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ABSTRACT

Maintaining habitat and its connectivity is a major conservation goal, especially for large carnivores. Assessments of habitat connectivity are typically based on the output of habitat suitability models to first map potential habitat, and then identify where corridors exist. This requires separating habitat from non- habitat, thus one must choose specific thresholds for both habitat suitability and the minimum patch size that can be occupied. The selection of these thresholds is often arbitrary, and the effects of threshold choice on assessments of connectivity are largely unknown. We sought to quantify how habitat-suitability and patch-size thresholds influence connectivity assessments for jaguars (*Panthera onca*) in the Sierra Gorda Biosphere Reserve in central Mexico. We modeled potential habitat for jaguars using the species distribution modeling algorithm Maxent, and assessed potential habitat connectivity with the landscape connectivity software Conefor Sensinode. We repeated these analyses for 45 combinations of habitat suitability based thresholds and minimum patch sizes. Our results indicated that the thresholds influenced connectivity assessments greatly, and different combinations of the two thresholds yielded vastly different map configurations of suitable habitat for jaguars. We developed an approach to identify the pair of thresholds that best matched the jaguar occurrence points based on the connectivity scores. Among the combinations that we tested, a threshold of 0.3 for habitat suitability and 2 km^2 for minimum patch size produced the best fit (area under the curve = 0.9). Surprisingly, we found low suitable habitat for jaguars in most of the core areas of the reserve according to our best potential habitat model, but highly suitable areas in the buffer zones and just outside of the reserve. We conclude that the best and most connected potential areas for jaguar habitat are in the central eastern part of the Sierra Gorda. More broadly, landscape connectivity analyses appears to be highly sensitive to the thresholds used to identify suitable habitat, and we recommend conducting sensitivity analyses as introduced here to identify the optimal combination of thresholds.

1. Introduction

Wildlife habitat and species' ranges are diminishing rapidly due to landscape modification (Lindenmayer and Fischer, 2013; Newbold et al., 2015), and human activities such as agriculture, livestock, mining, and the expansion of urban areas (Wood et al., 2013). In addition to the loss of habitat, changes in habitat configuration can diminish the connectivity among areas occupied by different populations of a given species (Tischendorf and Fahrig, 2000). This could reduce the ability of species to survive extreme events such as fires, diseases, and predation (Clark et al., 2011), thereby increasing the risk of extinction (Reed, 2004). Changes in landscape connectivity are particularly detrimental to apex predators that require large areas of suitable habitat, and securing habitat corridors for these species is critical for their long-term conservation (Soisalo and Cavalcanti, 2006). Thus, it is important to both preserve the remaining habitat available for species and to maintain or enhance habitat connectivity (Peterson, 2011; Sanderson et al., 2002a, 2002b).

Mapping species distributions is the first step when developing conservation management strategies that account for population and habitat patterns at local and landscape scales (Cavalcanti and Gese, 2009; Turner et al., 2001). Often, obtaining the actual species distribution is not possible because of time constraints or incomplete data. This is why presence-only models are often used to estimate potential habitat based on species occurrences (presence-only data) and predictor variables that are biologically meaningful for the species (Bradley et al., 2012). The resulting models can then be used to identify additional areas with similar environmental conditions that could potentially serve as habitat for the species of interest. Once these potential habitat areas are identified, they can be analyzed in terms of their spatial configuration and connectivity.

Connectivity can be measured in many different ways, either focusing only on patches of suitable habitat, or on the entire landscape (Calabrese and Fagan, 2004). However, connectivity assessments based on graph theory, which quantify the arrangement of habitat

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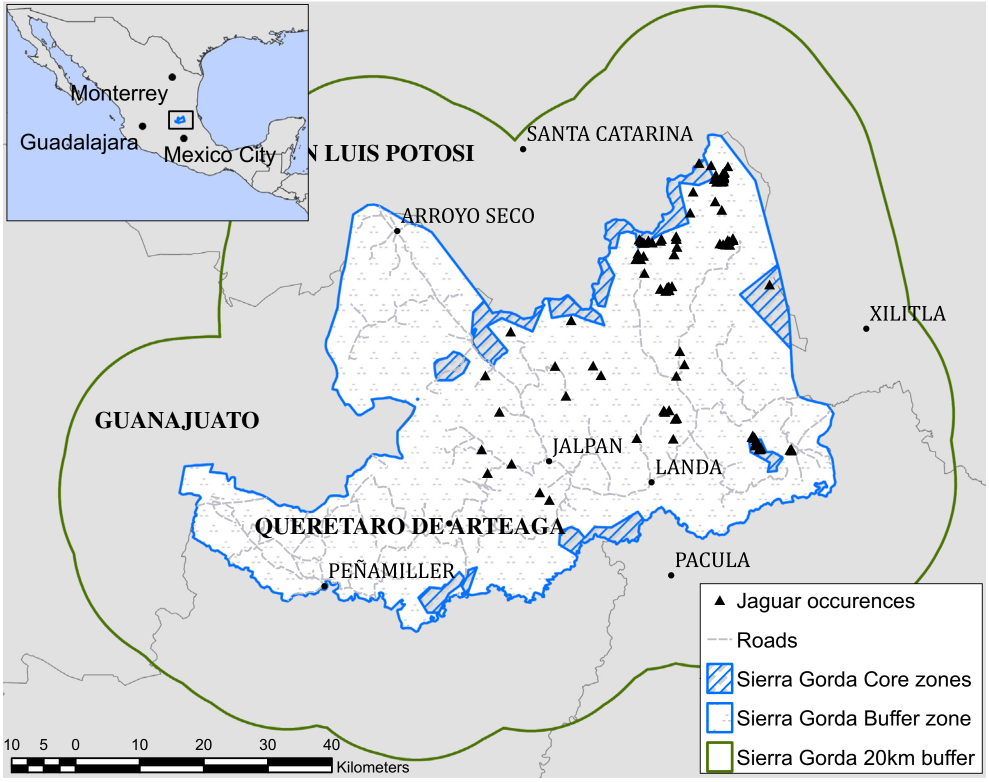

Fig. 1. Sierra Gorda Biosphere Reserve in Central Mexico. The core zones are located at the margins of the reserve.

patches, have become popular for conservation purposes (Correa Ayram et al., 2015). In the graph theory framework (Bunn et al., 2000), a potential habitat network is organized in patches of potential habitat (nodes) that are connected via edges (Urban and Keitt, 2001). However, there are several challenges associated with the assessment of habitat connectivity in this framework. First, because the output of potential distribution models is a continuum of suitability values, it is necessary to choose a threshold to differentiate habitat from non-habitat and hence delimitate potential habitat nodes. Different techniques have been proposed to define suitable habitat areas, such as using an arbitrary threshold (Manel et al., 1999) or to determine the threshold that minimizes the error rate for positive and negative observations in a potential habitat model (Jiménez-Valverde and Lobo, 2007; Liu et al., 2013). A second challenge is that any threshold of habitat suitability will result in patches that are highly variable in size, but many species can only occur in patches of a certain minimum patch size (Schutltz and Crone, 2005). Ultimately, the selection of both the suitable habitat and the minimum patch size thresholds may greatly affect the configuration of potential habitat patches (Saura and Martinez-Mlian, 2001; Turner, 1989; Wu, 2004) and therefore affect subsequent habitat connectivity analysis.

Analyses of habitat connectivity are inherently place- and species-specific, but case studies are valuable, especially in areas with high biodiversity and when the results can be translated to other ecosystems. One such area is Mexico, which has a high diversity of mammals, including several species of felines (CONABIO, 2008). Felines are considered a keystone species because they can control herbivore populations (Miller et al., 2001; Terborgh et al., 2001). Furthermore, felines are an important target for conservation plans, and their presence can indicate healthy ecosystems (Sanchez et al., 2002; Terborgh et al., 2001). However, populations of many felines, including jaguar (*Panthera onca*), have decreased in Mexico, and their habitats have become increasingly fragmented (Polisar et al., 2003). Prior studies have analyzed the potential habitat distribution of jaguars throughout Mexico (Cevallos et al., 2007; Rodríguez-Soto et al., 2011). There are also some local studies of jaguar habitat in southern (Figel et al., 2009), central (Monroy-Vilchis et al., 2008), and northern Mexico (Navarro-Serment et al., 2005), and jaguar habitat connectivity at local level in the northeast of Puebla state (Petracca et al., 2014). However, there is still uncertainty about landscape-scale jaguar habitat patterns, i.e., the scales where most conservation decisions are made. In terms of management, understanding habitat connectivity is important for the prioritization of conservation efforts, and to promote the effective allocation of conservation resources (Moilanen et al., 2009). Furthermore, studies on habitat connectivity are limited, despite their importance for the long-term conservation of wide-ranging species such as jaguar (Soisalo and Cavalcanti, 2006).

Here our goals were to a) assess potential habitat for jaguars and its connectivity in the Sierra Gorda reserve in Central Mexico, b) examine in detail the effects of different thresholds of habitat suitability and minimum patch size on the resulting connectivity, and c) develop a method to identify the optimal combination of these thresholds. Our hypothesis is that larger habitat patches, obtained with lower thresholds both for habitat suitability and minimum patch size, will promote better landscape connectivity for jaguars (Saura and Pascual-Hortal, 2007). It has been shown that larger patches of habitat promote landscape connectivity for large carnivores (Maehr and Deason, 2002; Theobald et al., 2011). Specifically, we predict that habitat suitability will have a stronger influence on connectivity than patch size. By integrating potential habitat and connectivity assessments, we hope to better understand habitat use by jaguars, and to assess habitat connectivity for other species and in other areas more accurately.

2. Methods

2.1. Study area

We conducted our study in the Sierra Gorda Biosphere Reserve (Sierra Gorda) in central Mexico, and all areas within 20 km of its border (11,548 km^2, Fig. 1). The Sierra Gorda is situated in the Sierra Madre

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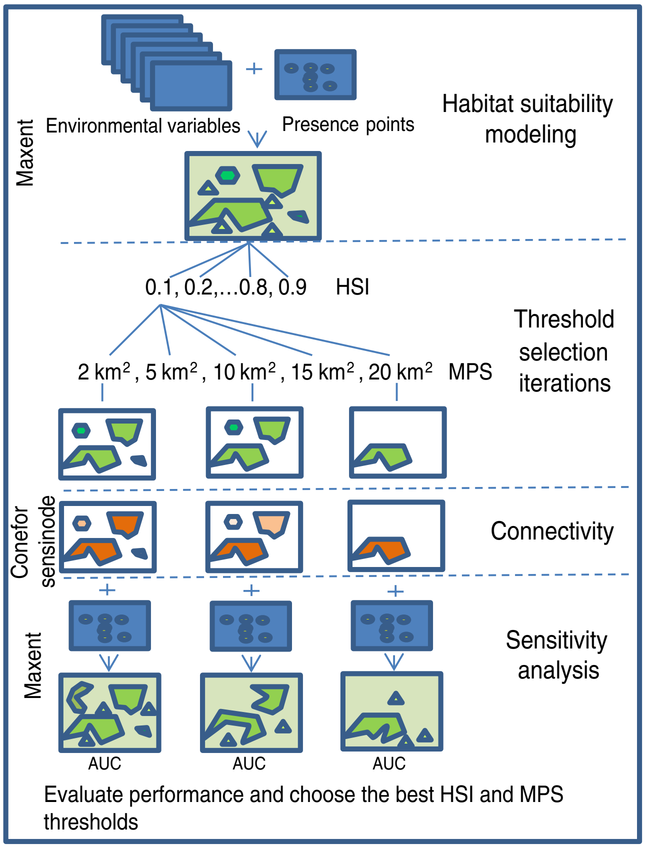

Fig. 2. Flow diagram of the approach that we developed to identify the best thresholds for habitat suitability index, HSI, and minimum patch size, MPS. We evaluated the performance of each combination of thresholds to describe connectivity based on the area under the curve, AUC. The processes are mentioned on the right while the tools used at each step are mentioned on the left. Only a few examples from the total of 45 combinations that we evaluated are shown here.

mountain range and contains many vegetation types, including semi-deserts, evergreen and deciduous tropical forest, oak, pine and cloud forests. Elevation ranges from 300 to 3160 m above sea level. Because of this variety of conditions, the reserve hosts a diversity of wildlife species and is one of the last refuges for jaguars in central western Mexico. The reserve contains a buffer zone, in which some human activities are allowed including agriculture and forestry in temperate areas and grazing on drier lands (INE, 1999). There are also eleven core zones within the Sierra Gorda reserve, in which human use is limited to conservation and research-related activities. All of the core areas are located at the edge of the reserve, which is different from the more typical pattern, where core areas are near the center of the reserves (Fig. 1).

2.2. Input data: Jaguar occurrences and environmental data

We obtained a digital georeferenced database of 117 jaguar occurrence points in the Sierra Gorda. The database was collected by the conservation group Grupo Ecologico Sierra Gorda between 2006 and 2009. The database includes direct animal observations (i.e., visual observations, camera trap photos), and indirect observations (i.e., footprints, droppings, reported cattle attacks). We assumed the database was accurate, as jaguars have a distinct appearance that is not easily confused with other species in the area. Although this database has not been updated since 2009, jaguars have been reported in the area since then (GESG, 2014). For the training and testing of our model, we divided the jaguar occurrence points into two sets. For model testing, we randomly selected 26 points (22% of total) that were at least 2 km apart from each other. For the remaining 91 occurrence points we conducted spatial filtering to eliminate points based on climatic heterogeneity using the SDM toolbox (Brown, 2014). The spatial filtering used the first three principal components of the environmental variables to find areas with low or high climate heterogeneity. Based on this assessment, we reduced the number of presence points in areas with similar climatic conditions to one point location for every 5 km^2, which is the minimum home range for female jaguars (Rodríguez-Soto et al., 2011). We applied this filtering to prevent the over-fitting of our model to environmental conditions present in clusters of points with low variability (Boria et al., 2014). The final training point database included 26 occurrence points. This number is low, but using a limited number of points is common when working with a rare species such as jaguar, and is preferable than several spatially autocorrelated points (Bean et al., 2012; Hernandez et al., 2006; van Proosdij et al., 2016). For the purpose of comparison, we also generated a model including the whole 117 points dataset and split it into two parts for training: 91 for training and 26 for testing.

We included six environmental predictor variables associated with the presence of jaguars (Spangle et al., 2014; Valera-Aguilar, 2010). These variables were temperature, precipitation, land cover, ecoregions, elevation and slope. Precipitation and temperature were obtained from the Servicio Meteorologico Nacional at 1-km resolution; elevation and slope were derived from Shuttle Radar Topography Mission (SRTM) at 90-m resolution; landcover from Instituto Nacional de Estadistica, Geografia e Informatica (INEGI, 2011) at a scale of 1:250,000, and ecoregions from the National Commission for Biodiversity (CONABIO, 1999) at a scale of 1:1,000,000. We retained all of these environmental variables after confirming that there was no strong correlation among them (Table A.1). All the environmental information was converted and scaled into raster format with 30-m resolution.

2.3. Potential habitat modeling

We performed a series of analyses to determine jaguars' potential habitat and connectivity for the Sierra Gorda (Fig. 2). To identify the areas of potential habitat for jaguars, we used the maximum entropy algorithm Maxent (Phillips et al., 2006). This machine-learning method uses species occurrence and environmental constraints from the study area, or background data, to estimate the probability of occurrence of the species based on the principle of maximum entropy. We restricted the calibration of our Maxent model to the areas within the Sierra Gorda found as suitable jaguar habitat in a previous coarse-scale analysis for jaguars in Mexico, which used a different jaguar dataset and a coarser resolution (Rodríguez-Soto et al., 2011). We did this to ensure that the background points were not taken at places that are widely afar from our occurrence data (Van Der Wal et al., 2009). We ran Maxent with the default settings (Phillips and Dudík, 2008) using 10, 000 maximum background points and 10 replicates with cross-validation. We then extrapolated the model to the rest of the study area to map potential habitat of jaguars within the entire Sierra Gorda.

2.4. Connectivity analysis

In order to assess habitat connectivity, we had to differentiate areas of habitat from non-habitat. We identified two types of thresholds to separate the areas suitable for jaguars from areas that are not suitable. The first threshold was based on Maxent's habitat suitability index, a continuous value ranging from zero to one, with values below the selected cutoff deemed to be non-habitat. The second threshold was based on the minimum patch size, with values below the selected cutoff deemed to be unsuitable, even if the habitat suitability value indicated the patch to be suitable. We performed 45 analyses using different values for our two thresholds in order to test how different combinations affected the subsequent connectivity assessment (Fig. 2). We first constructed multiple habitat suitability maps, where suitable habitat was defined as values greater than or equal to 0.1, 0.2, 0.3, …, 0.9 in

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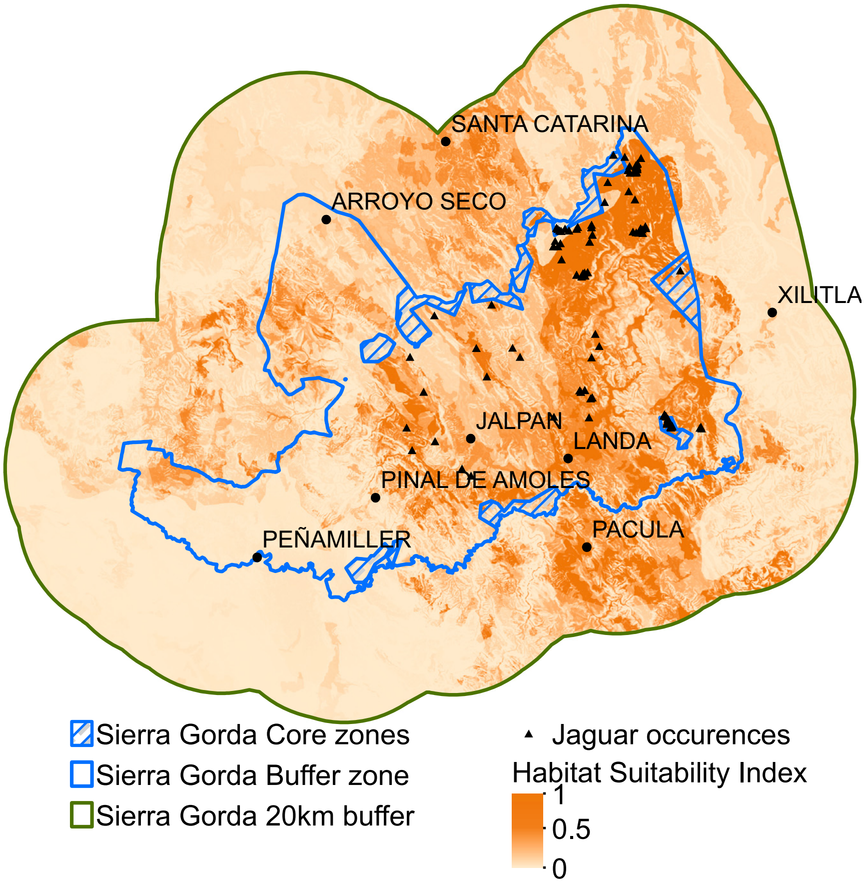

Fig. 3. Habitat suitability in the study area as determined by our model. The most suitable areas are in the central-eastern part of the reserve and in the south.

Maxent's habitat suitability index, increasing in steps of 0.1 units. We then eliminated potential jaguar habitat patches smaller than 2, 5, 10, 15, and 20 km^2 in each of the previous habitat suitability maps, for a total of 45 different potential habitat maps. We selected this range of minimum patch values because jaguars generally prefer large habitat patches of at least 20 km^2 (Núñez et al., 2002) but can temporarily occupy areas as small as 2 km^2 (Chavez and Cevallos, 2007). We measured the effects on landscape configuration caused by varying the thresholds in the resulting potential habitat maps. For this reason we calculated four landscape fragmentation metrics (number of patches, total patch area, mean patch area, and edge density) for each of the potential habitat networks obtained by each threshold combination using the software Fragstats (McGarigal et al., 2012).

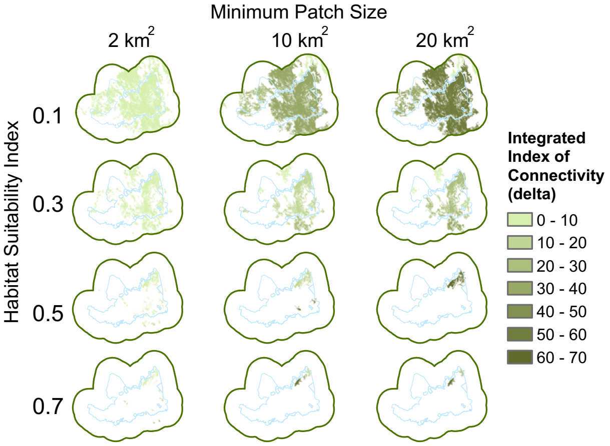

Fig. 4. Performance of the integral index of connectivity, dIIC, obtained with different habitat suitability thresholds and minimum patch size for the jaguar presence points. Patches with dark colors provide better connectivity for the patch network. For display purposes we do not include all the different combinations tested at different habitat suitability indexes and minimum patch size. No patches remained at a HSI larger than 0.8.

We employed Conefor Sensinode (Saura and Pascual-Hortal, 2007) to assess the patch connectivity within each potential habitat map obtained with a particular combination of thresholds. Conefor Sensinode is a decision-support tool that complements habitat analyses by quantifying the importance of specific habitat patches for overall landscape habitat connectivity (Ziółkowska et al., 2012). Conefor Sensinode calculates several connectivity indices, and we report here the delta of the Integrated Index of Connectivity (dIIC) because it has been proposed as ideal for connectivity analysis (Pascual-Hortal and Saura, 2007). The dICC ranges from 0 to 100 and assigns a value to each habitat patch, where small values indicate low importance for the overall connectivity of the habitat patch network and large values indicate high importance.

2.5. Identification of the optimal combination of thresholds

We performed a sensitivity analysis to identify the optimal combination of thresholds for habitat suitability index and minimum patch size that best described our data. For this we created 45 potential habitat maps using the connectivity scores as the only environmental input for habitat modeling and evaluated the performance of the model to describe our jaguar presence dataset (Fig. 2). We started with the maps obtained from the connectivity analysis, which contain the dIIC values obtained, and transformed it into a raster format. We then used Maxent with each of these maps with dIIC values as the only predictor variable for our jaguar presence points. Finally, we ranked the performance of each of the new runs using the area under the curve (AUC) for both the training

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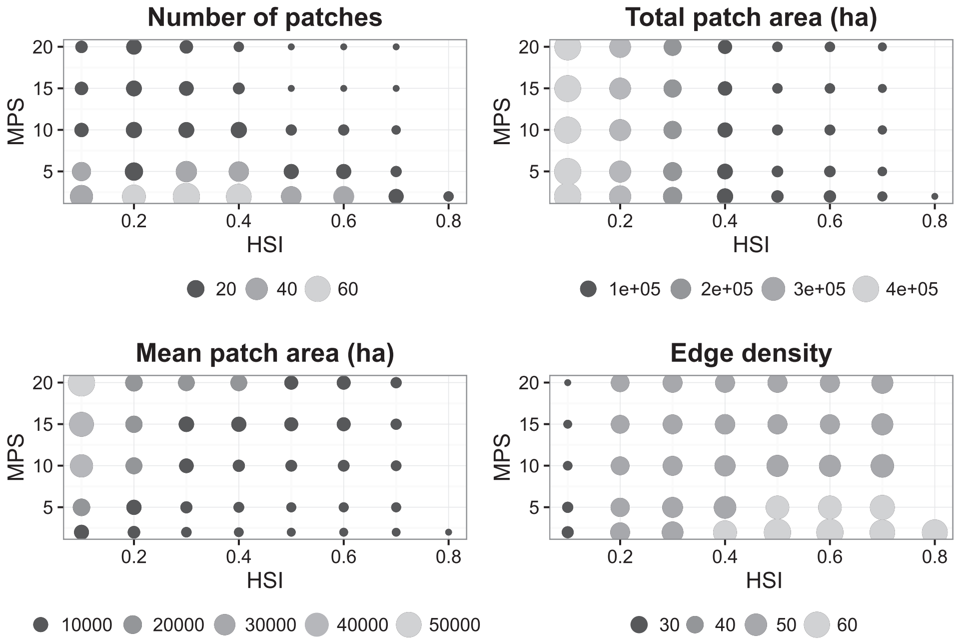

Fig. 5. Landscape configuration metrics for different habitat suitability index, HSI, and minimum patch size, MPS.

and testing presence points. AUC scores above 0.5 are considered better than random predictions and values above 0.9 considered highly accurate (Bateman et al., 2012; Guisan et al., 2007). In this way we identified which model combination of thresholds best described the relationship between the connectivity values obtained and the occurrence points.

3. Results

We obtained a potential habitat model based on the spatially filtered jaguar occurrences ($n = 26$). The model had an AUC of 0.91 for the training data and an AUC of 0.83 for the testing data. For comparison purposes, we obtained a model using all 117 occurrence data that resulted in an AUC of 0.92 for training and 0.86 for testing. The model results based on all occurrence points were overall very similar, but predicted a smaller area as highly suitable habitat than the model with the subset of points (Appendix 1). The model we used for subsequent analysis was the one produced with the subset of presence points, because of the potential spatial autocorrelation of the training points in the model produced with the full dataset of points.

We found that two of the eleven core zones of the reserve contained highly suitable habitat for jaguars (Fig. 3). However, most of the potential habitat was located in the central eastern part of the reserve in areas that are formally designated as buffer zones. No areas were identified with a habitat suitability index > 0.87. Among the environmental predictor variables, ecoregions, land cover, and slope were the main explanatory variables, contributing 91% of the model's explanatory power, while precipitation, temperature and elevation contributed only 9% (See Appendix 2). The most important ecoregions for jaguar habitat were the Sierra Madre Oriental pine and oak forest and the Planicie Costera Tamaulipeca dry forest. The vegetation types with higher likelihood for jaguar occurrences were tropical deciduous forest and temperate forest, and areas with precipitation of 1000–2000 mm/year. There was minimal potential jaguar habitat in the desert and semi-desert regions within the study area. The habitat model also indicated that occurrence points were primarily located on slopes < 40 degrees.

3.1. Threshold selection

The 45 binary maps of potential habitat versus non-habitat generated with different combinations of habitat suitability index and minimum patch size thresholds resulted in vastly different total areas and spatial configurations of remaining habitat patches (Fig. 4). As expected, when selecting smaller habitat suitability index values, we obtained relatively few, large and continuous suitable patches across our study area (Fig. 5). In contrast, with higher habitat suitability index thresholds, only small patches remained, which were concentrated in the north eastern part of the reserve. We also observed our expected changes in the configuration of suitable habitat patches when applying different minimum patch size thresholds. Small thresholds ($<10\ \text{km}^2$) resulted in numerous patches located across the reserve. In contrast, higher thresholds ($>10\ \text{km}^2$) led to a smaller number of patches located towards the central and eastern part of the reserve (Fig. 4). The mean patch area decreased proportionally to minimum patch size, and the edge density increased as we restricted the habitat suitability threshold. Large thresholds on both of the variables reduced the total area of the potential habitat patches.

3.2. Habitat connectivity

Different combinations of our two thresholds resulted in vastly different connectivity dIIC values, which changed according to the number and size of the habitat patches. The dIIC connectivity values ranged from one, for patches that contributed little for the connectivity of the patch system, to 100, for those patches that contributed the most. Among the different sets of patches obtained with different threshold combinations, the dIIC values ranged from 0 to 6 in landscapes comprised on numerous patches, and 0–95 for a habitat landscape with fewer patches (Fig. 4). As anticipated, the patches that were most important for maintaining connectivity were generally the larger ones, and the most important patches for connectivity were located towards the center and eastern part of study area. However, the potential habitat patch configuration resulting from lower threshold combinations indicated that patches located in the central area of the reserve had the highest dIIC values.

3.3. The optimal combination of thresholds

When we used the potential habitat patches and their respective connectivity values as the only explanatory variable for Maxent, we obtained different model performances and AUCs ranging from 0.49 to

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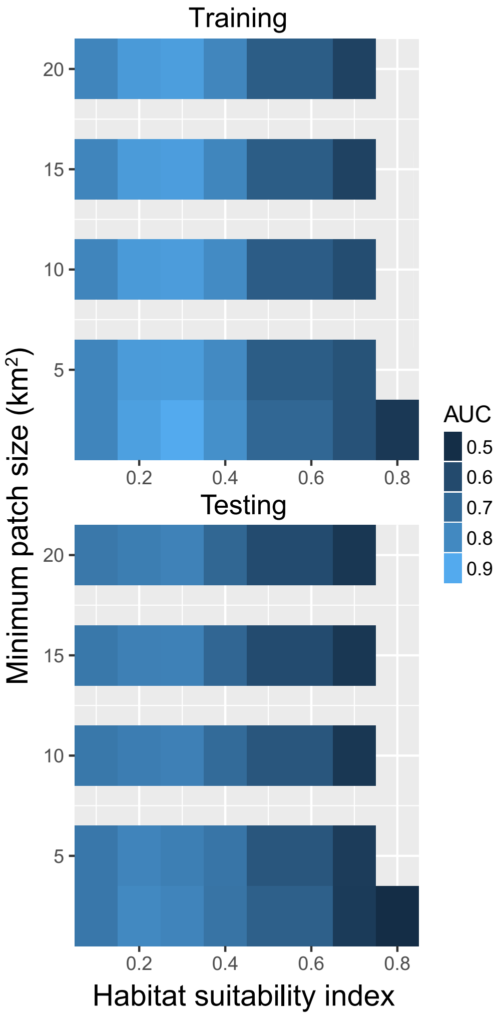

Fig. 6. Performance of the integral index of connectivity obtained with different habitat suitability thresholds, and minimum patch size for the jaguar presence points. A better model has a higher area under the curve (AUC), and therefore a lighter color. No patches were left with a HSI larger than 0.8.

0.90 for the training data (Fig. 6). Based on these results, we selected the best performing model, which was based on a habitat suitability index threshold of 0.3 and minimum patch size of 2 km^2. This model had a performance an AUC of 0.90 for the training data and 0.78 for the testing one. From the two variables, changes in habitat suitability index resulted in a larger variation in the AUC compared to changes in the minimum patch size. The resulting potential habitat and connectivity map (Fig. 7) showed the areas that promote better connectivity towards the central eastern part of the reserve as well as southeast of it.

Fig. 7. Connectivity of the potential habitat for jaguars in the reserve using the combination of thresholds for habitat suitability index 0.3 and a minimum patch size of 2 km^2. The habitat areas that are most important for the connectivity of the area are located in the eastern portion of the reserve.

4. Discussion

Potential habitat mapping is a tool that is widely used in conservation science and conservation planning (Elith and Leathwick, 2009; Guisan and Thuiller, 2005), and forms the basis for most habitat connectivity analyses. Here we mapped the potential habitat for jaguars in the Sierra Gorda reserve and assessed its connectivity. We found that connectivity was highly sensitive to the thresholds used to delimit potential habitat. Based on our novel approach to identify the optimal threshold values, we found that a threshold of 0.3 for the habitat suitability index and of 2 km^2 for minimum patch size resulted in the optimal potential habitat assessment, because the corresponding connectivity assessment best matched our jaguar observations.

The potential habitat map for jaguars that resulted from our analysis captured jaguar occurrences in the Sierra Gorda well, as evidenced by the high AUC of 0.91. The predicted areas of high habitat suitability also coincided with the vegetation types reported as habitat for jaguars in other studies such as temperate, deciduous and tropical forest (Navarro-Serment et al., 2005; Zarco-González et al., 2009), and oak-pine forest (Figel et al., 2009; Monroy-Vilchis et al., 2008). Drier vegetation types in the western parts of the study area were not detected as potential habitat for jaguars, although xeric vegetation is occupied by jaguars in other parts of Mexico (Sanderson et al., 2002a, 2002b; Valera-Aguilar, 2010). Not including xeric vegetation as habitat in our map may be a consequence of not having presence points on such dry land. However, our map is consistent with a nationwide analysis of jaguar habitat in the area, which found low habitat suitability in the xeric areas of the reserve (Rodríguez-Soto et al., 2011). However, our model showed more limited potential habitat areas for our study area compared with the previous national model, possibly because we had a local dataset and incorporated a sensitivity analysis on both thresholds. In the future, given the opportunistic nature of our presence data, there are opportunities to incorporate a more systematic data set via GPS or camera traps, which could improve model outputs by capturing a larger variability of conditions in which the species occurs (Tobler et al., 2008) and also by ensuring the accuracy of the observations with precise location data. This highlights the need for local and regional analyses of habitat suitability even for wide-ranging species, such as jaguars, because their habitat use can differ within larger areas.

Selecting thresholds correctly is crucial when using the output from a potential habitat model for further analyses such as connectivity assessments (Liu et al., 2005). Several threshold selection criteria have been proposed to delimit suitable habitat (Freeman and Moisen, 2008; Jiménez-Valverde and Lobo, 2007; Liu et al., 2013; Norris, 2014), but none of these took into account how the thresholds may affect connectivity. In our analysis, we produced numerous connectivity assessments, and these assessments varied greatly in their ability to explain jaguar presence data. While changing the habitat suitability thresholds, we observed a tradeoff of either being very restrictive in our analysis (with higher habitat suitability index thresholds) or too permissive (using lower habitat suitability index scores). When using large thresholds, only few areas remained as potential habitat and many of our presence points were outside of those areas.

From our analysis of 45 combinations of thresholds, we found that the best connectivity assessment was the one resulting from a habitat suitability index threshold of 0.3. This number is consistent with two of Maxent's calculated logistic thresholds: the 10th percentile training presence (0.36) and the maximum training sensitivity plus specificity

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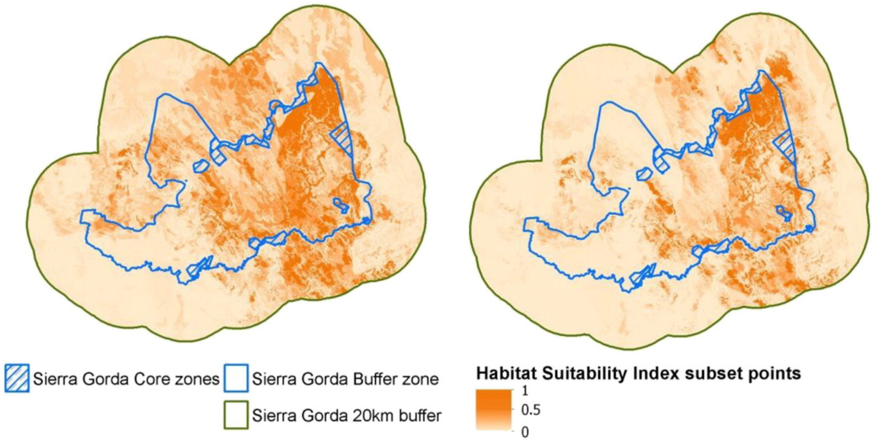

Fig. A.1. Habitat suitability index for the study area obtained with 26 spatially filtered subset of training points (left) and with all the 91 training points (right).

thresholds (0.32). Maxent's thresholds are calculated by evaluating model performance based on omission rate (number of training/test presences that fall into unsuitable pixels) and the proportional predicted area (the proportion of all pixels that are predicted suitable for a species) (Phillips et al., 2006). The 10th percentile threshold corresponds to the predicted habitat suitability value with a 10% omission rate on occurrence points, which has been suggested as an ideal threshold in similar studies (Escalante et al., 2013; McFarland et al., 2013). The maximum training sensitivity plus specificity threshold balances the chance of correctly identifying suitable areas (sensitivity) with the change of correctly assigning unsuitable areas (specificity). By maximizing specificity plus sensitivity we delimit the best areas within our landscape that can host jaguars, and eliminate areas with lower habitat potential and thus being more specific. A higher threshold value can be used to target the best areas able to host jaguars by reducing the risk of choosing low quality sites but with the risk of eliminating some locations with actual jaguar observations and therefore being less sensitive (Pearce and Ferrier, 2000; Pearson, 2007).

Minimum patch size had previously been identified as important for landscape connectivity (Pascual-Hortal and Saura, 2007), and for the delineation of potential habitat (Olson et al., 2014), and our results highlighted the extent to which connectivity depended on minimum patch size. However, the effects of minimum patch size on connectivity were smaller than those of the habitat suitability index threshold. The AUC changed much more when varying the cutoff value of habitat suitability index and less when varying the minimum patch size cutoff value. We found that the best performance in terms of predicting our jaguar occurrence points occurred with a minimum potential habitat patch size of 2 km^2. Jaguars have a large range and they have been reported to prefer large habitat patches of 20 km^2 or more (Núñez et al., 2002; Valera-Aguilar, 2010). However, jaguars may also explore areas as small as 2 km^2 when dispersing to other territories or for hunting (Cavalcanti and Gese, 2009). In our study, larger patch size thresholds (>15 km^2) reduced the number of potential habitat patches to a level where they no longer captured the presence points. This may indicate that jaguars, although preferring large habitat patches, are forced to use relatively small patches of fragmented potential habitat in Sierra Gorda, such as farm areas, where prey might also be available including livestock.

The most important potential habitat patches for overall connectivity were generally the largest patches. This is partly a function of the dICC metric which weighs the area of each of the potential habitat patches, giving priority to larger patches. Ecologically though, these large patches are also very important for jaguars because their large home range and therefore the remaining large potential habitat patches should be a priority for conservation. The dIIC has been used previously to identify the most important patches for maintaining and prioritizing forest protection (García-Feced et al., 2010; Pascual-Hortal and Saura, 2007; Shanthala Devi et al., 2013), as well as providing habitat for other large mammals such as tapir (García and Leonardo, 2016). Therefore, we suggest that based on our analysis, the best-connected areas in the central eastern part of the reserve deserve particular conservation attention (Fig. 7), because they have vegetation types that are highly suitable for jaguars and these areas are part of the proposed jaguar corridor for central Mexico (Rabinowitz and Zeller, 2010).

The current designation of core and buffer areas in the Sierra Gorda reserve neither captures the highest quality habitat for jaguars nor the most important patches for connectivity very well. In our potential habitat map, a small percentage of the core area of the reserve was suitable for jaguars. When created in 1997, the Sierra Gorda reserve included eleven core zones to preserve forests located at the edges of the reserve, with the purpose of having multiple ecosystems represented and to have more conserved lands with restricted access (INE, 1999). However, most of these areas have little potential for hosting jaguars according to our results, whereas the central buffer zone has higher likelihood for jaguar presence. We also detected areas outside of the reserve that are suitable for jaguars. Our finding parallels that of another study, which found that the current core areas of the reserve have also lower potential for providing bird habitat in the region, compared to central regions of the reserve (Almazán-Núñez et al., 2013). We suggest that additional core areas in the center of the Sierra Gorda reserve could be highly valuable for conservation.

In summary, we were successful in mapping potential jaguar habitat and its connectivity in the Sierra Gorda reserve. In our analyses, we focused in particular on the effects of thresholds for habitat suitability and minimum patch size, showed that these two thresholds have large effects on subsequent connectivity assessments, and developed a new method to identify the optimal combination of these thresholds. This approach for assessing landscape connectivity can easily be transferred to other ecosystems and different species. In terms of conservation we identified the areas more suitable to provide habitat for jaguars in the Sierra Gorda reserve, and those that contribute most to their connectivity. Unfortunately, many of these areas are not currently designated as core zones of the reserve. These areas could host jaguars and other species that may well be using the landscape regardless of current protection status. Therefore local-scale studies such as ours one might highlight the opportunities for reaching larger and integrated conservation goals. Managers and stakeholders may want to use our findings in combination with other local studies to improve their conservation efforts.

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Appendix A. Appendix

Fig. A.2. The contribution of the main variables to the habitat suitability model. Slopes are in degrees. The ecoregions are 1: Northern Meseta Central desert; 2, Veracruz coastal plain tropical moist forests; 3, Southern Meseta Central desert; 4, Northern Sierra Madre Oriental pine-oak forests; 5 Tamaulipas coastal plain tropical dry forests; 6, Sierra Madre Oriental pine-oak forests; 7, Veracruz montane tropical cloud forests. The y-axis represents the logistic output from Maxent, which is the relative probability of occurrence of the species for the given category.

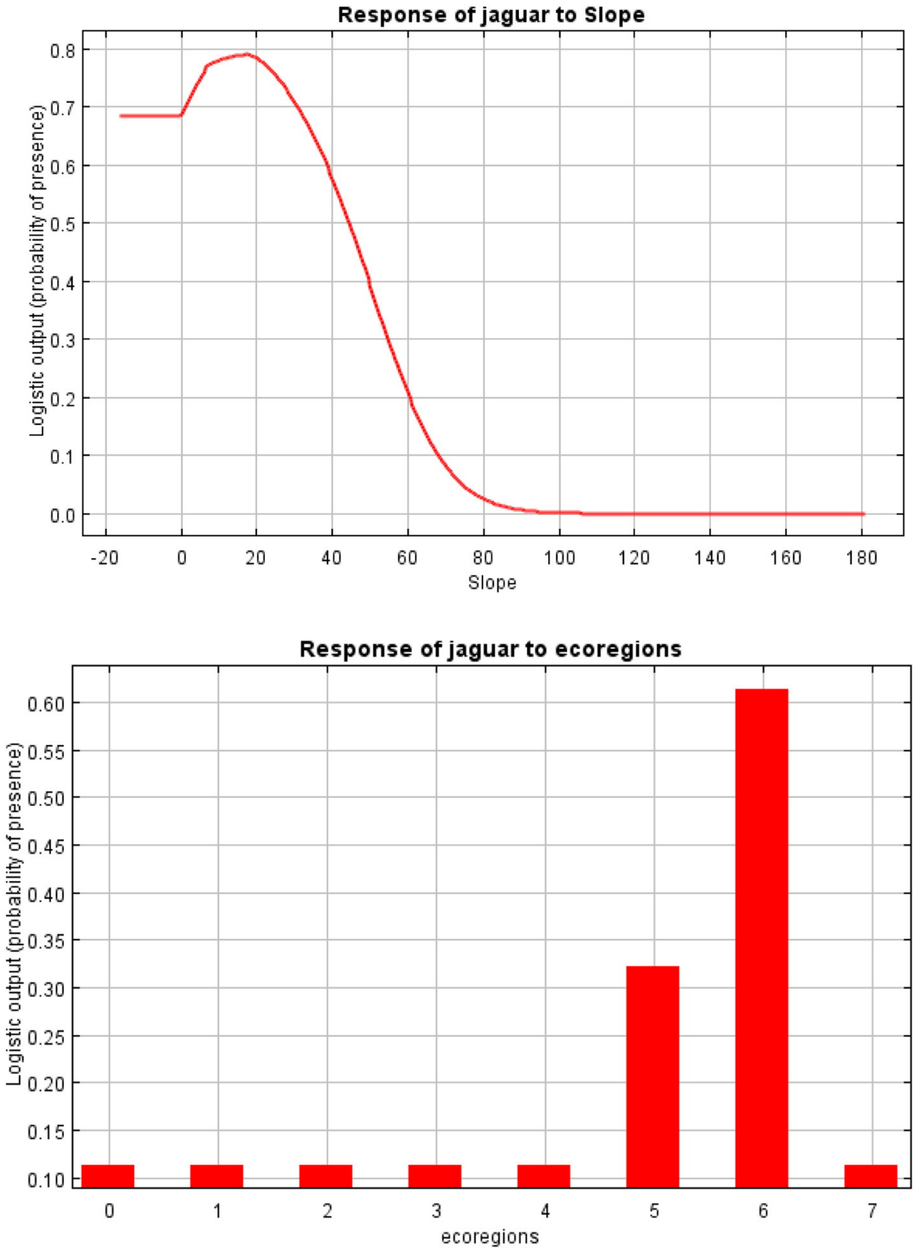

Table A.1
Pearson's correlation coefficients for the used predictor variables.

	Ecoregions	Elevation	Precipitation	Slope	Temperature	Landcover
Landcover	−0.02	−0.27	0.35	0.04	0.2	1
Temperature	−0.11	−0.57	0.44	−0.03	1	
Slope	0.23	0.2	0.04	1		
Precipitation	−0.1	−0.58	1			
Elevation	0.26	1				
Ecoregions	1					

Appendix B. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.biocon.2016.10.020. These data include the Google map of the most important areas described in this article.

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