# A systematic review of potential habitat suitability for jaguar *Panthera onca* in central Arizona and New Mexico, USA

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SUPPLEMENTARY MATERIAL 1 Summary of habitat analyses of the jaguar *Panthera onca* in Arizona and New Mexico, USA, during 2000–2019.

Below we review nine previous studies modelling jaguar habitat in the United States that cover areas north of U.S. Interstate-10 in Arizona and New Mexico. Each study is described in terms of its purpose, spatial extent, data inputs, methods, and results. Table S1 summarizes this information in one table for easy comparison. Figure 2 in the main text shows each model result on individual maps; Figure 3 shows their spatial overlap. Studies are presented in chronological order of publication. Three additional models, computed for this study, are described in the main text: extensions of Model 13 (i.e. Model 14 and Model 15) and a re-analysis of the Hatten et al. (2005) model.

*Sierra Institute (2000)*

Purpose: The Sierra Institute Field Studies Program (2000) [Sierra Institute] created a model to identify areas in Arizona and New Mexico with current or future jaguar occupancy for the Habitat Committee of the Jaguar Conservation Team, a group of government and non-governmental organizations and other individuals concerned about the status of the jaguar in the United States. For a retrospective description of Jaguar Conservation Team activities, see Arizona Game and Fish Department (2020).

Extent: The model covered portions of southern Arizona and New Mexico, which were the primary focus of the Habitat Committee of the Jaguar Conservation Team. Western and eastern geographic boundaries were established using peripheral historical locations of jaguar as plotted with a 50-mi radii by the Arizona Game and Fish Department (Arizona Game and Fish Department, 1999). Southeastern New Mexico was included following historical jaguar presence (New Mexico Department of Game and Fish, 1999). Tohono O'Odham, San Carlos and Fort Apache [White Mountain] Indian Reservations were excluded from analysis.

Data Inputs: Topography (based on published U.S. Geological survey map at 1:500,000 scale); road maps; Sierra Institute Field Studies Program land development data; satellite imagery of southeastern Arizona (provided by Arizona Game & Fish Department at 1:230,000 scale); riparian areas (Valencia et al., 1993).

Method: Habitat suitability categories were mapped following habitat suitability criteria developed by the Habitat Committee of the Jaguar Conservation Team, based on the Jaguar Conservation Agreement (Arizona Game and Fish Department, 1997). Three habitat suitability categories were assigned: unsuitable habitat, suitable habitat or secondary habitat. Unsuitable habitat consisted of areas that would not support jaguar occupancy (e.g., areas of high human activity or impact). These areas were mapped as agricultural, residential and industrial lands with the aid of road maps, Sierra Institute Field Studies Program data on land development in the region and satellite image of southeastern Arizona. Colorado River Sonoran desert scrub was also designated as unsuitable habitat (Brown, et al., 1980). Primary habitat was defined as areas that meet all of a jaguar's biological requirements (e.g., prey, cover, water). Primary habitat was mapped to incoroproate important geographical features including riparian areas, major connective wash complexes, mountain ranges and associated canyons and washes. Secondary habitat was defined as areas less likely to be used by the jaguar that may only meet part of its biological needs; jaguars may temporarily occupy such habitat but not establish permanent residence. All areas not designated as unsuitable or primary habitat were mapped as secondary habitat. The importance of an adequate prey base and water availability were recognized but information on prey densities and surface water were not available, and so were not explicitly addressed in the mapping of habitat suitability.

Results: The study region's mountain ranges including associated canyons, riparian areas, and major washes and wash complexes constituted primary jaguar habitat. The largest blocks of contiguous habitat included the Baboquivari Mountains – Altar Valley washes; the mountains and highlands associated with the lower Santa Cruz River; the Cienega Creek area and adjacent mountains; Santa Catalina and associated mountains to the southeast; the Upper Aravaipa Valley and nearby mountain ranges; the Chiricahua Mountains and associated mountain ranges; the southern Peloncillo Mountains with the San Bernadino and Animas Valley wash complexes; the central Arizona – New Mexico Mountains (from the Black River north to the San Francisco Mountains and east to the Leopold Wilderness area – Nimbres Mountains region); and the Animas Mountains and nearby ranges. The study also identified important connecting habitats in Agua Verde Creek – Davidson Canyon, the San Pedro River and associated washes, the Dos Cabezas Mountains, the northern Peloncillo Mountains, and the San Simon wash complexes.

*Sanderson et al. (2002b)*

Purpose: A comprehensive assessment of the state of knowledge about the ecology, distribution, and conservation status of the jaguar was conducted at the turn of the century to identify priority areas for its conservation on a range-wide basis and to build an international consensus for conservation of the species.

Extent: The historic range of the jaguar around 1900 (Seymour 1989), extending from the United States to Argentina.

Data Inputs: Expert opinion from thirty-five researchers and managers as listed in appendix to Sanderson et al. (2002b, 2002c). Experts compiled maps on the geographic extent of knowledge of jaguar status and distribution; the areas where jaguars were present as of March 1999; important areas for jaguar conservation ("jaguar conservation units"); and point localities where jaguars have been observed between 1989 - 1999.

Method: Prior to a workshop, experts received based maps at 1:2,000,000 - 1:4,000,000 scale to self-report the data types listed above. Through a collaborative workshop process, these data were compared and synthesized in regional groups to resolve contradictions and build a consensus information base. One of those groups focused on the northern part of the jaguar's range in Mexico and the United States. Point localities were aggregated and obscured in circular areas with a 10 km radius.

Results: Within the United States only three locations were noted with respect to jaguars, based on observations in the late 1990s (Glenn, 1996; Childs et al., 2008). Three point locations were represented by circles with 10 km radii in the Baboquivari and Peloncillo mountain ranges. The historical range of the jaguar in the United States was limited to habitat types that extended into northern Mexico, the "Mexican / Xerics", including the Sonoran and Chihuahuan Deserts. Seymour's (1989) map did not recognize jaguar observations as far north as the observations documented in Brown and Lopez-González (2001) or as noted in the Sierra Institute Field Studies Program (2000) report.

*Menke and Hayes (2003)*

Purpose: : In 1997, state, federal, and local governments with land-management responsibilities agreed to characterize and identify potential jaguar habitat in Arizona and New Mexico (Hatten et al., 2002, 2005). Menke and Hayes (2003) were contracted by the New Mexico Department of Game and Fish to evaluate the relative suitability of potential jaguar habitat in New Mexico. See Hatten et al. (2005) below for the Arizona analysis and Robinson et al. (2006) for a complementary analysis in New Mexico.

Extent: Menke and Hayes (2003) studied areas within 50 miles of jaguar observations accompanied by physical evidence (Class 1) or reported as first-hand observations from a reliable source (Class 2; see definitions in Tewes and Everett, 1996) within the State of New Mexico. They included only those sightings that were reported with sufficient locational precision to reliably plot and analyze their locations. For example, the study area definition did not consider sightings that were reported only with general locations e.g., "Otero County". The study area boundary was expanded to include entire New Mexico Big Game Management Units (see New Mexico Game and Fish Department, 2016) that intersected the 50-mile buffer, to be inclusive of (as opposed to bisecting) contiguous mountain ranges and potential prey populations.

Data Inputs: Due to the small number of documented jaguar locations, Menke and Hayes (2003) did not attempt to determine patterns of habitat use for jaguars in New Mexico. They identified positive and negative potential habitat features for jaguars based on literature sources and evaluations from the Jaguar Habitat Subcommitte and Jaguar Scientific Advisory Group (Miller et al., 2000) and in the analysis of potential jaguar habitat in Arizona (Hatten et al., 2002). The variables were:

- Road density (U.S. Census Bureau 2000)
- Vegetation community (specifically Madrean Evergreen Forest, sourced from Brown et al., 1980)
- Distance to water (see U.S. Geological Survey, 2004)

- Prey abundance for selected species, including collared peccary (*Tayassu tajacu*) (New Mexico GAP Analysis – see Prior-Magee et al., 2007), white-tailed deer (*Odocoileus virgianus*) (New Mexico GAP Analysis), mule deer (*O. hemionus*) (New Mexico GAP Analysis), elk (*Cervus elaphus*) (Rocky Mountain Elk Foundation – see Rocky Mountain Elk Foundation, 2013), and coatimundi (*Nasua nasua*) (New Mexico GAP Analysis)
- Terrain ruggedness (see USGS, 2017; calculated based on method in Riley et al., 1999).

Method: Menke and Hayes (2003) combined the five potential habitat variables (road density, vegetation community, proximity to water, prey availability, terrain ruggedness) into a relative habitat suitability model with a weighted overlay operation. They classified the results of the combined potential habitat grid into five suitability categories based on natural breaks in the data.

Results: Two locations within the study area contained relatively contiguous blocks of land that fell within the two highest relative suitability classes: the Animas/Peloncillo Mountains of extreme southwestern New Mexico, and portions of the Gila/San Francisco River drainages on the far west-central portion of the study extent. The more rugged and remote portions of the Sacramento Mountains were also identified as having high potential habitat suitability, but were surrounded in all directions by areas of lower habitat potential.

*Boydston and González (2005)*

Purpose: Boydston and González (2005) examined the difference in ecological niche modelling between male and female jaguars in the southwestern U.S. and northwestern Mexico. They test the assumption that males would show a broader ecological niche than females, and females would have a more restricted niche, as their distribution should be more closely tied to the distribution of resources (Sunquist and Sunquist, 1989).

Extent: In the U.S., the States of Arizona, New Mexico, and the panhandle of Texas; and in Mexico, the States of Sonora and Chihuahua. The Madrean Archipelago is contained within this arid region, which extended from 25º26’ and 36º56’ N latitude, and 103º04’ and 113º58’ W longitude.

Data Inputs: The layers used represent abiotic characteristics for the climate and landscape, including temperature, wetness, vapor pressure, frost days, snow accumulation, radiation, soil type and other geologic features, elevation, aspect, slope, compound topographic index, water flow, and runoff. Raster and vector data were available from the Intergovernmental Panel on Climate Change (see Yohe, et al. 2006; also www.ipcc.ch), U.S. Geological Survey, 2004 (also edcdaac.usgs.gov/gtopo3/hydro), and ESRI ArcAtlas (ESRI 1996). Layers were projected into geographic coordinates and resampled to 25 $km^2$ pixel size to match the resolution of the occurrence data.

Method: Boydston and González (2005) included jaguar observation records with sufficient locality information to plot occurrence points within 25 $km^2$ accuracy and that included the sex of the individual. They assembled a database of jaguar occurrence records, including museum records, photographic records, and verified kills for the study area. They estimated the distribution of northern jaguars using the Genetic Algorithm for Rule Set Production (GARP, Sachetti-Pereira, 2002; Stockwell and Noble, 1999; Stockwell and Peters, 1999). For males, females, and males and females together, then generated the four best models, choosing those with the highest precision values, highest number of records, and lowest omission errors. They used multivariate discriminant analysis to explore niche specificity for male and female jaguars and examined differences in the environmental data allowed grid cells to be classified according to whether or not they were from the predicted distributions. Finally, they focused on females and compared the predicted female distribution to a land cover map from the USGS North America Landcover Database (see Homer et al., 2015; also edcdaac.usgs.gov/glcc) resampled to 25 $m^2$. Using the grid cell values for land cover and the female distribution, they performed a chi-square analysis to compare land cover types in the female distribution to the land cover types for the entire study area.

Results: Both male and female distributions included areas in central Arizona and New Mexico, with wider distributions observed for males. In total the predicted area of distribution for jaguars was 367,000 $km^2$, with an area of 391,000 $km^2$ predicted based on males only and 145,000 $km^2$ based only on females.

*Hatten et al. (2005)*

Purpose: In 1997, state, federal, and local governments with land-management responsibilities agreed to characterize and identify potential jaguar habitat in Arizona and New Mexico (Hatten et al., 2002, 2005). Specifically, Hatten et al. (2005) had two objectives: (1) characterize potential jaguar habitat in Arizona from historic sighting records and (2) create a statewide habitat suitability map. See the Menke and Hayes (2003) and Robinson et al. (2006) for analysis in New Mexico. Hatten et al. (2002) discusses an earlier version of the analysis reported in Hatten et al. (2005) and summarized here.

Extent: State of Arizona

Data Inputs: Four variables were used: (1) distance to perennial/intermittent waters from NHDPlus (data model version 2.1) database (McKay et al., 2012), (2) terrain ruggedness index (Riley et al., 1999) based on elevation data (see US Geological Survey, 2017), (3) landcover data from the GAP/LANDFIRE National Terrestrial Ecosystems database, based on the NatureServe Ecological Systems Classification (Comer et al., 2003; Homer et al., 2015), and (4) a human disturbance mask, based on all areas mapped as urban or agriculture in the GAP/LANDFIRE database.

Method: Hatten et al. (2005) used a geographic information system to characterize potential jaguar habitat by overlaying 25 historic jaguar sightings on landscape and habitat features believed important (e.g., vegetation biomes and series, elevation, terrain ruggedness, proximity to perennial or intermittent water sources, human density). Three distinct models were created from these four geographic information system (GIS) layers: Model A was the most restrictive model that only selected areas that were within 10 km of perennial/intermittent waters, moderately to extremely rugged terrain, outside agricultural/urban/disturbed lands, and within shrub-grasslands or forested areas. Model B was identical to model A but did not incorporate a terrain ruggedness index mask. Model C was identical to Model B except that various riparian biomes and the Madrean montane forests (Brown et al., 1980; see also Brown, 1994) were included.

Results: Most jaguar sightings were in scrub grasslands between 1,220 and 1,829-m elevation in southeastern Arizona, in intermediately to extremely rugged terrain, and within 10 km of a water source. The amount of Arizona (%) identified as potential jaguar habitat ranged from 21% to 30% depending on the input variables. Model A, the product of combining all four variables (the land use mask, vegetation, distance to water, and terrain ruggedness index) and extracting overlapping cells, resulted in 14,234 $km^2$ of predicted suitable habitat in Arizona. Model B, the product of combining three variables (no terrain ruggedness mask) and extracting overlapping cells, resulted in 42,118 $km^2$ of predicted suitable habitat in Arizona . Model C, the product of combining two variables (no terrain ruggedness mask or distance to water) and extracting overlapping cells, resulted in 63,088.9 $km^2$ of predicted suitable habitat in Arizona . Hatten et al. (2005) emphasized that conservation efforts should focus on protecting the most suitable jaguar habitat in southeastern Arizona (i.e., Santa Cruz, Pima, Cochise, Pinal, Graham counties), travel corridors within and outside Arizona, and jaguar habitat in the Sierra Madres of Sonora, Mexico.

*Robinson et al. 2006*

Purpose: The interagency Jaguar Conservation Team was established in 1997 to identify and coordinate protection of jaguar habitat. In 1999, the Habitat Subcommittee of this team agreed on criteria to identify jaguar habitat in the United States. In 2005, the Center for Biological Diversity contracted with Arizona Game and Fish Department and published a report and habitat model based on these criteria for New Mexico (Robinson et al., 2006). See complementary analyses by Hatten et al. (2002, 2005) and Menke and Hayes (2003).

Extent: State of New Mexico.

Data Inputs: Documented jaguar occurrences in New Mexico (Schmitt, 1998, Hatten et al., 2002); Vegetation/Land Cover (Prior-Magee et al., 2007); topography (Tachikawa et al., 2011) and computed topographic ruggedness (following Riley et al., 1999); distance from surface water, computed based on the National Hydrography Dataset (U.S. Geological Survey, 2004); Industrial and Residential Development (U.S. Census Bureau, 2000).

Method: The Habitat Subcommittee developed 4 criteria for inclusion or exclusion of jaguar habitat summarized as follows. A description of how these criteria were mapped can be found in the report.

1) Areas within 50 miles of a documented jaguar occurrence. This would include an entire mountain range, if a portion of that range is within 50 miles of the occurrence;
2) Brown and Lowe (1980) ecoregions, which were crosswalked to (i.e. interpreted in terms of) GAP categories, were used to define habitat: Semidesert Grassland, Plains and Great Basin Grassland, Subalpine Grassland, Interior Chaparral, Madrean Evergreen Woodland, Great Basin Conifer Woodland, Petran Montane Conifer Forest, Petran Subalpine Conifer Forest, Chihuahuan Desertscrub, Arizona Upland Sonoran Desertscrub, or Great Basin Desertscrub. Lower Colorado River Sonoran

Desertscrub, Mojave Desertscrub, and Alpine Tundra are not considered jaguar habitat;
3) Areas within 10 miles of seasonal or perennial surface water;
4) Areas with continuous row crop agriculture over an area greater than 1 square mile and any agricultural crop areas immediately adjacent to those areas were not considered habitat as well as areas with human residential development in excess of 1 house per 10 acres. Areas developed for industrial purposes or a combination of industrial and residential development that create a footprint equal to or greater than 1 house per 10 acres were not suitable jaguar habitat.
5) Jaguar observations within the study extent from Baird (1859), Bailey (1931), Halloran (1946), Hill (1942), McKenna (1971), Glenn (1996), and Jaguar Conservation Team (various)

Results: Robinson et al. (2006) found extensive suitable habitat for jaguars in three broad regions of New Mexico comprising over half of the state's land mass. The largest swath of habitat occurred in southwestern and west-central New Mexico, followed by north-central and south-central New Mexico. While the Jaguar Conservation Team, based on input from its scientific advisory group, declined to include prey base or road density in its criteria, it is also noteworthy that southwestern New Mexico harbors the largest populations of elk, mule deer and collared peccary in the state, and the state's largest roadless areas.

*Grigione et al. (2009)*

Purpose: Grigione et al. (2009) developed a preliminary blueprint of important conservation areas, composed of core habitats and corridors, for each species of Neotropical cat in the border region. Their work occurred in three phases: (1) compilation of reliable sightings for each species in the border region from the early 1900s to 2003, (2) field surveys in the border region to ascertain the presence of felids (Grigione et al., 2007; Crooks et al., 2008), and (3) coordination of an expert-based, GIS habitat mapping workshop.

Extent: The study area corresponds to the pre-industrial northern historical range of three wild cat species [jaguar, ocelot (*Leopardus pardalis*), and jaguarundi (*Herpailurus yagouaroundi*)], in the U.S. states of Arizona, New Mexico and Texas, and the Mexican states of Sonora, Chihuahua, Coahuila, Nuevo Leon and Tamaulipas. This area corresponds approximately with the northern and southern limits of the Sonoran Desert, Sinaloan thornscrub, Sierra Madre Occidental pine-oak forest, Chihuahuan Desert, Tamaulipan mezquital, and Western Gulf coastal grassland ecoregions (Olson et al., 2001). The western bioregion encompassed the Sierra Madre Occidental and Sky Islands, and the eastern the Sierra Madre Oriental. The east/west divisions were made because they represented two distinct habitat areas in the border region and for practical cartographic purposes at the workshop.

Data Inputs: Spatial data included elevation data (see U.S. Geological Survey, 2006), the 2003 World Database on Protected Areas (see UNEP-WCMC, 2020), historic species ranges digitized from range maps (Nowell & Jackson, 1996), and topographical data (ESRI, 2003). Sighting records were transferred to a GIS and plotted for each bioregion. This information was used as a starting point for the workshop. Each sighting was classed 1–3 using the criteria developed by

Tewes & Everett (1986) for evaluating ocelot and jaguarundi sightings in southern Texas. For our study only Class 1 sightings (sightings made by a credible observer, with physical evidence such as a carcass) were retained for subsequent analyses because Class 2 (detailed description of event provided by reliable observer, no physical evidence) and 3 (details of observer vague, no physical evidence) sightings were not as reliable.

Method: Twenty-nine scientists and conservationists from seven U.S. states and four Mexican states attended a workshop where they could review the results of each sighting map for each species and answer more detailed questions regarding species distribution and status, following roughly procedures outlined for jaguars on a range-wide scale described in Sanderson et al. (2002b). Specifically, participants were asked to identify important habitat areas, dispersal corridors, required or existing underpasses, and to characterize habitat areas and corridors. In addition, they were asked to give additional sighting information not previously identified. To ensure that adequate knowledge existed for the entire border region each participant was asked to delineate his or her area of knowledge for each species onto maps of the border region. Each participant was also asked to delineate Cat Conservation Units and Cat Conservation Corridors for their area or areas of knowledge onto respective maps for each species. Units were defined as habitat areas important to the long-term survival of a species, often where populations are currently located or areas likely to support relocated populations. Corridors were defined as linear or curvilinear strips of habitat connecting otherwise isolated Units that had documented Class 1 sightings. Each participant filled out a data sheet for each Unit and Corridor they identified, per species, to rank and characterize each according to population status, prey species present, threats, land ownership and level of land protection. To determine the level of current land protection, polygons from the World Database on Protected Areas (WDPA, 2003) was intersected with each Unit and Corridor. The result was a measure of how much each Unit and Corridor is currently protected by the six IUCN management categories (WDPA, 2003). To establish priorities for research and conservation a generalized weighting scheme was established. Units were ranked by: (1) connectivity between the Unit and other habitat areas, (2) habitat quality, (3) size, (4) hunting of felids, (5) hunting of prey, (6) population status, (7) threats from roads, (8) effectiveness of protection, and (9) human density in and around the Unit. Corridors were ranked by (1) continuity of connectivity, (2) habitat quality, (3) width, (4) length, (5) hunting of felids, (6) hunting of prey, (7) gaps/barriers, (8) threats from roads, (9) effectiveness of protection, and (10) human density in and around the Corridor. Each participant was asked to rank these factors by importance from 1 (most important) to 9 (least important) for each species.  Values from all participants were averaged for each factor by species, and the sum of all factors (for Corridors and Units separately) was normalized to 100%. This provided a measure of importance of each factor for each species. Each participant then ranked the importance of each factor, as good (2), neutral (1) or bad (0) as applied to a specific Unit or Corridor. When multiplied by the weighting scheme, these data allowed a ranking of Units and Corridors in terms of relative importance to the conservation of each species. Units and Corridors identified as potentially important for particular species but requiring further study were termed Cat Conservation Unit and Corridor Study Areas, respectively. Data sheets were filled out for these Areas but they were not ranked with the Units and Corridors.

Results: The historic range for all three species was well covered by participant knowledge.  The densest coverage was for jaguar in southeast Arizona, where six participants had specific expertise. A total of 97 Class 1 Sightings with latitude and longitude were assembled for the Jaguar. For Conservation Units, size, habitat quality and connectivity were the most important factors, whereas prey hunting by humans, threats from roads, and effectiveness of protection were the least important. For Conservation Corridors, connectivity was the most important and threats from roads the least important factor for jaguars. Four Conservation Units were identified for Jaguars in the western Bioregion. The connections between the Units are poorly understood and were determined to require further study. Approximately 34% of the U.S. Conservation Units are protected by a suite of Wilderness Areas and National Forests. The Sierra Madre North Unit and Sky Islands Unit were ranked as very high priority. The Sky Islands Unit has a particularly high level of protection; however, the status of jaguars there is uncertain. The Mogollon Rim Unit was ranked as high priority and was deemed to be an area that deserves conservation attention in the near future. There was only one Conservation Corridor designated as very high priority -- Sierra Madre North to Sierra Madre South. This Corridor currently has no protection. Two underpasses were identified as being needed in northern Sonora, where jaguars are believed to be crossing roads as they disperse.

*Theobald et al. (2017)*

Purpose: A model of jaguar habitat suitability was created to update and refine prior habitat maps by Sanderson and Fisher (2011; 2013) in the U.S. Fish and Wildlife Service (USFWS) draft recovery plan (USFWS 2016) based on finer-grained spatial data and a gradient-based (rather than binary habitat/non-habitat) model using the same observational data on jaguars. This report was used to inform how the infrastructure and activity along the U.S. Mexico border might impact jaguars in Arizona and New Mexico (see Bravo and Davis, 2017).

Extent: The model extent was defined as the USFWS jaguar draft recovery plan Northwestern Jaguar Recovery Unit (USFWS, 2016), with an extension to the north bounded by Interstates 40 and 25 between Flagstaff, AZ and Albuquerque, NM.

Data Inputs: Jaguar observation data—see Sanderson and Fisher (2011; 2013; and jaguardata.info); percent tree cover from the Global Land Cover Facility's Landsat Tree Cover Continuous Fields (www.landcover.org; see Sexton et al., 2013); topographic position index (see Theobald, et al. 2015); and degree of human modification.

Method: Modeling followed the general approach outlined by Sanderson and Fisher (2011; 2013) with updates, and was run in Google Earth Engine. Models were created using 48 jaguar observation locations selected from the 229 observations used in the jaguar draft recovery plan (USFWS 2016) because the subset had reliable geographic coordinates; were considered defined or determined points within the states of Arizona, Chihuahua, Sinaloa and Sonora; and were observed since 1917. Tree canopy cover (TCC) was fit to an exponential model that assumed habitat use increases with increasing tree canopy cover and was calculated as $y = 0.0487e(0.0386*TCC)$, where TCC represents the average tree canopy cover (0-100%) for 2005 and 2010. The terrain ruggedness variable of Sanderson and Fisher (2013) was replaced with topographic position index (TPI), which was more appropriate for the fine-grained scale of the updated analysis. TPI was calculated as the odds-ratio of TPI values at jaguar locations against the distribution of TPI values and fit to the polynomial model $y = 0.00008TPI + 0.00007(TPI 2)$

+ 0.0169. Degree of human modification (H), which replaced degree of human influence in Sanderson and Fisher (2013), was calculated as a ratio scale ranging from 0.0 (no modification) to 1.0 (high modification). This variable integrated land cover data from the National Land Cover Dataset 2011 (30 m resolution; see Homer et al. 2015), global land cover for Mexico (30 m resolution; Chen et al. 2015), global human settlement data (300 m; Pesaresi et al. 2015), VIIRS night-time lights (see Elvidge et al. 2017; 400 m resolution) and a 2016 detailed road map from Open Street Map (www.openstreetmap.org). Human modification was transformed into a naturalness value (N) to reflect the assumption that high jaguar habitat suitability is inversely related to the presence of human modification, and modeled as N = (1-H). Distance to water was not included due to poor data quality, overlap in representation with other variables and accessibility to streams present in the landscape (see Theobald et al. 2017 for details). No elevation threshold was set since a substantial number of jaguar observation events occurred above 2000 m. Finally, habitat suitability (S) was calculated as the product of the tree canopy cover, topographic position and degree of human modification covariate models, such that S = 0.0487e(0.0386*TCC) * (0.00008TPI + 0.00007(TPI 2 ) + 0.0169) * (1-H) 2 .

Results: Potential habitat was found in areas north of the Interstate-10, including “cores” of habitat exceeding $75^{th}$ and $90^{th}$ percentile of the habitat index (S) in contiguous patches of at least 100 $km^2$ in area.

*USFWS (2018)*

Purpose: A habitat model was constructed to inform the USFWS’ Endangered Species Act mandated recovery planning process for the jaguar in the Northern Recovery Unit (Sanderson and Fisher, 2011; 2013) and to support a Population Habitat Viability Analysis (Miller, 2013). The model required datasets that spanned the U.S.-Mexico border.

Extent: The northwestern jaguar recovery unit USFWS (2018) covers a 100 – 200 km swath of land from the northern part of Colima State in Mexico to the Interstate-10 Highway in the United States. This area includes most of the Sierra Madre Occidental Mountains and the “Sky Islands” region of southeastern Arizona and southwestern New Mexico.

Data Inputs: Ecoregions (Olson et al., 2001); Vegetation or tree cover (Townshend 2013); topography (Tachikawa et al., 2011) and computed topographic ruggedness (following Riley et al. 1999); distance from water, computed based on the Hydrosheds rivers dataset (Lehner 2013); human influence (Sanderson et al., 2002a); and jaguar observations, as compiled in Sanderson and Fisher (2011, 2013; also see jaguardata.info).

Method: Working under the advice of the technical sub-team of the USFWS Jaguar Recovery Team, the authors analyzed as “Class I” type jaguar observations (Tewes and Everett, 1986) against putative habitat variables. Habitat variables were resampled to a spatially-consistent 1 $km^2$ grid across the Northwestern Recovery Unit, represented using the North America version of the Albers Equal Area Conic projection defined on the NAD83 datum (ESRI, 2019). Classes of these variables were represented as binary choices. The model included areas with >1 and <=50% tree cover, intermediate, moderate, and high ruggedness (defined in Riley et al., 1999), and within 10 km of a waterway. Areas of high human influence (defined as a human influence index > 20) and above 2000 m elevation were excluded from the model. Remaining areas were weighted based on the ecoregion where they occurred (see main text). The technical sub-team assigned weights based on observed jaguar densities in different ecoregions, with highest weights provided to the subtropical, dry and moist forest, ecoregions in Mexico. Lower weights were assigned to pine and pine-oak forest types, and lowest weights to desert ecoregions. Ecoregions entirely outside the Northwestern Recovery Unit (e.g. the Arizona and New Mexico Mountains ecoregion; Olson et al., 2001) were excluded. Finally, the model was translated to jaguar densities (jaguars / 100 $km^2$) by regressing the habitat values for areas where jaguar studies had occurred against known densities in those study areas. The y-intercept of the regression was forced through zero. Various iterations of this model are documented in Sanderson and Fisher (2013); the final version used in the recovery plan was labelled "model 13."

Results: Model 13 suggested that the Borderlands Secondary Area – U.S. portion could provide habitat to an estimated six jaguars potentially (USFWS, 2018, p. F-40). A small portion of the modelled area (which extended beyond the Borderlands Secondary Area) overlapped with the definition of the Central Arizona / New Mexico Recovery Area used in this paper. In contrast, the models suggested that the Jalisco and Sonora Core Areas in Mexico could support more than 1000 jaguars each. The USFWS concluded that "in the Northwestern Recovery Unit, Mexico will be the primary contributor to recovery for the jaguar because over 95 percent of the species' suitable habitat in the NRU exists within the borders of Mexico. In the Pan-American Recovery Unit, countries within the jaguar's range will be the principal contributors to jaguar recovery." (USFWS, 2018, p. 2).

Note: Three additional models are described in the main text: Extensions of Model 13 (i.e. Model 14 and Model 15) and a re-analysis of the Hatten et al. (2005) model.

SUPPLEMENTARY TABLE 1 Descriptions of scale, units, data format, and criteria for top 50% of habitat and any habitat for 12 models or assessments of potential jaguar *Panthera onca* habitat in the USA and Mexico.

| Model or Assessment | Spatial Extent | Spatial Resolution* | Data format | Units | Value range | Potential habitat definitions |
|---|---|---|---|---|---|---|
| Sierra Institute, 2000 | Southern Arizona | unknown | vector | Three qualities of habitat | Primary /secondary /none | primary/ secondary |
| Sanderson et al., 2002b | Range-wide | 314 $km^2$ minimum mapping unit | vector | Currently occupied habitat / potential habitat | Approximate jaguar range (AJR) / Jaguar geographic regions (JGR) | JGR |
| Menke and Hayes, 2003 | Southwestern New Mexico | 200 m | raster | Unitless index | 3-24 or 0 | >=3 |
| Boydston and Gonzalez, 2005 | Arizona and New Mexico | 0.01 degree (lat/lon) | raster | Number of submodels that agree | 0 - 10 | |
| Hatten et al., 2005 | Arizona | 30 m | raster | Number of submodels that agree | 0-3 | 1-3 |
| Robinson et al., 2006 | New Mexico | unknown | vector | Unitless index | 1/0 | 1 |
| Grigione et al., 2009 | U.S. Southwest and northern Mexico | unknown | vector | Three levels of priority and connectivity habitat | high/ medium/ study area /corridor | high/ medium/ study area /corridor |
| Model 13 (USFWS, 2018) | Ecoregions found in Northwestern Recovery Unit | 1 km | raster | Number of adult jaguars per 100 $km^2$ | 0-6 | >0 |
| Theobald et al., 2017 | Northwestern Recovery Unit and adjacent areas | 90 m | raster | Unitless index | 870-16206 or 0 | >=870 |
| Model 14 (this paper) | most of Arizona and New Mexico | 1 km | raster | Number of adult jaguars per 100 $km^2$ | 0-6 | >0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Model 15 (this paper) | most of Arizona and New Mexico | 1 km | raster | Number of adult jaguars per 100 $km^2$ | 0-6 | >0 |
| Hatten (this paper) | Arizona and New Mexico | 1 km | raster | Number of submodels that agree | 0-3 | 1-3 |

*For raster datasets, resolution is given as the length of one side of a square cell.

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