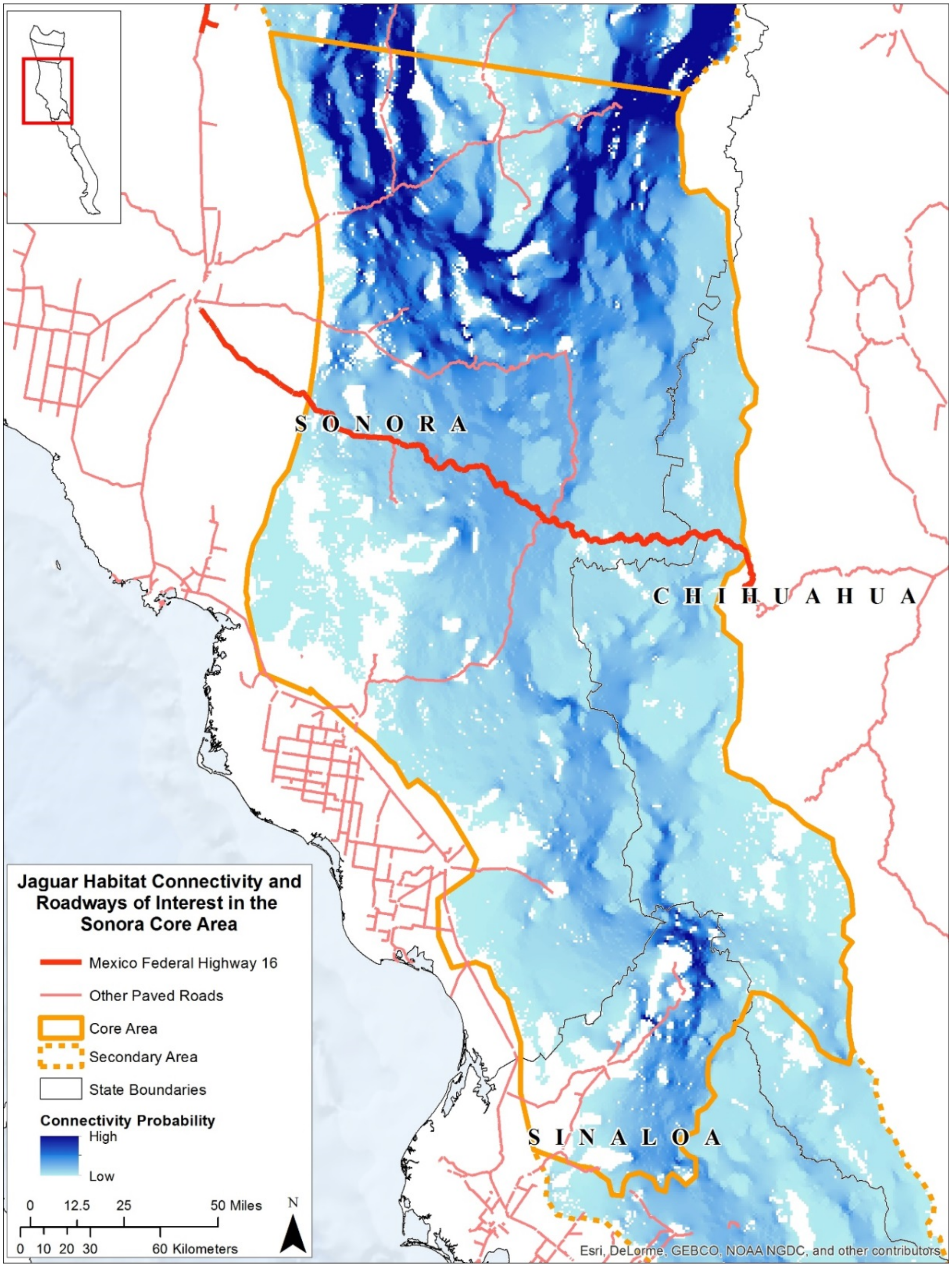

Figure 7. Habitat connectivity and a roadway of interest through the Sonora Core Area of the Northwestern Jaguar Recovery Unit (some road segments in densely populated areas omitted). Connectivity is diffuse in the central part of the Sonora Core Area, but narrows to a more obvious corridor in the southern part of the Area. Although Mexico Federal Highway 16, depicted here, does not intersect with any corridors, it still has the potential to act as a barrier to jaguar dispersal. Additional site-based assessments are needed to identify precise locations for future road mitigation efforts.

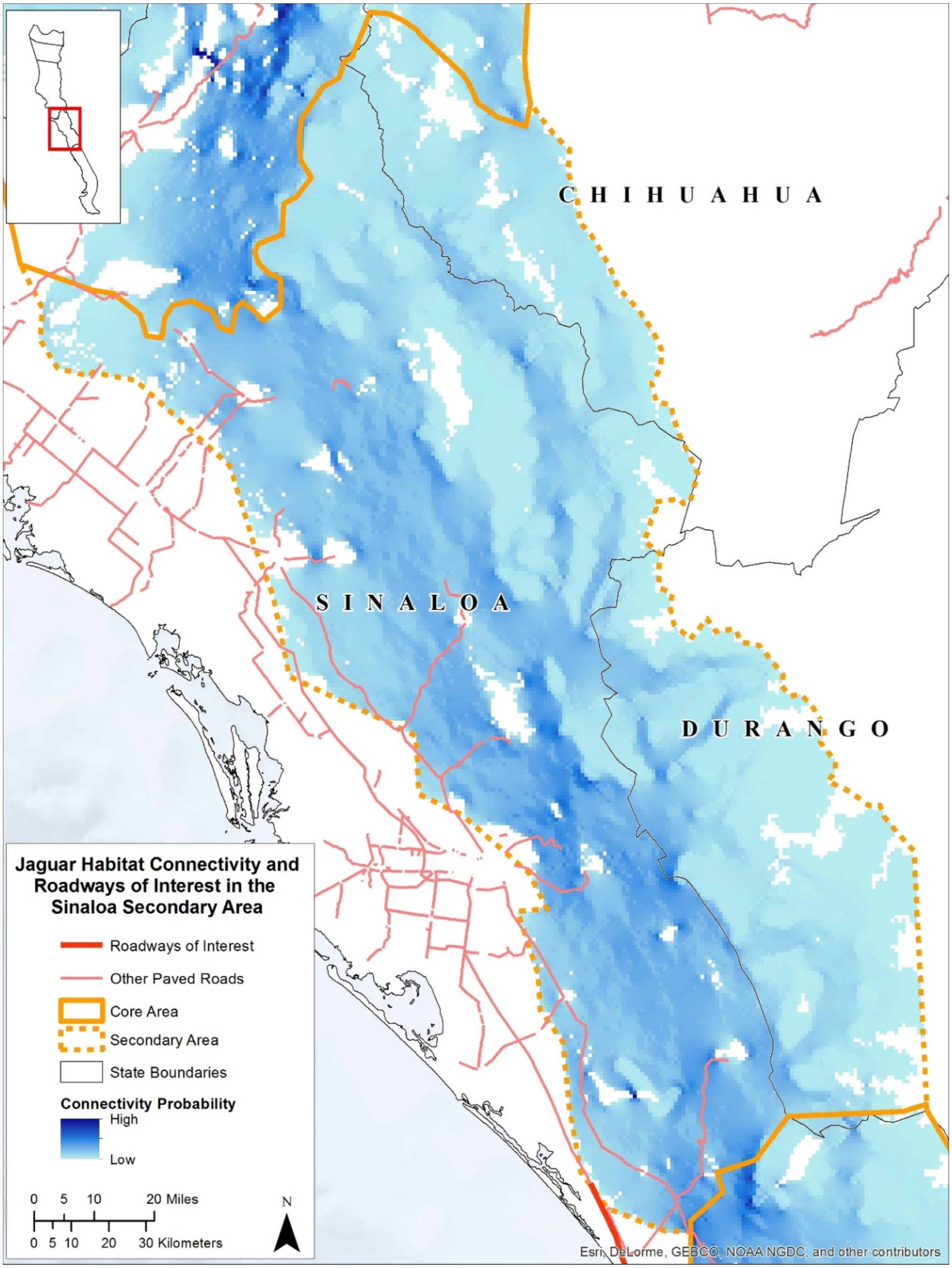

Figure 8. Habitat connectivity and roadways of interest in the Sinaloa Secondary Area in the Northwestern Jaguar Recovery Unit (some road segments in densely populated areas omitted). Connectivity probabilities are diffuse across the Area, but a clear corridor running from north to south is still apparent in the central part of the Area. There are no roads of interest bisecting this Area.

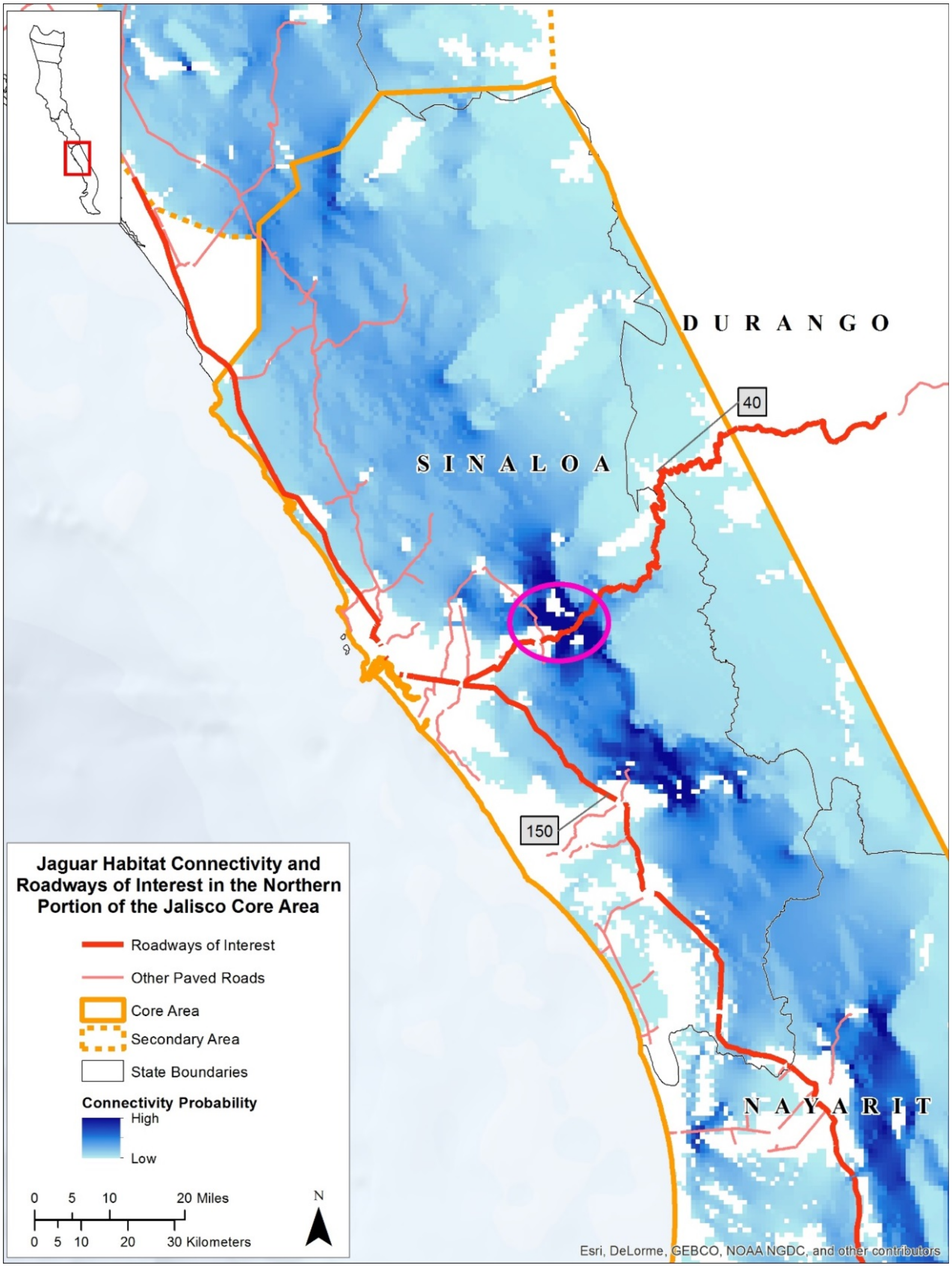

Figure 9. Habitat connectivity and roadways of interest through the northern portion of the Jalisco Core Area of the Northwestern Jaguar Recovery Unit (some road segments in densely populated areas omitted). Connectivity is concentrated near the center of the Core Area, running primarily from north to south. Mexico Federal Highway 40 intersects 1 corridor, indicated by the circle. The highlighted area is suitable for further assessment and potential road crossing mitigation structures.

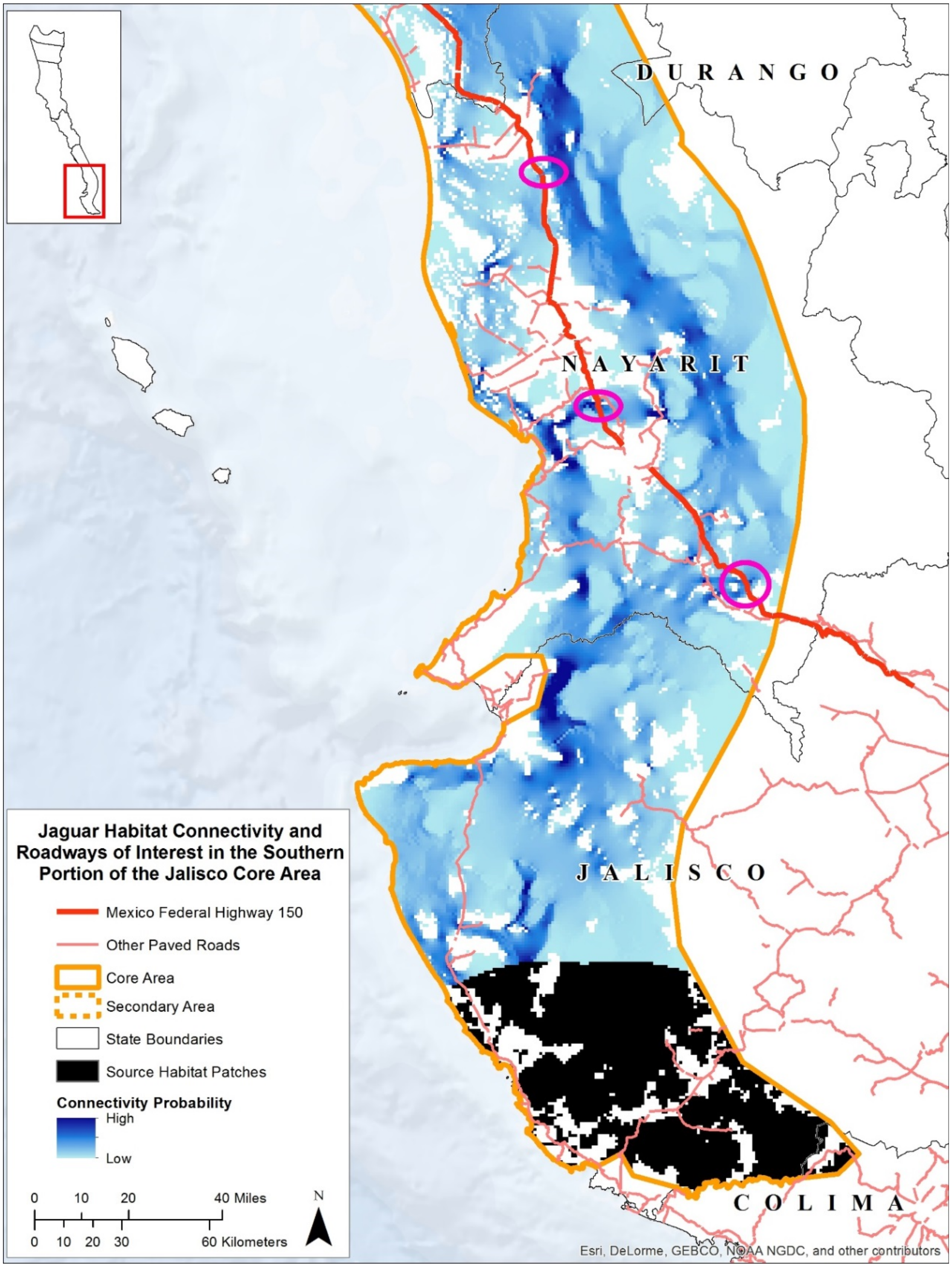

Figure 10. Habitat connectivity and roadways of interest through the southern portion of the Jalisco Core Area of the Northwestern Jaguar Recovery Unit (some road segments in densely populated areas omitted). The connectivity is concentrated along several north-south corridors in this part of the Core Area. In particular, Mexico Federal Highway 150 intersects with 3 corridors, circled in pink, suitable for further assessment and potential road crossing mitigation structures.

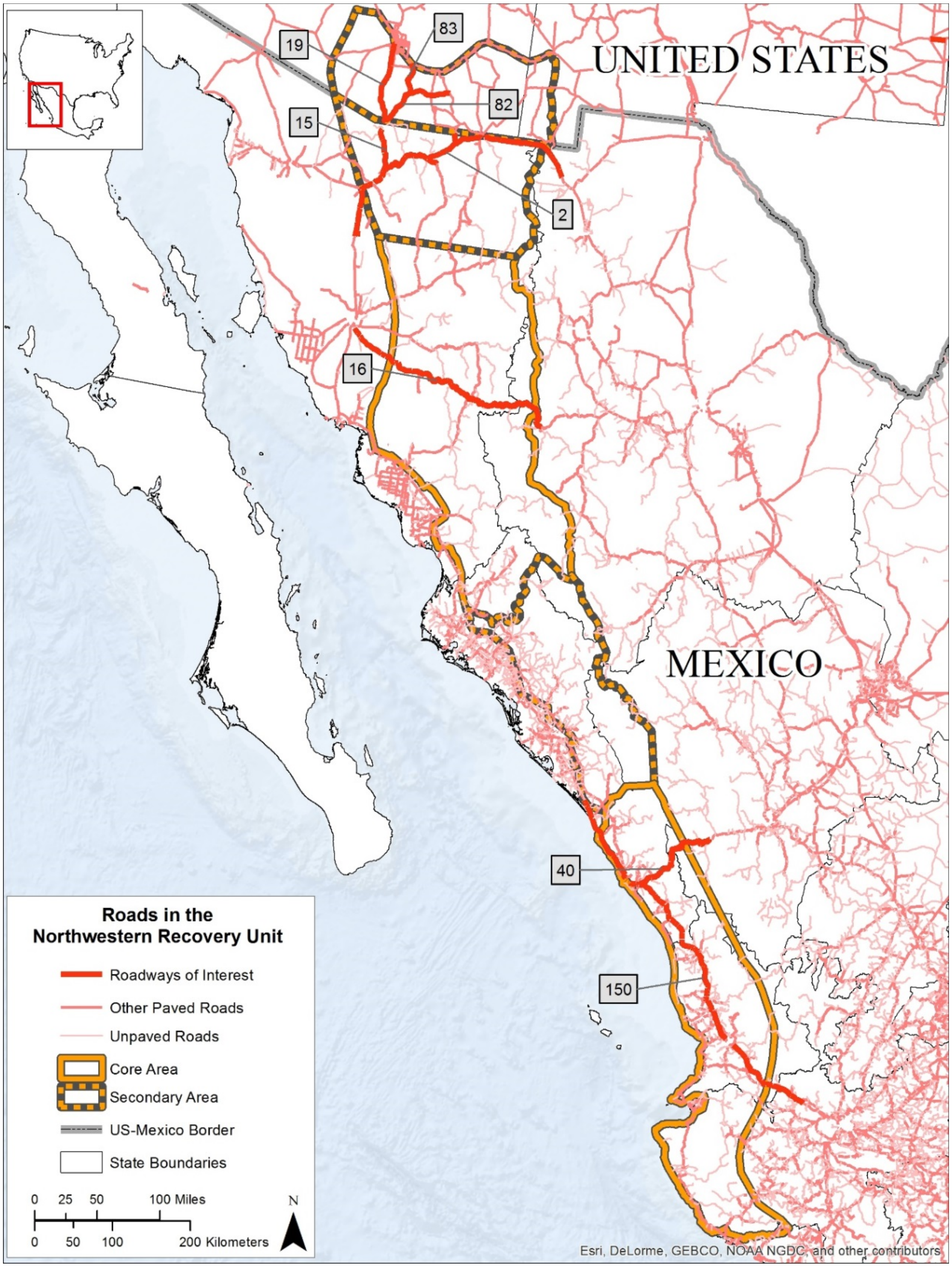

Figure 11. Roads of interest across the Northwestern Recovery Unit. All roads may affect jaguar movement to varying degrees; however, highly trafficked 2- and 4-lane roads (Mexico 2, 16, 40, and 150) may have the greatest potential to interfere with jaguar movement, and thus were isolated for further examination. Additionally, other roads that intersect source habitat and have the potential to become more heavily trafficked in the future (U.S. 19, 82, and 83) were isolated for future examination.