Jaguar Distribution in Brazil: Past, Present and Future

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Historically, jaguars lived from southern Argentina to the southwestern United States, but due to anthropogenic pressure, their range has been reduced to less than 46% of its original size. As almost half of this area is within Brazilian territory, the country is key to future jaguar conservation. Knowledge of geographic distribution has been recognized as an important issue to support conservation plans, and recently, climatic change has been shown to influence species distribution. This study estimated potential jaguar distribution using ecological niche modeling. We accumulated 1,049 jaguar occurrence points and used climate and topographic data as predictive variables. We employed the Mahalanobis Distance Method to produce a historical and future distribution map, considering values for current and future climate, respectively. To estimate current jaguar distribution, we restricted the historical distribution according to the jaguar's preferred habitat classes. While range of distribution changed little from current to future climate, the extent of more suitable areas was reduced. Areas with high predicted future suitability are currently under habitat conversion. Comparison of these maps enables the identification of important areas for jaguar conservation in Brazil.

On a global scale, the biggest threats to biodiversity result from human occupation of natural landscapes (Ehrlich 1997). The conversion of natural habitat and its fragmentation are direct consequences of this trend (Wilcox & Murphy 1985). Recently, global climate change has been cited as responsible for relevant alterations of species' geographic distributions (Burns *et al*. 2003). The species' response to past and current climate modifications suggests that human climate change can act as a significant cause for extinction in the near future (Thomas *et al*. 2004).

The jaguar *Panthera onca* is the largest feline of the Americas, with a historical distribution ranging from southern Argentina to the southwestern United States (Seymour 1989). However, under hunting pressure and natural habitat conversion (Fig. 1), the jaguar's geographical distribution has reduced significantly. It is considered regionally extinct in El Salvador and Uruguay (IUCN 2007), and is presently estimated to occupy less than 46% of its original range (Sanderson *et al*. 2002a). Approximately 50% of the remaining distribution area is within Brazilian territory, making this country extremely important to guarantee long term jaguar conservation. Habitat variables, mostly related to vegetation cover, are important to determine jaguar distribution and possibly local abundance. Therefore, there is an increased concern about the loss of their habitats both due to direct human conversion and the possible alteration due to long-term climatic change.

At the present time, one of the main goals of conservation is to quickly and inexpensively identify the most important areas for biodiversity conservation. But species distribution data at precise scales are scarce and expensive to obtain in sufficient quantities to implement this kind of analysis based on species occurrences only (Williams & Gaston 1994). Therefore, it is important to adopt different approaches. Range-wide conservation plans should rely on the knowledge of a species' past and present geographic distribution, as well as on distribution of the known impacts affecting its populations. This would enable a more precise assessment of its conservation status based on remaining habitat and estimated population size yielding better design of conservation efforts at a landscape scale (Sanderson *et al*. 2002a,b, Wikramanayake *et al*. 2002).

A common method long used to study species geographic distribution consists of projecting available presence records on a map and defining the area between them as a qualitative estimation of the species' range. However, this "dot map"–based estimation excessively simplifies biotic and abiotic distinctions of the covered area such as geographic variables, climatic differences and habitat types (Lim *et al*. 2002). More recently, Species Distribution Modeling (SDM) based on Geographical Information System (GIS) methods has been widely used as an alternative. This innovative method produces maps that indicate where species are likely to occur (Fuller *et al*. 2007, Pearson *et al*. 2007) by a measure related to the probability of occurrence. This modeling approach has been favored as large scale climatic and ecological datasets have become available. Consequently, the efficiency and options to model and map complex relationships between species and environment have increased (Rushton *et al*. 2004, Johnson & Gillingham 2005).

Fig. 1. Deforestation for extensive cattle ranching in the Brazilian Amazon biome (Photo Jaguar Conservation Fund/Instituto Onça-Pintada).

The use of SDM to predict the potential distribution of a species based on its ecological requirements, extrapolating the data to unknown areas, can be useful for several objectives, including, among others, the prediction of effects of climatic change or estimating the real distribution of threatened and rare species (Peterson *et al*. 2002, Johnson & Gillingham 2005, Ortega-Huerta & Peterson 2005). However, as a species' distribution is also constrained by biotic interactions, anthropogenic effects, stochastic events and other factors that are not incorporated into the presence-only methods, results must be considered as potential distributions and not necessarily as realized ones (Hortal *et al*. 2008, Jiménez-Valverde *et al*. 2008). Further, extending a regression beyond the limits of the data from which it is derived bears uncertainty as it is impossible to know if the described relationship will persist in the same way (Kearney 2006).

Here, we estimate potential past, present and future jaguar distribution in Brazil using predictive modeling approaches. Considering the high dispersal abilities of this species (Quigley & Crawshaw 2002), small-scale conservation efforts that focus on narrowly defined areas may not be sufficient to guarantee its conservation (Sanderson *et al*. 2002a), and species distribution models may be an important tool to establish efficient conservation strategies for the jaguar.

Methods

Modeling methods

There is a wide array of SDM techniques and a number of reviews of their performance (e.g., Elith *et al*. 2006). It is recommended that biologists evaluate the performance of several methods to determine which one presents the best estimation for the species of interest (McNyset & Blackburn 2006, Stockman *et al*. 2006a,b). We chose modeling techniques based on the constraint of using presence-only data, as absence data are rarely available (collections typically have no information about failure to observe the species at any given location, and true absence can usually not be distinguished from failure of detection). Thus, we evaluated three modeling procedures: the Genetic Algorithm for Rule Set Production (GARP) (Stockwell & Peters 1999); the Maximum Entropy (Maxent) (Phillips *et al*. 2006) and the Mahalanobis Distance Method (Mahalanobis 1936). Available techniques to evaluate model performance based on the Receiver Operating Characteristics (ROC) curve (Manel *et al*. 2001) show very similar results for the three methods that varied from 0.910 to 0.952, and reveal a good predictive value. However, Mahalanobis Distance method (MD) was the most consistent predictor of jaguar distribution at the majority of areas where its presence is known, so we present results under this model only.

Mahalanobis Distance is a method that ranks potential sites by their Mahalanobis distance to a vector that expresses the mean environmental conditions of all the records in the environmental space. For each cell in the grid, the distance from this mean is projected and represents a quantitative variable that is expected to be monotonic inversely correlated to the cell habitat suitability for the species. It is possible to define a distance threshold based on the ROC procedure that is considered the boundary of the ecological niche (Farber & Kadmon 2003). This methodology provides a robust way of measuring how similar a set of conditions is to an optimum set, and can be useful for identifying which regions in a landscape are most similar to an optimum landscape (Jenness 2003). Besides, MD is based on both the mean and variance of the predictive variables, as well as the covariance matrix of them, and thus makes use of the covariance between the considered variables (Jenness 2003). Among the various methods designed to produce species range distribution based on a niche modeling approach, MD was considered one of the most efficient methods in recent reviews (Farber & Kadmon 2003, Nogués-Bravo *et al*. 2008).

Jaguar occurrence data

We compiled information (geographic coordinates) on known jaguar occurrence (from 1998 to 2008) from:
1) scientific books and papers;
2) online data bases: Global Biodiversity Information Facility GBIF - http://www.gbif.org/; SpeciesLink - http://splink.cria.org.br; Museum of Vertebrate Zoology - http://www.mip.berkeley.edu/mvz/index.html);
3) field records from the NGO Jaguar Conservation Fund, which were obtained through camera trapping and interviews with locals; and
4) unpublished records from partner researchers that kindly authorized the use of this information.

We accumulated 1,053 occurrence points that were standardized to decimal degrees. A detailed list of references and locations is available from the main author upon request.

We used a cell precision of 0.0417 degrees (nearly 4 km precision in cells near the Equator Line). Under this constrain there were 795 spatially unique records to use in the modeling process.

Predictive variables

The predictive data for past and current distribution modeling consisted of six climatic variables (precipitation of warmest quarter, precipitation seasonality (coefficient of variation), annual precipitation, mean temperature of driest quarter, temperature seasonality (standard deviation *100) and annual mean temperature) derived from the WORDCLIM (http://www.worldclim.org/) and

Table 1. Land cover classes preferred by Jaguars, selected from a Vegetation Map of South America (Eva *et al.* 2002).

Land cover classes selected	
Closed evergreen tropical forest	Semi deciduous transition forest
Open evergreen tropical forest	Fresh water flooded forests
Bamboo dominated forest	Permanent swamp forests
Closed semi-humid forest	Grass savannah
Open semi-humid forest	Shrub savannah
Closed deciduous forest	Periodically flooded savannah
Open deciduous forest	Closed shrublands
Closed semi deciduous forest	Open shrublands
Open semi deciduous forest	Periodically flooded shrublands

two topographic variables (altitude and slope) derived from the Hydro-1K global digital elevation model (http://edcdaac.usgs.gov/gtopo30/hydro/). All variables were converted to a grid resolution of 0.0417 degrees. To model future jaguar distribution, the same variables were used considering the Community Climate System Model – CCSM 3 (Vertenstein et al. 2004). Composed of four separate models simultaneously simulating the earth's atmosphere, ocean, land surface and sea-ice, and one central coupler component, it allows evaluation of future climate states (Vertenstein *et al*. 2004).

To obtain a reliable prediction of the current jaguar distribution, we restricted our past distribution model to areas of currently remaining natural vegetation classes preferred by jaguars, derived from a vegetation map of South America from 2000 (Eva *et al*. 2002), as vegetation types are not directly modeled under our approach. This was not possible for future predictions as information on natural vegetation changes is not available.

Results

Modeling results for past jaguar distribution were similar to historical maps from the literature (Seymour 1989), showing its distribution throughout most of Brazil, with the majority of the country's area being highly suitable for the jaguar, except most of the Pampas biome (Fig. 2).

A model restricted to the species' preferred habitat (Fig. 3) to estimate current distribution shows areas that currently have the climatic conditions for potential occurrence of the jaguar and still present native vegetation cover, considering information from 2000 (Eva *et al*. 2002). It shows large suitable vegetation blocks in the Amazon and Pantanal biomes, some parts of the central Cerrado (especially the Cerrado-Amazon ecotone) and the Caatinga biome. For the Atlantic Forest biome, however, the potential for jaguar occurrence is predicted only in extremely fragmented and isolated areas.

The results based on climate change models shows that the main areas for jaguar persistence with suitable conditions for its occurrence in the future will be concentrated in the Amazon, Cerrado and Atlantic Forest biomes (Fig. 4).

Comparing historical and future distributions (Fig. 2 and 4), the overall area of distribution is not expected to change based on climate changes, but a decrease in the most suitable areas is obvious. This prediction seems to be more serious if comparing with current distribution (Fig. 3) as many areas predicted to be suitable in the future actually suffer from deforestation.

Discussion

Studies on conservation biology have confirmed the importance of increasing the scale of conservation planning, especially adopting methodologies that emphasize entities other than populations or the species as a target for conservation effort. Thus, species distribution models are increasingly being used to inform conservation strategies, providing insights into the broad-scale environmental niche of a species and its potential distribution (Soberón & Peterson 2005, Araújo & Guisan 2006, Soberón 2007).

The apparent success of the MD method in describing jaguar distribution in Brazil may be due to the broad environmental and geographic range of the jaguar occurrence dataset and the use of predictor variables that closely reflect known limits to its environmental distribution. Some other studies have concluded that MD is an efficient technique for SDM (Farber & Kadmon 2003, Hellgren *et al*. 2007, Tsoar *et al*. 2007).

The use of a vegetation map to restrict potential distribution makes the estimation more consistent, and our results can be considered a reliable map of current jaguar distribution in Brazil.

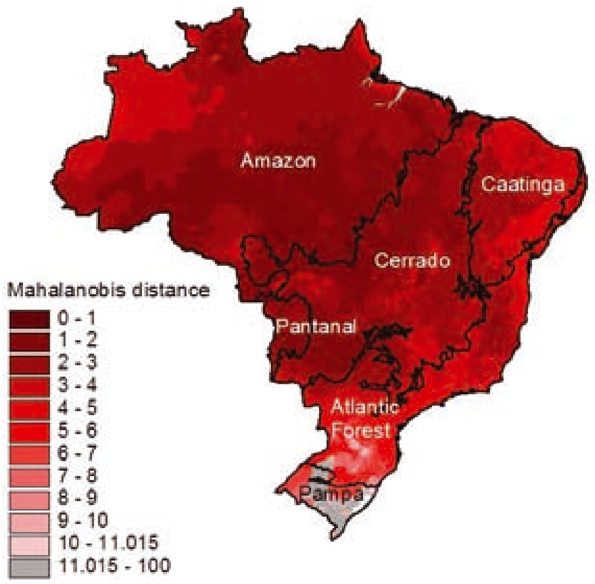

Fig. 2. Map of historical jaguar distribution in Brazil based on habitat modeling using Mahalanobis Distance. Progressively lower MD values (darker red) indicate progressively higher habitat suitability for the jaguars, while higher MD scores (grey) indicate unsuitable areas.

Fig. 3. Current jaguar distribution (shown in red), as predicted by the Mahalanobis Distance Method constrained by remaining native vegetation cover in Brazil.

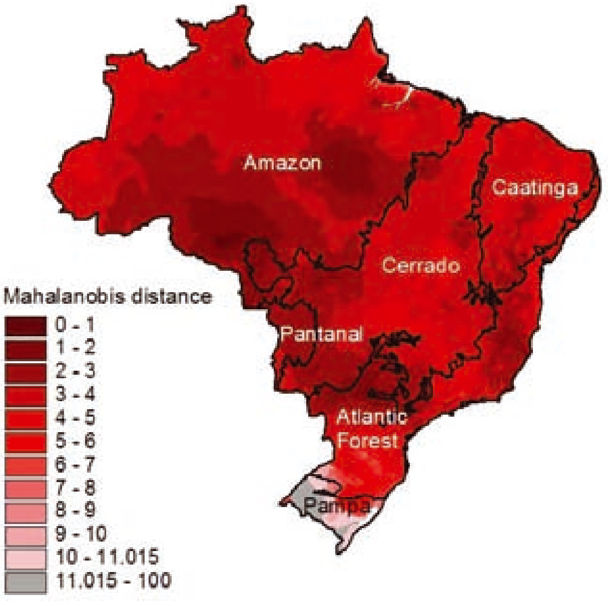

Fig. 4. Map of future jaguar distribution in Brazil based on habitat modeling using Mahalanobis Distance considering climate change. Progressively lower MD values (darker red) indicate progressively higher habitat suitability for the jaguars, while higher MD scores (grey) indicate unsuitable areas.

The areas indicated in this map must be considered as primary targets for jaguar conservation, especially if we consider the future distribution map, which shows that some areas predicted as highly suitable in the future are presently suffering severe human impact by deforestation.

Recently, modeling has been used to estimate distributions of species under future climatic scenarios, as the climatic global changes are apparently responsible for significant alterations in species' geographic distributions (Burns *et al*. 2003, Thomas *et al*. 2004, Broenniman et al. 2006). Nevertheless, these analyses are based on complex climatic change scenarios and should consider variation in land use, which may change as a response to climate change. Especially for jaguars, which present a broad bioclimatic envelope, the potential negative effects of climatic changes might not be too dramatic generally. The potential overall jaguar distribution in Brazil does not seem to change when present or future climate variables are examined, but a considerable difference is observed in the most suitable areas. However, incorporating changes in land use might provide different results.

Considering that under current theoretical niche models, smaller Mahalanobis distances mean habitats with near optimum conditions, and assuming a direct relation between optimal conditions and jaguar abundance, the most important prediction of our models is the decrease of overall jaguar abundances under a climatic change scenario. Even if the potential distribution does not change, a decrease in local abundance in peripheral areas may lead to increased local extinction. The worst prediction for jaguar conservation is that those areas with good habitat suitability in the future (mainly Amazon and Cerrado areas) are located in the 'arc of deforestation' (Nogueira *et al*. 2008; Fig. 5), currently under strong pressure of habitat conversion to soybean and sugarcane plantations. The interaction of current deforestation and the potential future decrease in jaguar abundance may restrict the opportunities for jaguar conservation actions and call for urgent measures to maintain viable jaguar populations in these areas. Considering that this is the most important threat for jaguars, monitoring of these changes is needed to guarantee its conservation.

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Fig. 5. Areal view of a region in the state of Mato Grosso, located within the so-called Arc of Deforestation, one of the main areas that retain high potential suitability for jaguars when modeling the species' distribution under future climate changes, but currently threatened by extensive habitat conversion (Photo Jaguar Conservation Fund/Instituto Onça-Pintada).

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