**FINAL REPORT**
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For the project entitled:

# Potential jaguar habitat and structural connectivity in and surrounding the Northwestern Recovery Unit

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## Background

The goal of this work was to map habitat and connectivity for jaguars (*Panthera onca*) in southern Arizona and the Northwestern Recovery Unit (NRU) study area. To do this, we followed the general approach outlined by Sanderson and Fisher (2011; 2013) but updated it using finer-grained spatial data and a gradient-based (rather than binary habitat/non-habitat) model using the same observational data on jaguars.

### Brief review of model in Draft Recovery Plan

The model in the USFWS draft recovery plan was generated by Sanderson and Fisher (2011; 2013), and updated by Stoner et al. (2015), which in turn is based generally on a potential jaguar habitat model for Arizona (Hatten et al. 2005). Sanderson and Fisher developed jaguar habitat suitability and connectivity maps at 1-km$^2$ resolution based on guidance from the technical subgroup of the Jaguar Recovery Team in the Northwestern Recovery Unit (USFWS Jaguar home page: https://www.fws.gov/southwest/es/arizona/Jaguar.htm). The binary (habitat/non-habitat) model was based on landscape characteristics at sites of ~200 jaguar observations (http://jaguardata.info/), and forms the basis for the Draft Recovery Plan (posted December 20, 2016), which is currently in review (comments due March 20, 2017). The landscape variables used to model habitat included: percent tree cover (*T*), distance to water (*W*), degree of human influence (*HII*), terrain ruggedness (*R*), and habitat cover type weight (*X*) (Table 1). The formula used was developed by Sanderson and Fisher (2013; model 11-13):

$$\text{Habitat} = (T + R) * W * HII * X,$$

where tree cover (*T*) was 1 if 1% < cover <= 50% in the north or 1% < cover <= 100% in the south; ruggedness (*R*) was 1 if in intermediate, moderate, or high class (unclear how classes were generated, possibly equal-area following Riley et al. (1999) where 161 < *R* < 958); distance from water (*W*), based on HydroSHEDS (threshold not defined), was 1 if <= 10 km; and human influence index (*HII*) was minimal, but equaled 1 if *HII* < 30 (Sanderson et al. 2002; Table 1).

**Table 1.** Variables and threshold values used in binary model of habitat for the Draft Jaguar Recovery Plan from Sanderson and Fischer (2013).

| Variable | 1 | 0 |
|---|---|---|
| Tree cover | 1-50% (northern NRU areas)<br>1-100% (southern NRU areas) | <1% or >50% (northern NRU areas)<br><1% (southern NRU areas) |
| Ruggedness | Intermediate, moderate, and high | Level, nearly level and extreme |
| Distance from water | <10 km | >10 km |
| Human influence | HII < 30 | HII >= 30 |

## Methods

We used the same jaguar event-record data (compiled for and used in the Draft Recovery plan). When accessed (January 31, 2017), the jaguar dataset contained 229 observations. Roughly half of these observations were represented as polygons (*n* = 105), and we excluded these, as the variability of our explanatory variables within each of the large polygonal areas is very large. We retained data for only 48 point locations that met the following criteria: they had reliable geographic coordinates; were considered defined or determined points within the states of

Arizona, Chihuahua, Sinaloa, and Sonora; and were observed within the last century (i.e., since 1917).

We considered each of the explanatory variables included in Sanderson and Fisher's (2013) model, and describe below the development of our revised habitat model, in which we: (a) leveraged more recently available landscape data at 30-m resolution (a 1000-fold increase in resolution); (b) estimated continuous rather than binary habitat suitability; and (c) re-examined the model logic to evaluate potential habitat use (or quality) as a function of availability within the study area. We also revised the study area for which this model was developed to extend beyond the defined NRU, because we were using refined data and a gradient-based model, we wanted to be able to examine the support of this modified model to support refinement of a map of suitable habitat extent (Figures 1 & 2). We derived this model in Google Earth Engine (GEE), a powerful cloud computing platform for efficiently processing and integrating large datasets, and provide GEE-generated maps of data inputs and model outputs.

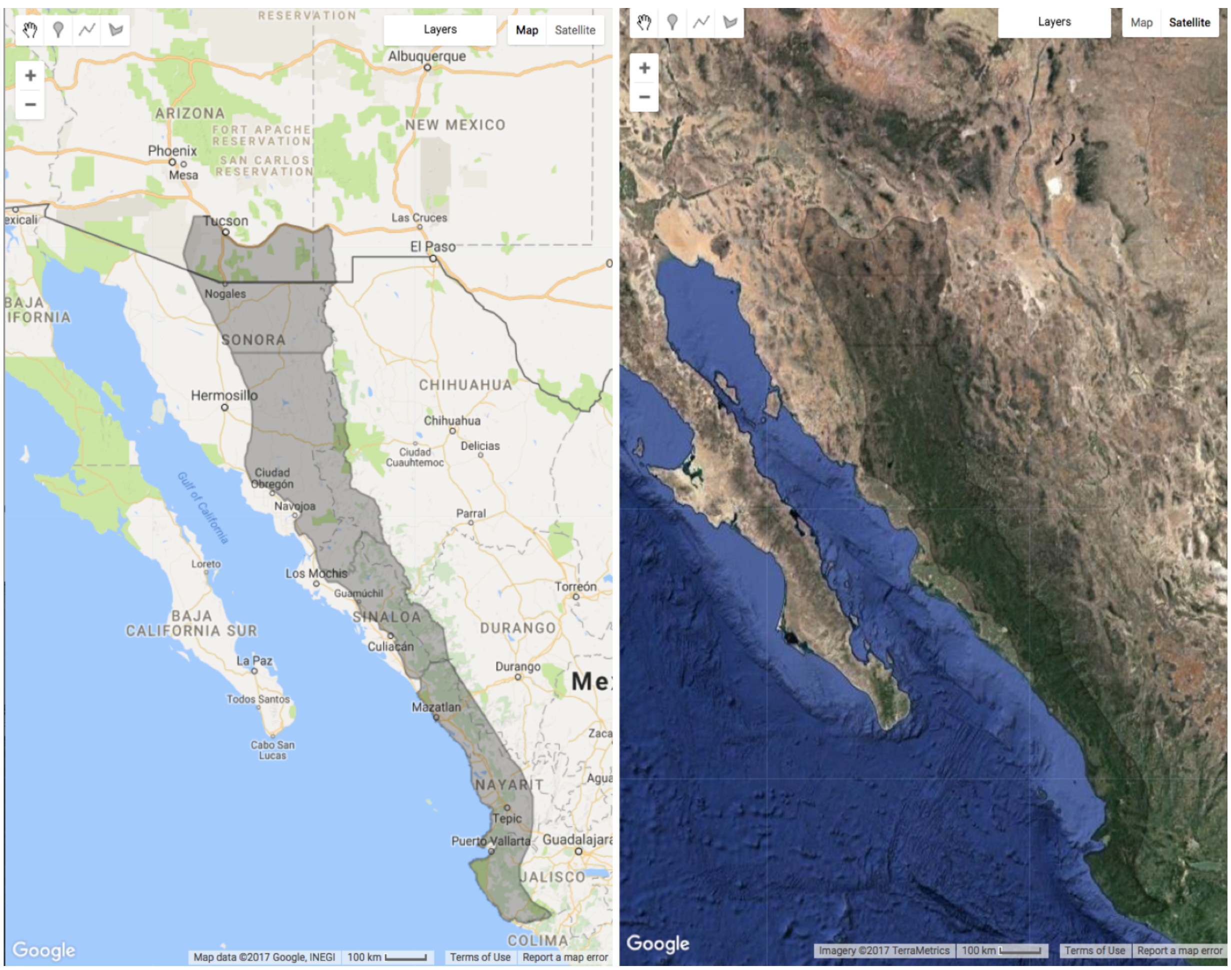

**Figure 1.** The study area for this work is the full extent shown here, which contains the Northwestern Jaguar Recovery Unit, with an extension to the north (not shaded but bounded by Interstates 40 and 25 between Flagstaff, AZ and Albuquerque, NM). Note that input layers for our model were wall-to-wall in the visible extent, and we did not use any additional boundaries to clip or remove other areas (e.g., the Baja or areas outside of the NRU).

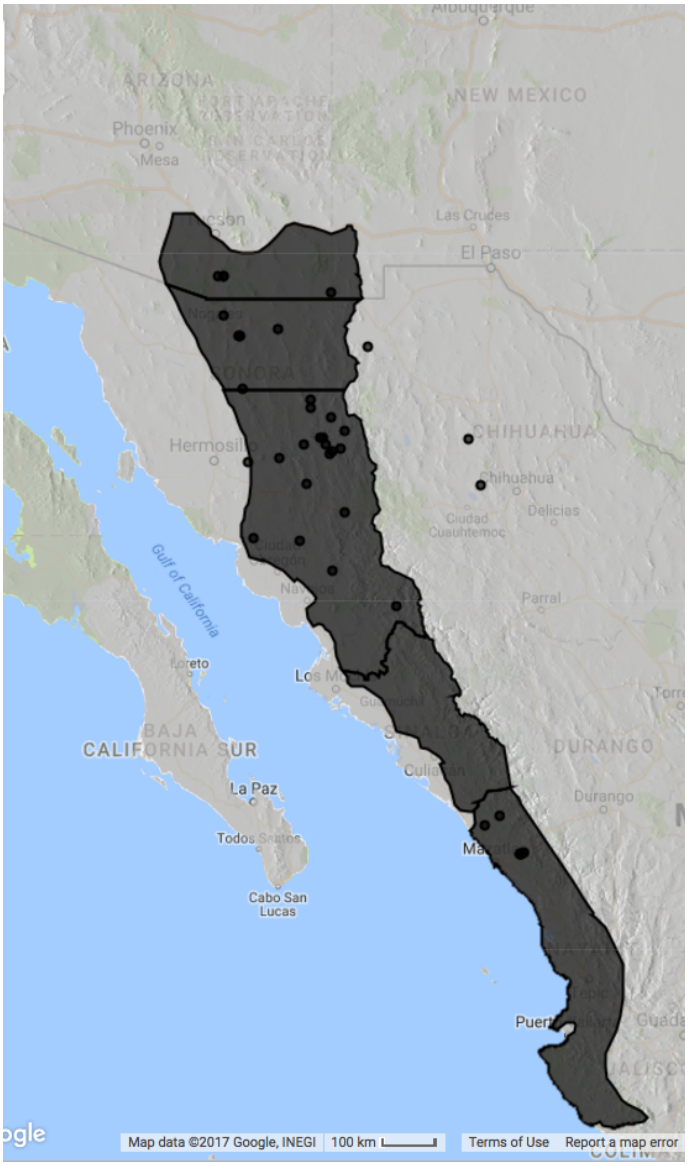


**Figure 2.** The 48 reliable locations of observed jaguars (as black dots) used in this study, drawn on top of the Northwestern Recovery Unit for reference. All of the 48 locations were used in our model.

### Tree canopy cover

Our assumption in the revised model was that habitat use by jaguar increased with increased percent canopy cover. To examine this, we used tree canopy cover (*TCC*) data from the Global Land Cover Facility's Landsat Tree Cover Continuous Fields (www.landcover.org; Sexton et al. 2013) and calculated the average canopy cover (0-100%) for 2005 and 2010 to minimize some abrupt changes in *TCC* that appeared as stripes in the data that appear at different locations in each of the datasets (i.e. at the edge of Landsat tiles). The average *TCC* was 12.48%. We examined the full distribution of *TCC* within the Northwestern Jaguar Recovery Unit polygon to represent the availability of different percent cover classes, and we then calculated, at 5%

increments, an odds-ratio of the proportion of the number of observation points to the proportion of the number of landscape raster cells covered by a given *TCC* increment to compare habitat use to availability. *TCC* increment classes that are used disproportionately to their availability in the landscape are assumed to be preferred by jaguars; likewise, *TCC* classes that are used less frequently than expected based on their availability are assumed to be avoided. We then fit a simple exponential model to these observed odds ratios, which yielded the following relationship:

$$y = 0.0487e\ (0.0386 \times TCC),$$

where *y* is the relative probability of jaguar use of a raster cell with percent cover *TCC*. Our model had an $R^2$ of 0.768, suggesting a good fit to the data (Figure 3).

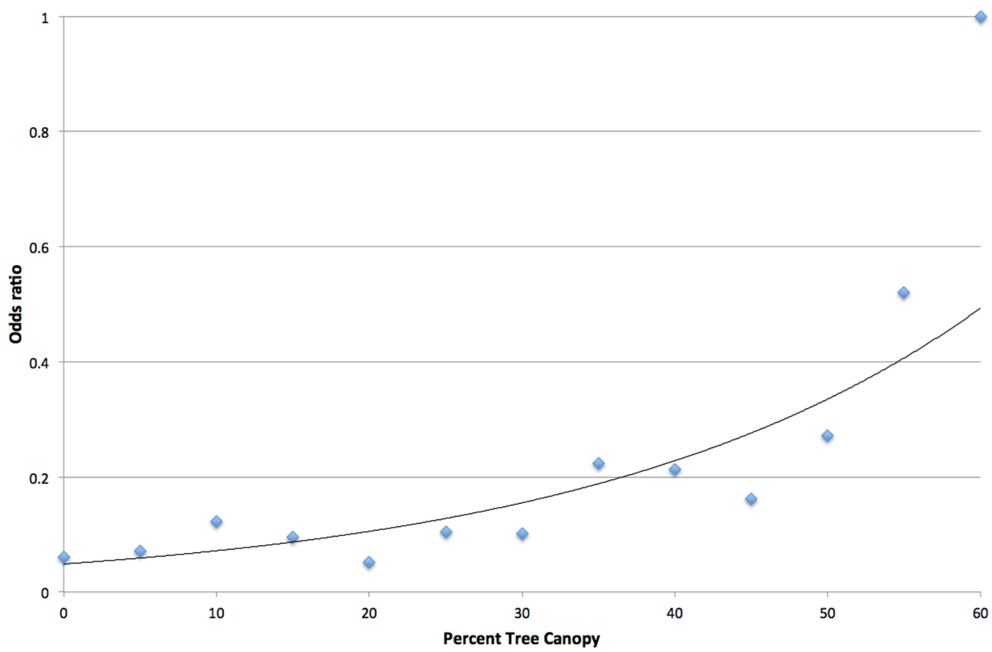


**Figure 3**. An exponential model assuming that habitat use increases with increasing tree canopy cover, fit to observations.

### Topographic position

Topographic position indicates where a particular location lies relative to surrounding slopes (e.g., ridge versus valley). We calculated a topographic position index (*TPI*) using a 30-m resolution digital elevation model (*DEM*) from the Shuttle Radar Topography Mission v4 (Jarvis et al. 2008). We used a multi-scale *TPI* in which topographic position was derived using an 810 and 2430 m radii neighborhood, and then combined by averaging the values (Theobald et al. 2015). *TPI* also allows valley bottoms to be distinguished from ridge tops, which presumably offer very different degrees of exposure/cover for jaguar. We considered calculating a terrain ruggedness index, but this index is calculated using a 3x3 window of neighbors, it is very sensitive to the DEM resolution used, and it does not distinguish exposed ridges from narrow valley bottoms. Therefore, we felt it was inappropriate for estimating the influence of topography on jaguar habitat suitability at fine-grained scales.

We calculated the odds-ratio of *TPI* values at observed locations against the distribution of *TPI* values (at 10-m *TPI* intervals) across the NRU, and then fit a polynomial model to estimate the relationship:

$$y = 0.00008TPI + 0.00007TPI^2 + 0.0169,$$

where *y* is the relative probability of jaguar use of a raster cell with topographic position *TPI*. Our model had an $R^2$ of 0.794, suggesting a good fit to the data (Figure 4). For *TPI* values outside the range of topographic positions where jaguar observations occurred (i.e. < -130 and > 130), we set habitat suitability values at 0.1.

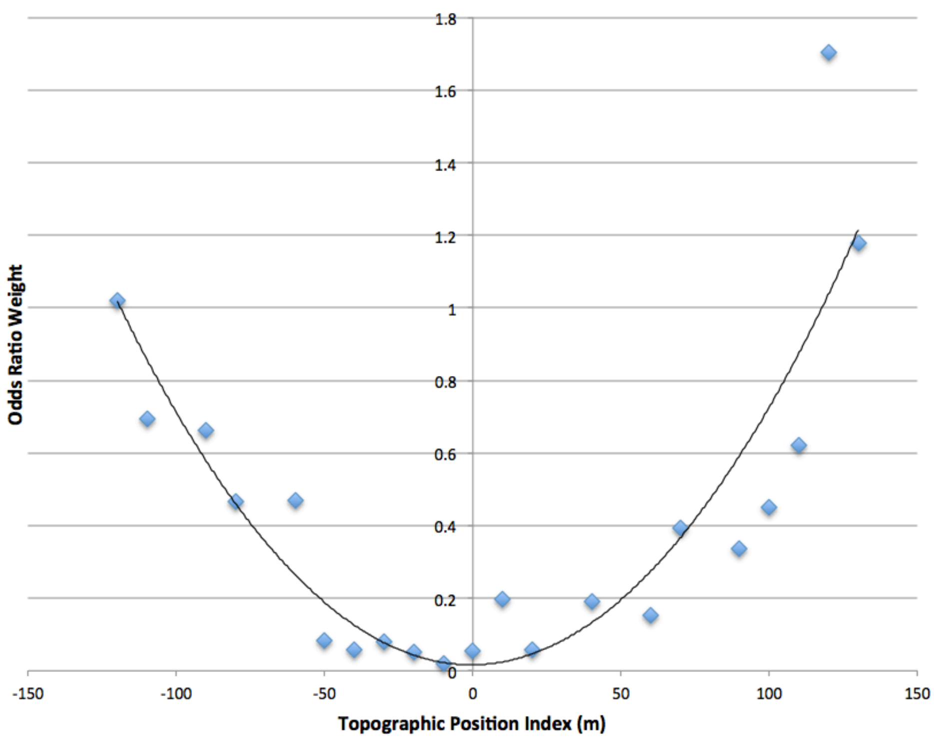


**Figure 4**. A second-order polynomial model of topographic position index values fit to observations.

## Distance from water

We did not include distance from water as a constraint on jaguar habitat suitability for three reasons. First, the poor quality of hydrologic data and the variability and periodicity of water in desert environments make it difficult to adequately and accurately represent availability of water across the study area landscape. The Sanderson and Fisher (2013) model represented "water" by identifying potential streams/rivers using HydroSHED data, but details were not provided in their report. We deduce from some unpublished graphics that the streams were represented at ~1 km resolution, and the accumulated upstream watershed area exceeded a threshold of ~500 $km^2$ (K. Fisher, pers. comm. March 2017). Although this is fairly common practice, estimating the presence of a stream based on watershed area alone does not incorporate information about precipitation or evapotranspiration, and in the NRU region, larger potential flow accumulation values do not translate well to actual presence of reliable water sources. This is because the region encompasses many small mountain streams with ephemeral water that occur in areas with relatively little upstream watershed area, as compared to larger upstream watershed areas that occur where alluvial washes have water very infrequently. Moreover, springs, stock tanks, cienégas, and other local features are likely important water resources for jaguar and their prey, and might contribute significantly to spatial patterns of water availability, but these sources are very difficult to reliably map. Second, if the assumption that distance to water is a proxy for presence of riparian areas and higher density of habitat, then the *TPI* index already represents valley bottoms in a much more discerning way. Finally, because of the dispersed pattern of the hydrologic network, most of the landscape is within 10-km distance of the modeled streams, and so this factor does little to narrow jaguar habitat suitability in the unique geography of this region.

**Human influence**

We calculated a higher resolution and more robust measure of human influence than that used by Sanderson and Fisher (2013). The degree of human modification (*H*, Theobald 2010, 2013) integrates measures of both the footprint extent and relative intensity of many forms of human influence on the landscape in a comprehensive and parsimonious way. Values are on a ratio scale and range from 0.0 (no human modification) to 1.0 (highly human modified). *H* was mapped using 30--90-m resolution data, including land cover data (30 m) from the National Land Cover Dataset 2011, global land cover for Mexico (30 m; Chen et al. 2015), global human settlement data (300 m; Pesaresi et al. 2015), VIIRS night-time lights (400 m), and a detailed 2016 road map from Open Street Map (with adjusted weight for number of lanes). Therefore, *H* improves on Sanderson and Fisher’s (2013) human influence measure with much higher resolution, more contemporary datasets, and explicit incorporation of both intensity and footprint of human disturbance.

The mean *H* value at sites of jaguar observations was quite low: 0.055 (median=0.02, SD=0.10). Because the *H* values were quite low and the distribution was skewed with many low values at the observed locations, we decided to transform *H* into a naturalness value (*N*) that reflects an assumption that high jaguar habitat suitability is inversely related to the presence of human modification. We used an exponential function:

$$N = (1 - H)^2$$

that assumes habitat use is related to “naturalness,” which is the inverse of *H* but declines exponentially (Figure 5).

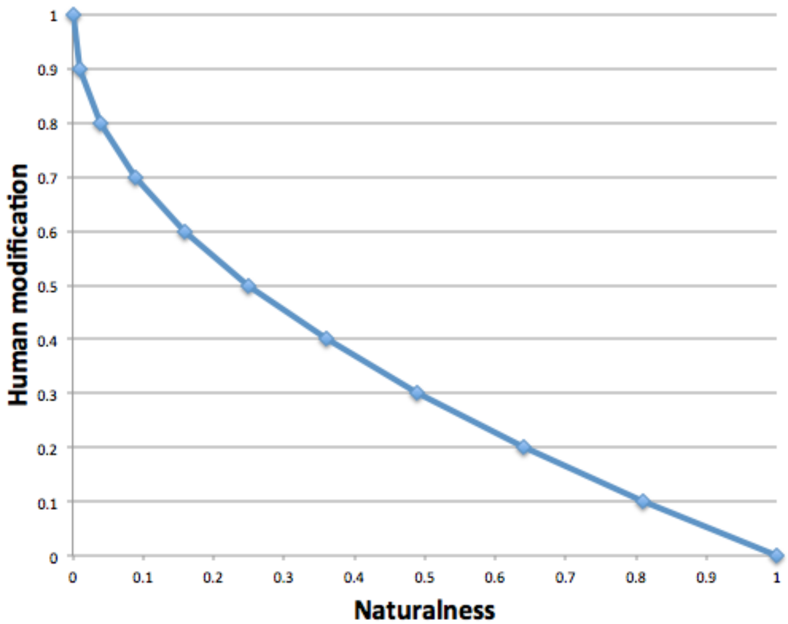


**Figure 5.** An exponential model transforming the degree of human modification to a naturalness value.

### Elevation

Sanderson and Fisher (2013) removed habitat that exceeded 2000 m in elevation: "[b]ecause only 20 events occurred above 2000 m, the JRT technical subgroup decided to mask out areas above 2000 m." We decided that an elevational threshold was not substantiated, because 20 observation events above 2000 m substantiate some jaguar use (20 events out of $n$ = 102 or 203, depending on evidence types selected in Sanderson and Fisher (2013) is 10-20%). Moreover, a histogram of elevation (Figure 6) in the NRU shows that higher elevation locations are fairly rare, suggesting that any use at higher elevations (>1500 m) may actually show preferential use, after accounting for low availability of high-elevation areas. We also note that *TPI*, which is an index of relative elevation, captures some of these effects.

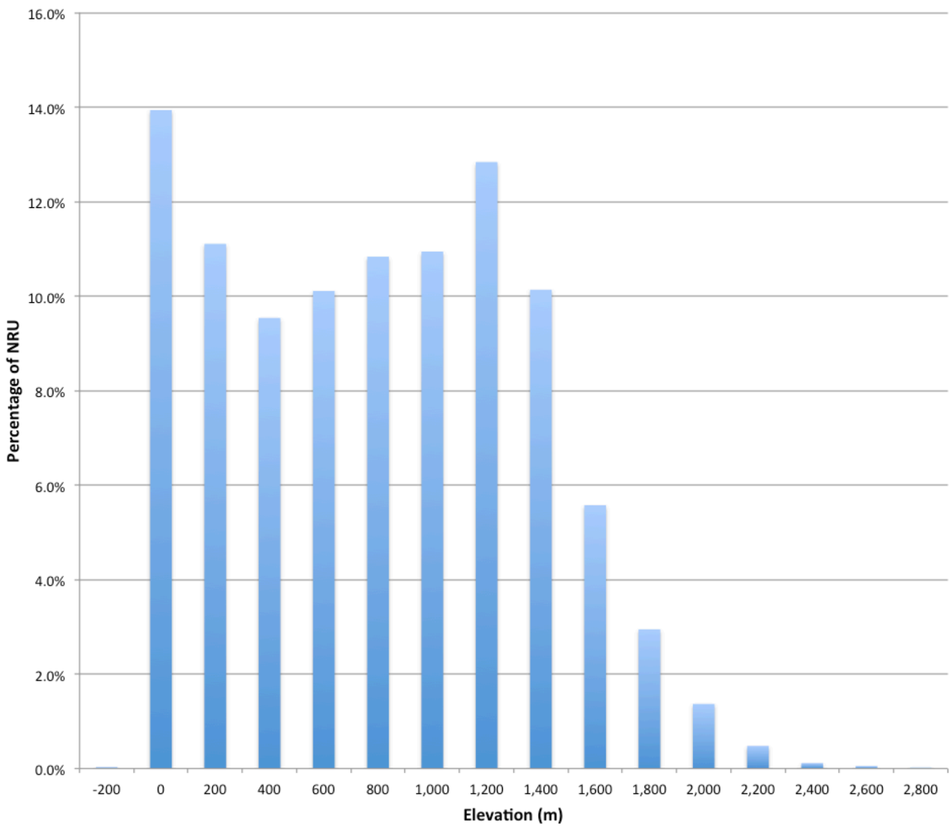


**Figure 6**. A histogram of elevation (x-axis in meters) in the Jaguar Northwestern Recovery Unit area.

### High habitat suitability and cores

We calculated habitat suitability (*S*) as the product of the three variables, representing the habitat quality related to tree canopy (*TCC*), topographic position (*TPI*), and human modification (*N*):

$$S = TCC * TPI * N.$$

We used the product of the variables because it is more robust to the distributions underlying each variable than addition (Tofallis 2014). For each pixel, we then calculated the average *S* value within a 100 km$^2$ circular area (i.e., 5,641-m radius), which was identified by the Jaguar Recovery Team as the minimum area needed to support a jaguar, and has also been used as the minimum patch size for corridor modeling (Stoner et al. 2015). We then identified "cores" of high habitat suitability by applying two arbitrary but standard thresholds ($S_{75}$, $S_{90}$) where cells with S values exceeding the 75th and 90th percentile of *S* formed contiguous patches at least 100 km$^2$ in area.

Note that Sanderson and Fisher (2013) applied as a final step a "habitat weight" in order to estimate overall jaguar density in the NRU. We did not perform this step because our goal was to map potentially suitable habitat and structural connectivity within and surrounding the NRU, rather than to estimate density.

**Connectivity model**
We estimated connectivity using circuit theory models. We modeled connectivity using Circuitscape (McRae et al. 2013) which borrows concepts from electronic circuit theory to estimate ecological flow (e.g., movement of individuals, gene flow; McRae 2006, McRae et al. 2008) among core areas, or the probability of movement from a source to a destination passing through a raster cell given its resistance to movement. Specifically, circuit theory models are useful for identifying 'pinch points', or bottlenecks, where flow is highly constrained as it passes through limited natural areas embedded in modified or otherwise highly resistant landscapes. These pinch points are likely to represent important conservation opportunities, where imposing a barrier to movement would cause disproportionate loss of connectivity.

We estimated resistance based on degree of human modification to identify pinch points where natural areas, regardless of other characteristics (i.e., canopy cover, topography) are most constrained by human influence. We rescaled degree of human modification ($H$) to range from 0 to 1, then applied a *Power(10)* transformation and converted to integer values using a multiplication factor of 10,000, as Circuitscape has difficulty solving networks with narrow ranges of values. We identified centroids of each 75$^{th}$ percentile core area as source nodes for Circuitscape models. Use of centroids as source nodes rather than complete core polygons not only speeds implementation, but also allows estimation of current flow within core areas rather than treating them as uniformly zero-resistance patches (e.g., Dickson et al. 2016). Designation of $S_{75}$ cores resulted in delineation of one very large core in the center of the study area (see Results below). In the case of this core, we 'shrunk' core edges inward by 900 m to separate it into two discrete patches at its narrowest point, then identified the centroid of each of the two resulting patches. Use of multiple points to represent the north and south portions of this large, central core resulted in better distribution of current flow throughout its area.

We implemented Circuitscape in one-to-all mode, in which one node at a time is charged with current and all other nodes are grounded, iterating and summing over all nodes (McRae et al. 2013). This mode allows estimation of ecological flow from each potential source to all potential destinations in the landscape, which we suggest is most realistic for representing natal dispersal processes. Circuitscape is computationally intensive, and speed and memory requirements increase exponentially with number of raster cells in the landscape and number of nodes connected. In order to achieve reasonable computation time (days rather than months), we reduced the analysis resolution to 540-m and limited connections among nodes to those < 100 km apart.

## Results
We calculated and mapped overall, continuous jaguar habitat suitability (Figure 7) and areas with suitability exceeding the 50th, 75th, and 90th percentiles. From the 75$^{th}$ and 95$^{th}$ percentiles of habitat suitability, we extracted "cores" that were at least 100 km$^2$ in area (Figure 8). We then calculated potential connectivity using Circuitscape to calculate current flow between 75$^{th}$ percentile cores (Figures 9 & 10). We also calculated potential connectivity using

Circuitscape at higher resolution (90 m) for a limited portion of the study area centered on the Arizona/Sonoran border (Figure 11).

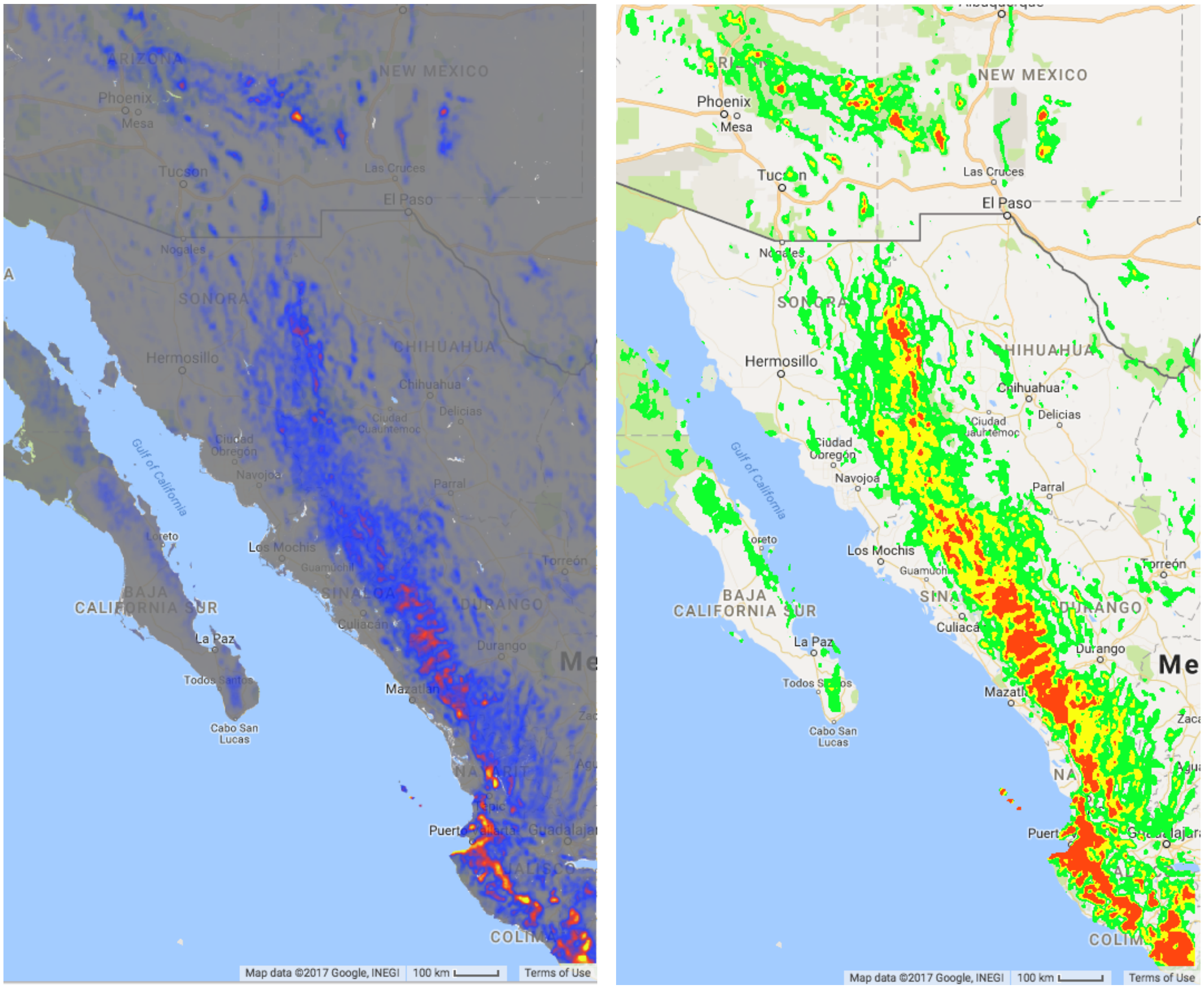

**Figure 7**. Potential northern jaguar overall habitat suitability (left) calculated as a function of tree canopy cover, topographic position index, and naturalness (complement to the degree of human modification), with a 100 $km^2$ averaging window. The range of habitat suitability quality is shown using a linear stretch ranging from bright yellow (high) to red (moderate) to blue (low). We also identified (right) high suitability habitat exceeding $50^{th}$ (green), $75^{th}$ (yellow), and $90^{th}$ (red) percentiles.

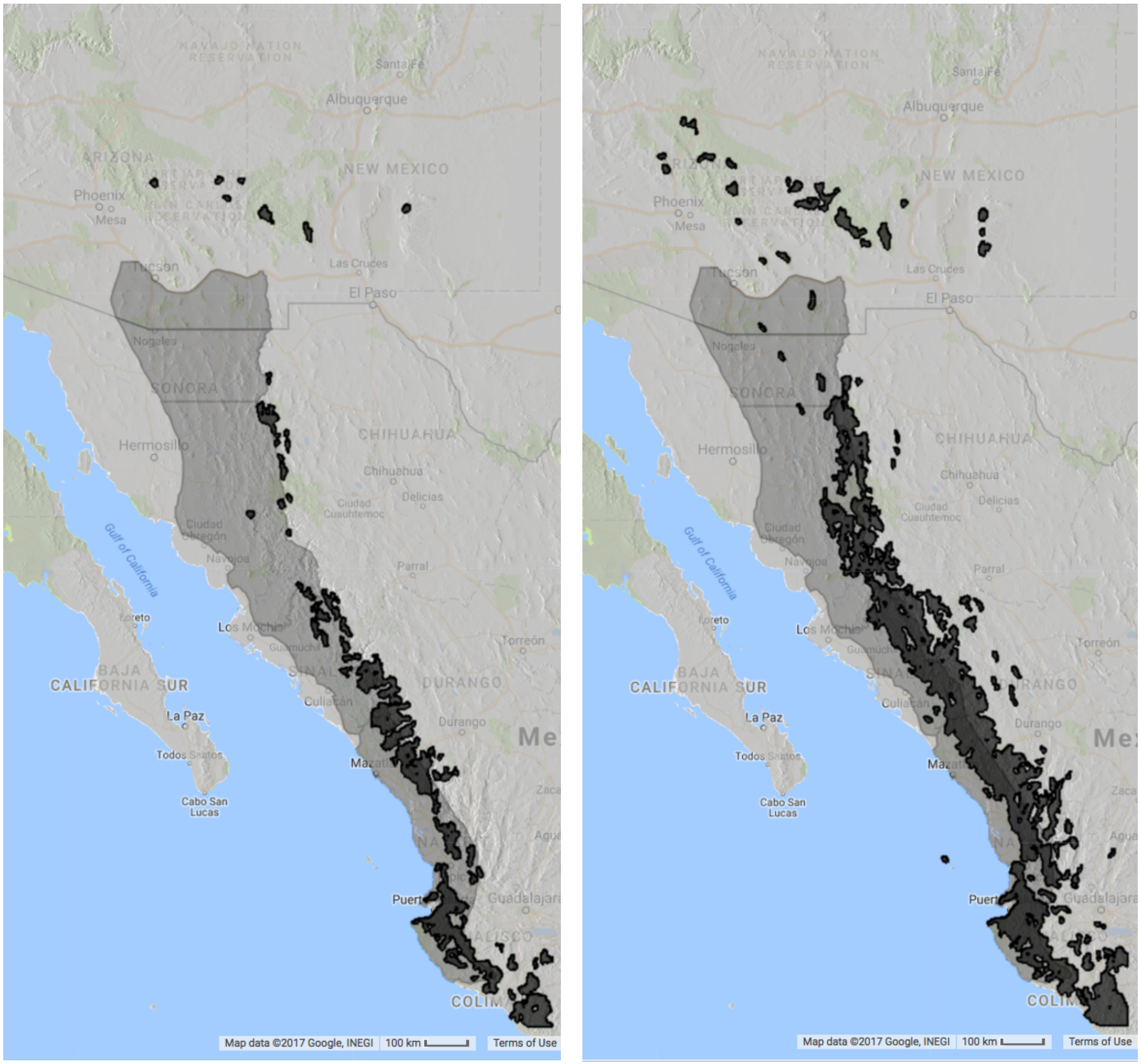


**Figure 8.** Core habitat areas > 100 square kilometers in area (shown as black outline and filled polygons), identified using 90th percentile (left) and 75th percentile (right). The Northwestern Recovery Unit is drawn as well for reference (in grey). We found 219 and 346 “cores” at the 90th and 75th percentile, respectively. Note that we did not artificially remove potential habitat areas from the Baja Sur, but these areas were removed because they did not contain 100 $km^2$ core areas. Also note that many of the identified cores lie along or outside the eastern edge of the NRU boundaries.

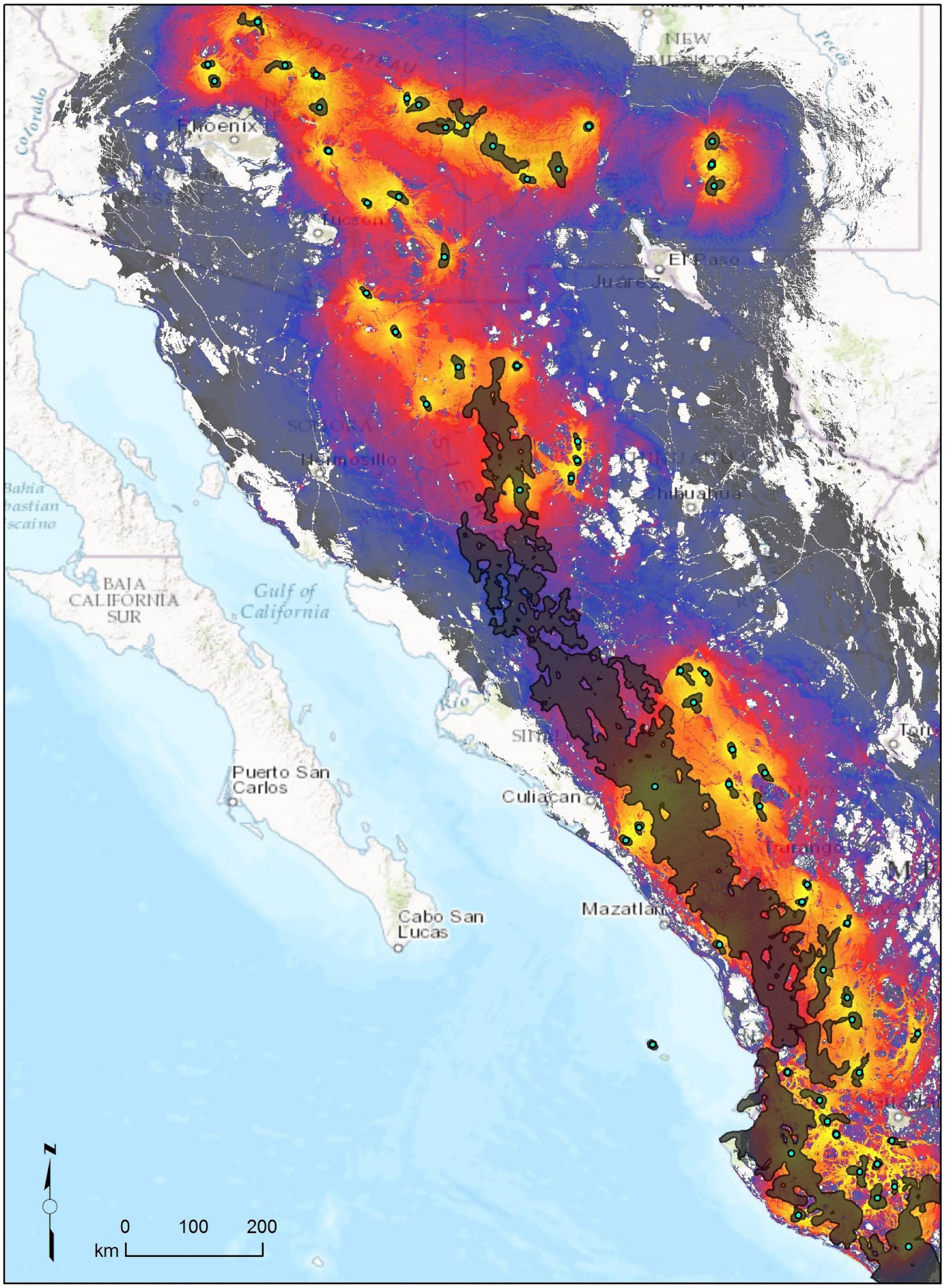


**Figure 9.** Potential connectivity modeled using Circuitscape from the centroids of 75th percentile suitable habitat cores. Areas of higher current flow (connectivity) are shown in yellow, moderate in red/blue, and low in dark blue/grey. Cores are shown in black, and core centroids are shown as turquoise points.

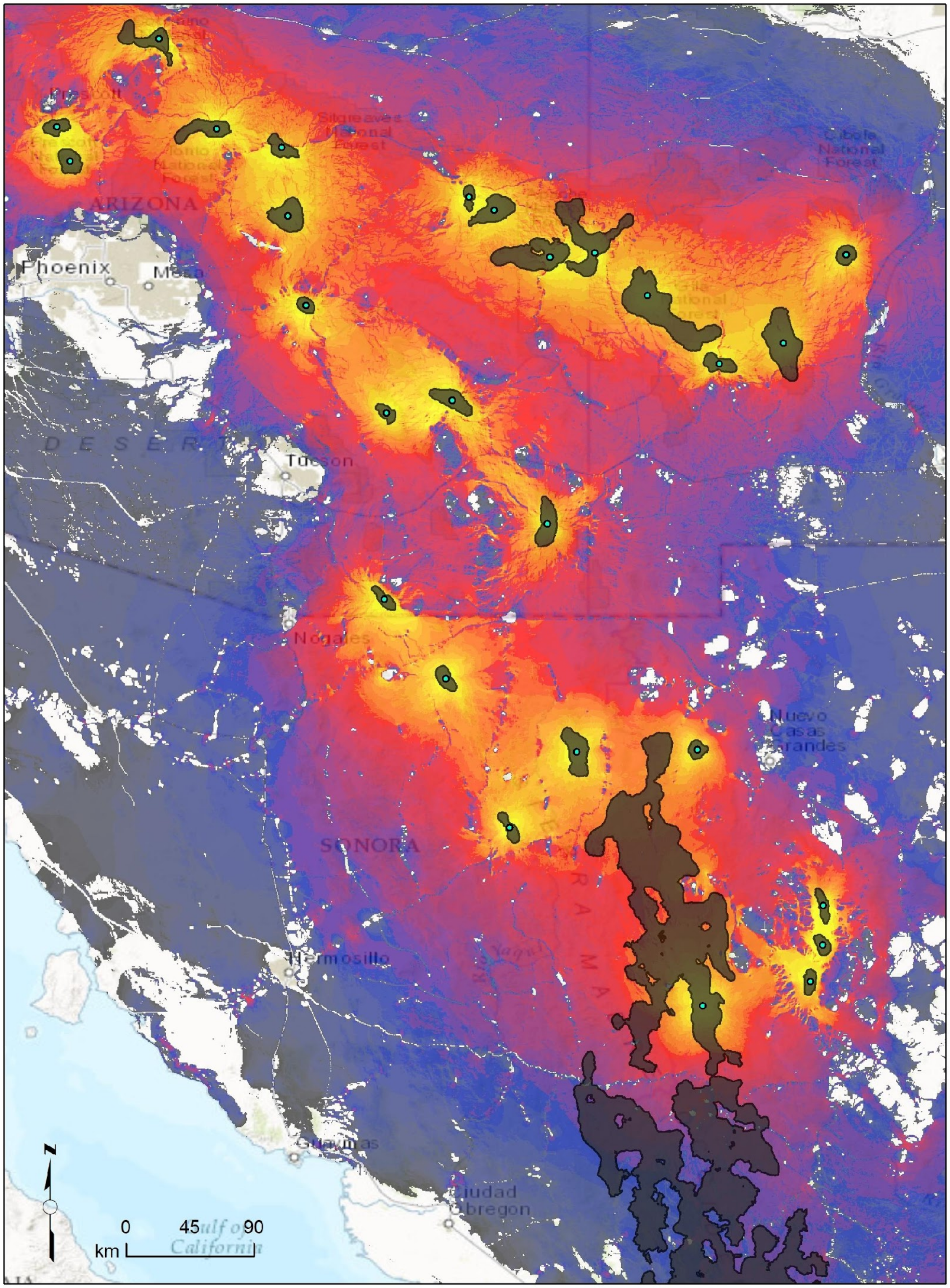


**Figure 10**. A zoom-in of an area on the US-Mexican border. Areas of higher current flow (connectivity) are shown in yellow, moderate in red/blue, and low in dark blue/grey. Cores from 75th percentile habitat suitability are shown in black, and core centroids are shown as turquoise points.

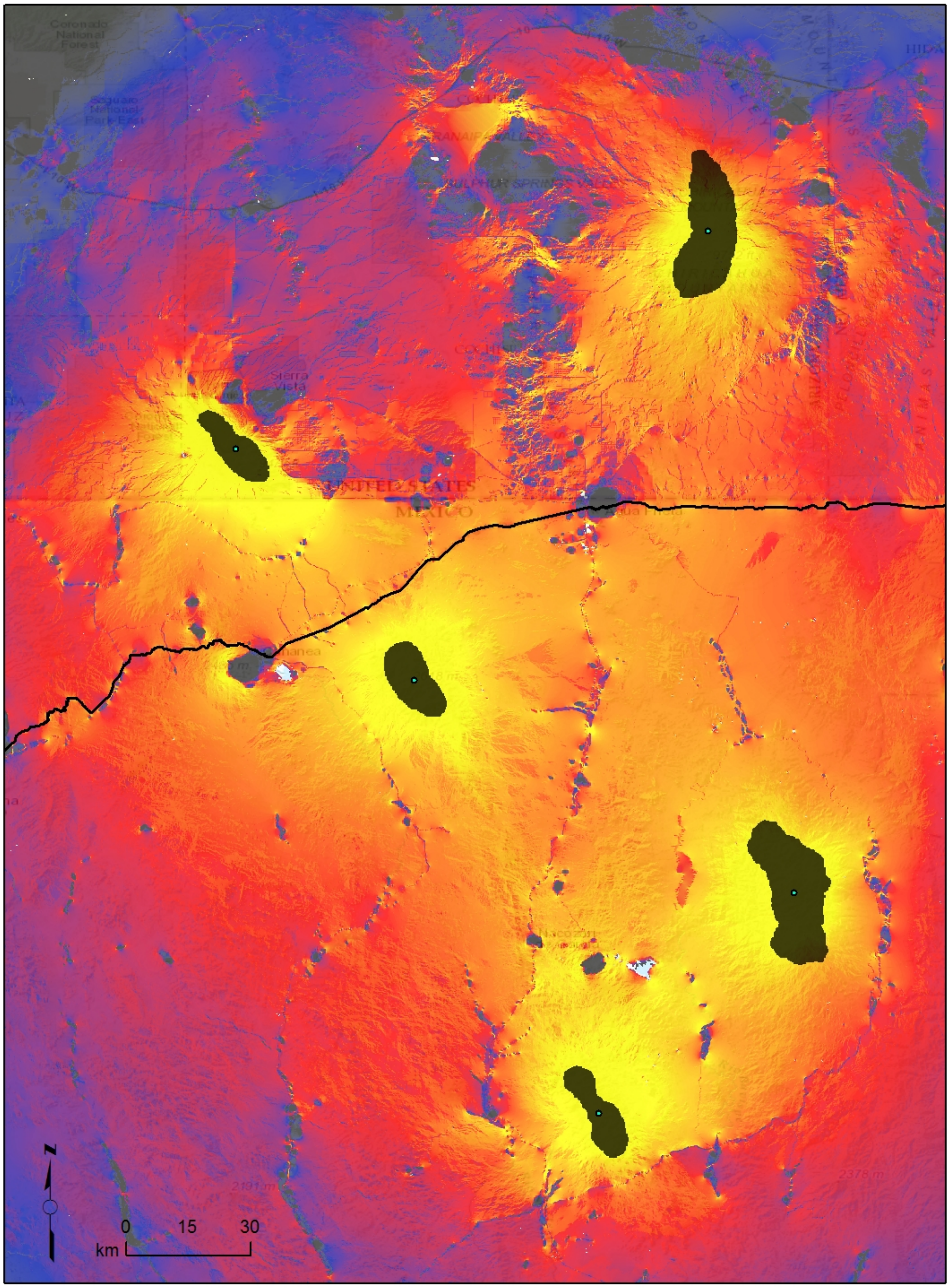


**Figure 11**. Connectivity results for southern Arizona and northern Sonora using a higher resolution (90 m) Circuitscape model run. US Interstate 10 is visible at the top of the image as a grey line winding east-west, and Mexican Federal Highway 2 is visible in the middle of the image as a black east-west line. Areas of higher current flow (connectivity) are shown in yellow, moderate in red/blue, and low in dark blue/grey. Cores from 75th percentile habitat suitability are shown in black, and core centroids are shown as turquoise points.

## Discussion

We mapped potential jaguar habitat and structural connectivity roughly following the guidance and logic developed by the Technical Subgroup of the Jaguar Recovery Team as reported in Sanderson and Fisher (2013), but also updated and refined this approach. Our refined model uses much finer-grained data (30 m vs. 1000 m) and represents gradients of habitat quality rather than a simple binary habitat model.

Our model suggests that jaguars show preference for greater tree cover, valleys and ridgelines, and lower human modification. Areas of highest suitability is variable, with a large central portion along the Sierra Madre, and 90$^{th}$ percentile cores are a more variable and disconnected, especially in northern portion of study area, whereas 75th and particularly 50th percentile cores are more connected. All but 7 observed locations fell within the 50th percentile, suggesting that these regions are generally traversable and used, and may also indicate the potential for movement between 90$^{th}$ percentile cores. We note that the observation locations are quite ad hoc and there is no formal statistical design that allows strong inference as to areas with little or few observations, as well as likely being biased to human accessibility

Connectivity model results suggest high levels of connectivity among northern cores and among southern cores, but little north-south connectivity (Figure 9). This may to some extent be an artifact of representing the single large core spanning the central portion of the study area as centroids of northern and southern sub-cores, divided at a very narrow natural breakpoint. These two sub-core centroids are far apart, and no other cores exist in the area between them, resulting in apparently little connectivity. However, this portion of the large central core also appears to have relatively low suitability (Figure 7) and is more 'permeable' compared to its northern and southern extremes, so it is likely that connectivity here is, in fact, relatively low as well.

The far southern portion of the study area appears to have more constricted pinch points among cores than in the north. In the north, current flow generally spreads smoothly out from core centroids, with some local-scale 'funneling' of current around highly developed places or across roads. In the south, however, flow among adjacent cores tends to be constrained to much more distinct, linear routes between more extensively modified areas of the landscape. These remaining paths offer important conservation opportunities.

Relatively few areas of high potential connectivity across the U.S.-Mexico border appear to exist. East of Nogales, our model suggests high potential flow between two cores in relatively close proximity on either side of the border. Provisions for jaguar in this area may be critical for their continued ability to move across the border if US border security measures continue to escalate. Maintaining connectivity from these two cores to nearby cores on each sides of the border will also be needed to ensure continued gene flow throughout the NRU via dispersal movements.

Overall, we found reasonable concordance between our models of potentially suitable habitat and connectivity with known observations -- both those used in our model, as well as the additional points *not* used in our model such as those found in Arizona (Figure 12). Note that we did not incorporate these additional points directly in the model because we were unable to obtain the precise *x,y* locations in the downloaded observation dataset, although the points are clearly viewable in the maps on the JaguarData.info website.

Our model also suggests that the existing NRU definition does not incorporate some potentially suitable and connected habitat presented in our results, both to the east in Mexico, as well as to the north in southern Arizona. These findings provide preliminary support for considering an extension of the boundaries of the jaguar recovery unit into these areas with suitable, connected potential habitat.

**Intended uses and caveats**

We intend these results to be useful in understanding potential suitable habitat that includes structural connectivity for jaguar extending beyond the NRU boundaries (up to roughly 300 km). Another key distinction between our model and that of Sanderson and Fisher (2013) is that we did not impose any factor that depicts the current estimated density of jaguars associated with different ecoregional areas (i.e., “habitat weights”). Also, we observe that 4 of the observed jaguar locations are not located in the NRU (as compared to 7 outside of the $S_{50}$ habitat).

The structural connectivity maps are intended to provide general guidance for potential jaguar connectivity between core habitat areas, but have only preliminary utility in identifying specific potential highway crossings at a very fine-scale or at the site-planning level (e.g., where movement would occur within < 3 km stretch).

It is important to consider that the observational data, while quite useful in generating general suitability models, are obtained on an ad hoc basis – and therefore do not represent a carefully structured study design. Due to the nature of the data used, model results may be affected by sampling bias, especially because we were unable to incorporate absence data. More appropriate data, particularly a stratified sample of presence-absence (Hirzel and Guisan 2002), would be ideal, but such data does not exist for the study area.

Finally, we mapped potential jaguar habitat and structural connectivity on the basis of relatively limited observations that were available, and we hope to update and further refine the model with additional observations.

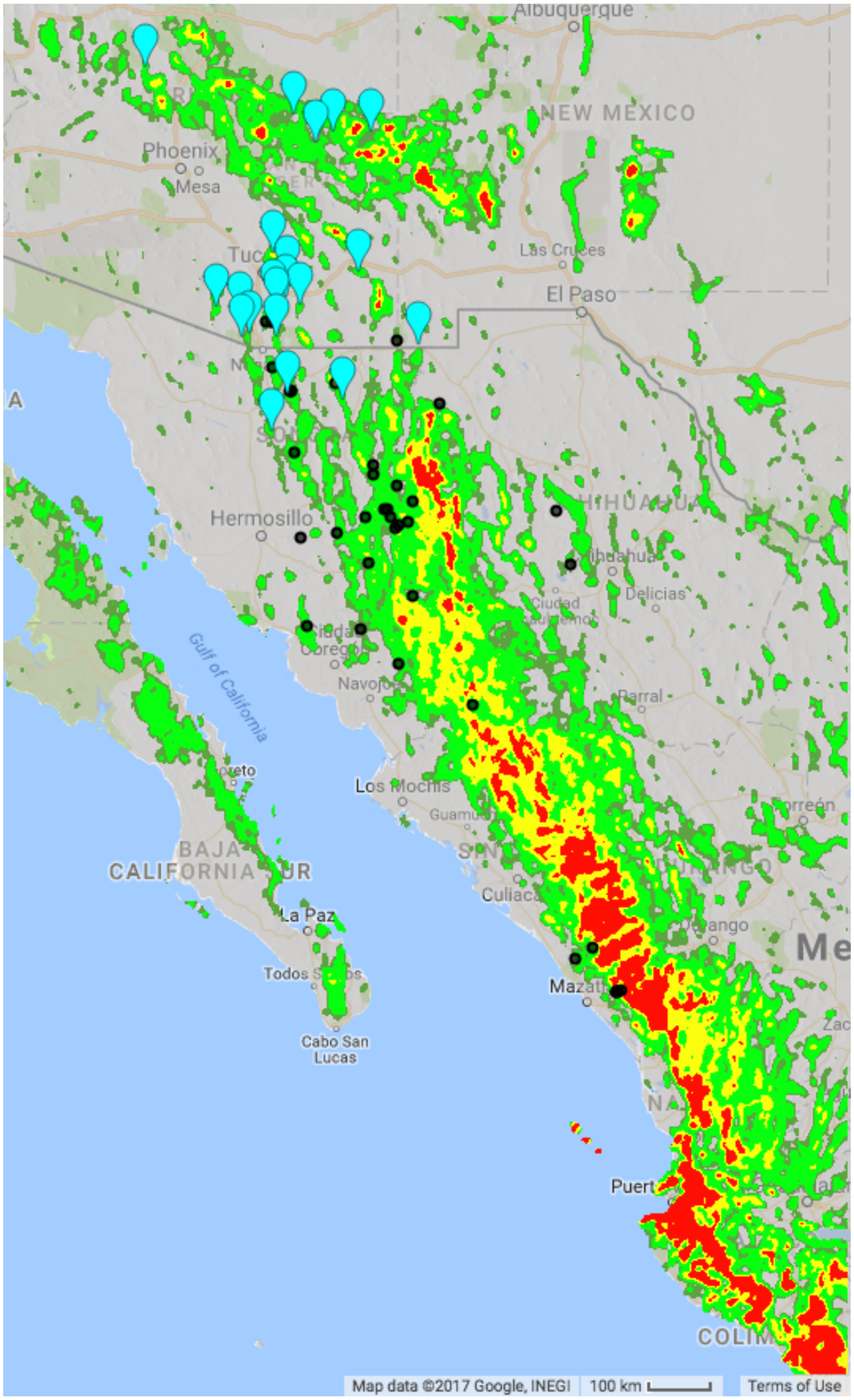


**Figure 12.** Our model of potential suitable habitat does a reasonable job predicting habitat compared to the locations of known jaguar observations. Points used in the model are shown as black dots, and additional ('validation') observations not included in the model are shown in cyan. The range of habitat suitability quality is shown ranging from high suitability habitat at 50th percentile (green), 75th (yellow), and 90th (red). Note that habitat on Baja California was too low and small to be considered habitat "cores" at 75th and 90th percentile.

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