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Date: June 2025

Projected Habitat Suitability and Range Change of the Jaguar (*Panthera onca*) in Response to Climate Change Habitat in Mexico and Central America

Introduction

The jaguar (*Panthera onca*) is the largest feline in the Americas and the only extant representative of the genus *Panthera* on the continent (Nowell & Jackson, 1996). Morphologically, the jaguar is characterized by a robust, muscular body, powerful jaws, and relatively short limbs, traits adapted to a non-cursorial lifestyle and dense forest environments (Seymour, 1989; Sunquist & Sunquist, 2002). Historically, its distribution extended from the southwestern United States to the Amazon basin and as far south as the Río Negro in Argentina (McCain & Childs, 2008; Di Bitetti et al., 2016).

Over the past century, jaguars have been virtually eliminated from the northernmost and southernmost parts of their range, including Arizona and New Mexico in the U.S., northern Sonora in Mexico, Uruguay, the pampas grasslands of Argentina, and parts of northern Brazil (Johnson & Van Pelt, 2016; de Azevedo et al., 2016; Di Bitetti et al., 2016; Pereira-Garbero & Sappa, 2016). By 2002, jaguars occupied only an estimated 46% of their historical range (Sanderson et al., 2002), and little improvement has been observed since then.

According to Sanderson et al. (2002), regions with high long-term conservation potential included the moist tropical lowland forests of Mexico and Central America, specifically the Selva Maya of Guatemala, Belize, and southeastern Mexico, as well as a narrow band of forest stretching from the Chocó-Darién of Panama and Colombia to northern Honduras. They estimated that 70% of the remaining jaguar range (more than 6 million km²) had a high probability of supporting viable populations, while 12% was classified as having a low probability of long-term persistence, including areas such as the Atlantic Forest and Cerrado of Brazil, the Gran Chaco of Argentina, and parts of Central America and Mexico.

Jaguar density estimates in Mexico range from 0.75 to 6 individuals per 100 km² (Ceballos et al., 2011; Chávez et al., 2016), and the national population was estimated at 4,000–5,000 individuals as of 2011 (Ceballos et al., in press). In Central America, density estimates based on 27 studies from 2000 to 2010 ranged from 0.74 to 11.2 individuals per 100 km² (Foster & Harmsen, 2012; Maffei et al., 2011; Tobler & Powell, 2013).). However, many of these studies lacked sufficient sampling areas to yield unbiased estimates. Later

reviews revealed that most pre-2010 studies tended to overestimate jaguar densities due to limited sample sizes and biased capture-recapture data (Quigley, H et al., 2017)

Jaguars face a broad range of threats throughout their range. Chief among them are habitat loss and fragmentation caused by deforestation, agricultural expansion, and infrastructure development (Medellín et al., 2002; Paviolo et al., 2008). Additional threats include retaliatory or opportunistic killings due to livestock depredation, poaching for body parts, and illegal wildlife trade (Zimmermann et al., 2005; Hoogesteijn & Hoogesteijn, 2008). Latin America continues to exhibit some of the highest deforestation rates globally, with agricultura, both industrial and subsistence, driving approximately 80% of tropical deforestation from 2000 to 2010 (D'Annunzio et al., 2015; FAO Forest Update). Habitat fragmentation also facilitates access for humans and livestock, further lowering prey availability and jaguar densities (Quigley, H et al., 2017). In addition to these persistent threats, climate change is emerging as an additional pressure on the species' long-term survival.

In response to these challenges, a number of conservation actions have been implemented. Jaguars are listed on CITES Appendix I and are legally protected across most of their range. Hunting is prohibited in countries such as Argentina, Brazil, Colombia, Costa Rica, Honduras, Mexico, Nicaragua, Panama, Paraguay, Suriname, the United States, and Venezuela, with partial restrictions in Guatemala and Peru (Nowell & Jackson, 1996). National conservation strategies have been developed in Mexico, Panama, Honduras, and Brazil, and numerous countries have adopted Jaguar Conservation Units (JCUs) and regional corridors as conservation frameworks (Rabinowitz & Zeller, 2010; Kay et al., 2015).

Key conservation actions include:

- Responding to reports of livestock depredation and promoting improved livestock management to reduce conflict.
- Monitoring and protecting core populations and JCUs.
- Identifying and maintaining biological corridors between key habitats.
- Promoting sustainable hunting practices of jaguar prey.
- Developing national and regional monitoring programs for jaguars and their prey.

This project aimed to model the current and projected climatic suitability for *Panthera onca* in Mexico and Central America, with a focus on understanding how future climate scenarios could alter the species' potential distribution by mid-century (2041–2060). By identifying areas of habitat loss, gain, and stability under projected climate conditions, this analysis contributes to regional conservation planning and provides insight into where the species may persist—or face new challenges—in the coming decades.

Methodology

An ecological niche modeling was used to assess current and future habitat suitability for the jaguar (*Panthera onca*) across Mexico and Central America, based on environmental variables and species occurrence records. Presence data were obtained from the Global Biodiversity Information Facility (GBIF), filtered to retain only georeferenced records, and cleaned to remove spatial duplicates and erroneous coordinates.

Although the jaguar's natural range extends across much of South America, the study area was deliberately limited to Mexico and Central America to focus on the regional application of ecological niche modeling (ENM). This spatial restriction allowed us to evaluate projected climate-driven habitat shifts at a relevant scale for transboundary conservation planning, while maintaining manageable computational and interpretative complexity. The results should therefore be interpreted as a regional scenario, not a continental-scale prediction.

Nineteen bioclimatic variables (BIO1–BIO19) at 10 arc-minute resolution were downloaded from the WorldClim v2.1 database. Current climatic conditions were used to model the present-day distribution, while future projections were based on the CMIP6 BCC-CSM2-MR general circulation model under the SSP5-8.5 emissions scenario for the period 2041–2060 (hereafter referred to as "mid-century"). This 20-year climatological window represents averaged projections rather than conditions for a specific year.

A topographic mask excluding areas above 3500 m was applied to limit the analysis to ecologically plausible habitats. The model was trained using the maxnet algorithm in R, with 10,000 randomly sampled background points. Model performance was assessed using the Area Under the Curve (AUC) of the ROC, and a cloglog threshold of 0.175 (based on max TPR+TNR) was used to binarize suitability maps.

Projections were made under both current and future climate scenarios, and binary maps were compared to classify habitat as Loss, Gain, or Stable. It is important to note that, due to the spatial extent of the environmental layers, certain areas beyond the species' natural distribution (e.g., Cuba) were included in the climatic raster. Any predicted suitability in such areas should be interpreted as climatic potential only, not actual colonization likelihood, due to biogeographic and dispersal constraints.

Results

The final model exhibited strong predictive power, with an AUC of 0.970, indicating a high capacity to distinguish between presence and background locations. Under current climate conditions, suitable habitat was concentrated in southern Mexico (including Chiapas, the Yucatán Peninsula, and the Pacific coast), as well as in Guatemala, Honduras, Nicaragua, Costa Rica, and Panama (Fig. 1).

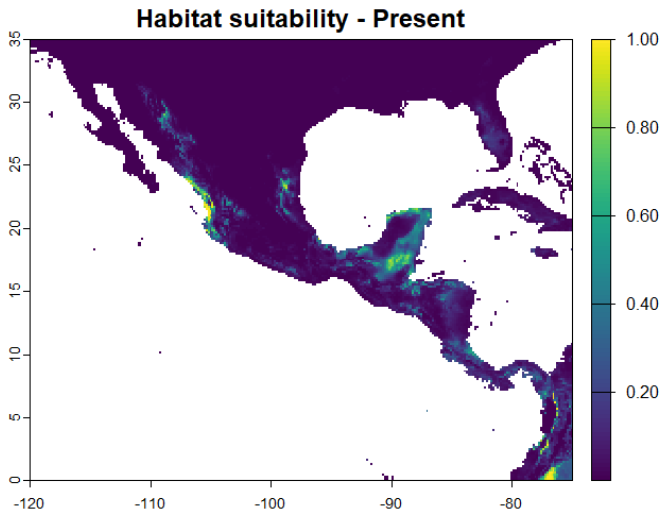

Figure 1 Current habitat suitability for *P. onca*

Under the SSP5-8.5 scenario for the period 2041–2060, the model projects a noticeable geographic shift in suitability patterns. Areas of high suitability are expected to move toward higher elevations and latitudes, particularly along mountain corridors such as the Sierra Madre and Central American highlands. Simultaneously, lowland areas, especially along the Pacific coast and parts of the Yucatán Peninsula, may experience reduced suitability due to increasing temperature and changes in precipitation seasonality (Fig. 2).

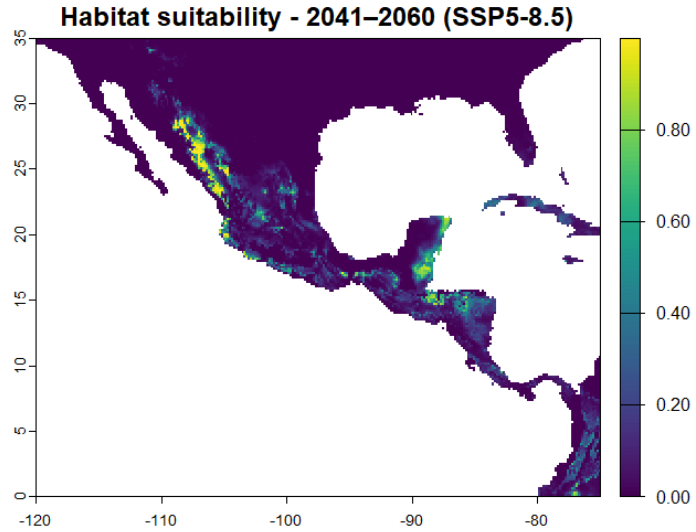

Figure 2 Projected habitat suitability for 2041–2060 (SSP5-8.5)

The habitat change analysis revealed the following proportions within the study área (Fig.3):

- **Loss** of suitable habitat: 33.8%
- **Gain** of new suitable habitat: 47.2%
- **Stability** (persistently suitable): 18.9%

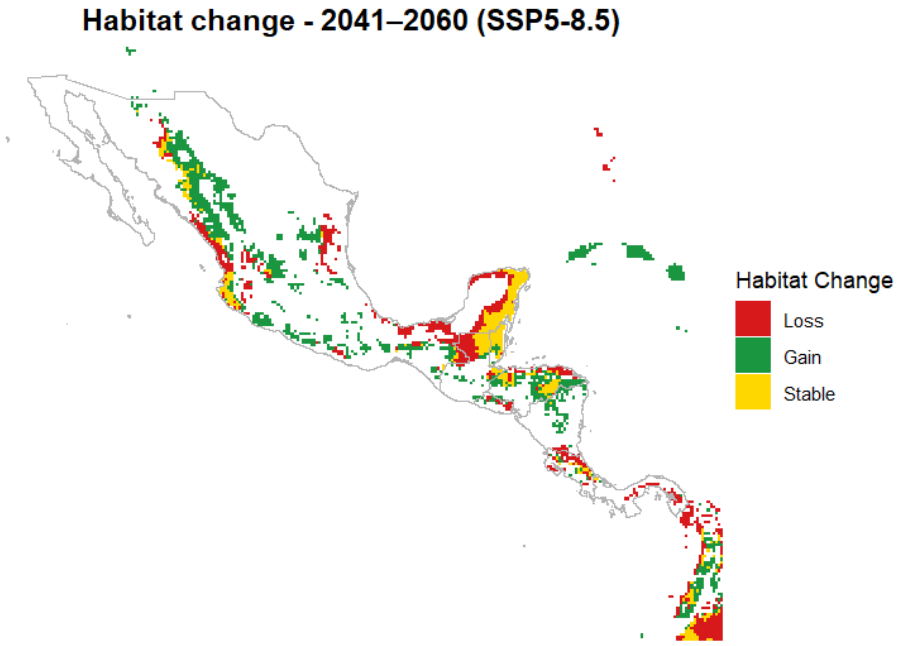

Figure 3 Projected habitat change between present and 2041–2060 (*SSP5-8.5)*

These findings suggest that climate change may lead to substantial habitat turnover for *P. onca*, potentially resulting in increased fragmentation and isolation of viable populations. Areas that are projected to remain stable could act as refugia, whereas areas of gain might represent potential targets for long-term conservation corridors or rewilding strategies. However, accessibility, landscape connectivity, and land-use pressures will be key determinants of whether such shifts in climatic suitability will translate into actual changes in distribution.

Again, we emphasize that certain model projections, such as apparent gains in island regions like Cuba, should be interpreted with caution. These reflect climatic conditions that match the species' niche requirements, but do not imply potential colonization or natural expansion, especially when geographic or ecological barriers exist.

Discussion

The results of this study suggest that the distribution of climatically suitable habitat for the jaguar (*Panthera onca*) in Mexico and Central America may undergo substantial shifts by mid-century under the SSP5-8.5 emissions scenario. The model indicates that while some current lowland hábitats, particularly in coastal areas and the Yucatán Peninsula, are likely to become less suitable due to increased temperature and altered precipitation patterns, new suitable areas may emerge at higher elevations and latitudes, particularly along mountainous corridors.

This projected turnover highlights the importance of maintaining landscape connectivity and ecological corridors, particularly between existing Jaguar Conservation Units (JCUs) and potential future refugia. Conservation strategies should prioritize the protection of stable habitat areas that are expected to remain suitable under climate change, while also identifying and managing emerging habitats that may serve as future strongholds for the species.

However, it is essential to acknowledge the limitations and assumptions inherent in correlative ecological niche models. The model used here is based solely on climatic variables, and does not incorporate land use, prey availability, human pressures, or barriers to dispersal. Thus, while projections may indicate climatic suitability, actual colonization or persistence will depend on a combination of ecological, behavioral, and anthropogenic factors. For instance, areas like Cuba appear in the model as climatically suitable under future scenarios, but this should not be interpreted as a likely expansion area for the species due to the absence of historical records, physical isolation, and lack of natural colonization pathways.

The high proportion of habitat "gain" observed in the projections (47.2%) offers a degree of optimism for jaguar conservation, especially if these areas are proactively managed and connected. However, the corresponding loss of 33.8% of current suitable areas is significant and may lead to increased habitat fragmentation, conflict with humans, and reduction in local population viability. This is particularly critical in Central America, where jaguar populations are already highly fragmented and vulnerable to extirpation.

In this context, climate change should not be viewed in isolation, but rather as an amplifier of existing threats such as deforestation, poaching, and human-wildlife conflict. Therefore, conservation policies must integrate climate projections into broader land-use planning, species monitoring, and habitat management efforts.

Conclusions

This study demonstrates the potential impacts of climate change on the future distribution of suitable habitat for the jaguar in Mexico and Central America. Using ecological niche modeling under a high-emissions scenario (SSP5-8.5), we identified areas of projected habitat loss, gain, and stability by the period 2041–2060. Our results suggest that jaguar habitat is likely to shift toward higher elevations and latitudes, with only 18.9% of currently suitable areas projected to remain stable.

These findings underscore the urgent need to:

- Preserve climate-resilient habitats, especially those projected to remain suitable;
- Ensure connectivity between current and future suitable areas to allow for potential range shifts;
- Integrate climate change into species recovery and conservation planning at national and regional scales.

While this study focused on climatic suitability, future research should incorporate land cover, prey dynamics, and socio-environmental variables to better estimate the jaguar's true future distribution potential. Proactive, science-based strategies will be essential to ensure the long-term survival of *Panthera onca* under the compounding pressures of habitat loss, fragmentation, and climate change.

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