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Corridors for jaguar (*Panthera onca*) in Mexico: Conservation strategies

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ABSTRACT

Several species of carnivores, as jaguar, live in low densities and require extent habitat areas for survive. One of their main threats is fragmentation and demographic isolation. Identifying the habitat corridors, we can help the conservation of these species. We identified the viable and potential corridors between jaguar management and conservation areas for *Panthera onca* in Mexico. We considerate an ensemble model of the potential distribution of *P. onca* in Mexico, from which were identified jaguar management and conservation areas (JCMA). According to these attributes, we identified the possible habitat corridors between the JCMA with Corridor Designer. Thirteen habitat corridors were between all JCMA. However only seven were viable corridors and six were potential corridors. Also, in two areas of potential corridors were identified Stepping Stones that can help the jaguar movement between large fragments. In the thirteen habitat corridors, the main threats for jaguars are habitat fragmentation, roads, highway and possible conflict human-wildlife (livestock predation). The results from this work can provide the bases to take actions on the protection of connecting zones and alleviate the mortality of wildlife in these areas.

Introduction

Large carnivores are often used to identify prioritized areas for biodiversity conservation (Carroll, Reed, & Paquet 2001; Crooks 2002; Singleton, Gaines, & Lehmkuhl 2002). Moreover, they are good models to design biological corridors at wide spatial scales (Carroll 2006; Noss & Daly 2006). To identify the corridors, three approaches are applied: intuitive (expert advice), empirical, and modeling (Noss & Daly 2006). For the modeling, the implementation of a permeability matrix based on the habitat distribution of the interest species is used (Theobald, 2006). There are useful methodologies to identify corridors based in modeling tools as the least-cost path or the cost-weighted distance (Crooks & Sanjayan 2006; Singleton et al. 2002). These models are with some carnivores' species: bear, coyote, puma, ocelot, jagouaroundi and jaguar (Beier 1993; Colchero et al., 2010; Grigione et al. 2009; Singleton et al. 2002). The jaguar (*Panthera onca*; Linnaeus, 1758) is important in the maintenance of equilibrium ecosystems where it occurs, regulating prey population sizes. Since the jaguar needs large areas for survive and reproduce, it is an umbrella species. By preserving, the habitat needed jaguar to survive, all other species in the ecosystem benefit from the protection (Jaguar conservation foundation, 2009). In this way *P. onca* is a good model to identify corridors. With this species there are studies that identify important areas for its conservation at continental level (Rabinowitz & Zeller 2010; Sanderson et al. 2002) and national level: México (Rodríguez-Soto et al. 2011), Nicaragua (Zeller et al. 2011), Guatemala (McNab & Polisar 2002) and Brazil (Tôrres et al. 2008).

For *P. onca* there are proposals of corridors for the Americas, that use a geographic information system (GIS) and expert input to create a dispersal cost surface and identify least-cost corridors connecting the 90 known populations across the jaguar's American range (Rabinowitz & Zeller 2010). The said study identified five corridors of concern and eight dispersal corridors in Mexico, one of the corridors of concern connect areas of northeast and northwest Mexico. However, are recommendable studies with better definition spatial, mainly in areas with variable environmental, biological and anthropic diversity, such as Mexico. This allows have more applicable and reliable conservation proposals at national level (Rodríguez-Soto et al. 2011; Sanderson et al. 2002).

The study of jaguar in Mexico (Rodríguez-Soto et al. 2011) suggests the necessity of generating corridors and offering national spatial strategies for jaguar conservation. Jaguar, as other carnivores, presents low densities and requires extensive habitat areas in order to survive; two of its main threats are habitat fragmentation and demographic isolation (Carroll et al. 2001; Crooks 2002; Singleton et al. 2002). Due to this, identifying the habitat corridors

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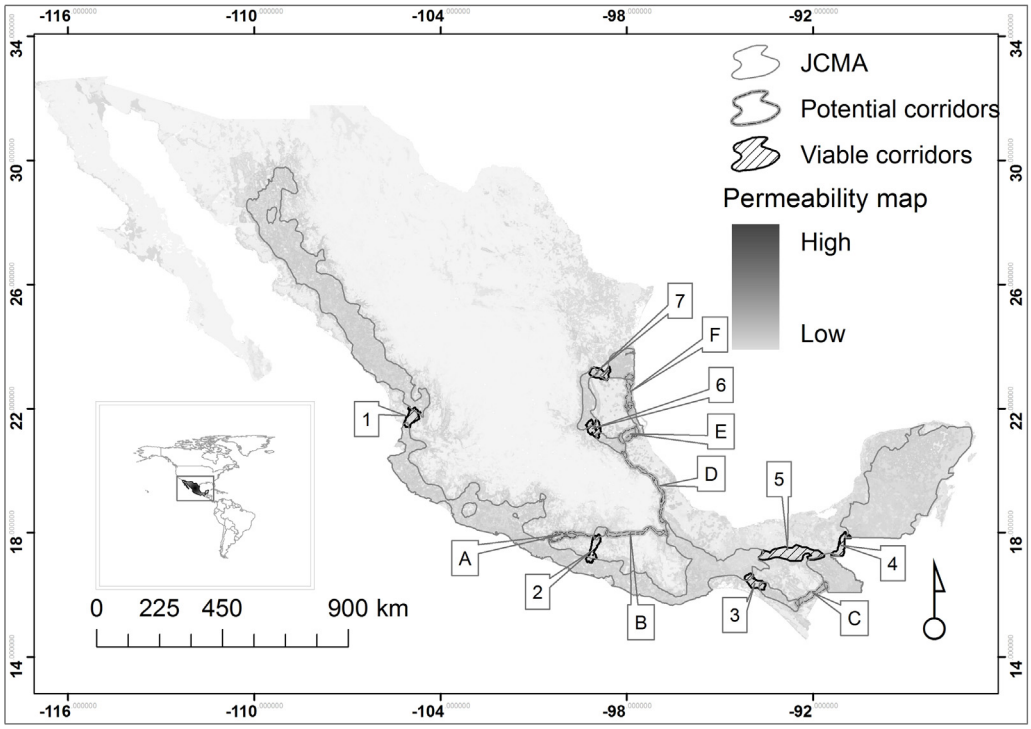

Fig. 1. Permeability map and habitat patches (Rodríguez-Soto et al., 2011) and the viable (letters) and potential (numbers) corridors for jaguar in Mexico. (1) North to south of the Pacific Coast, (2) North of Olinala to south of Pacific Coast, (3) South Pacific coast to southern Chiapas, (4) Lacandona to Yucatan Peninsula, (5) Southeast of Pacific Coast to Lacandona, (6) Sierra Madre Oriental to Chapulhuacan, (7) Sierra Madre Oriental to Tamaulipas Sierra. (A) Pacific South Coast to Olinala North, (B) Olinala North to Mazateca Sierra, (C) South of Chiapas to Montes Azules, (D) Could Forests of Sierra Madre Oriental to Sierras of Northern Mixe Oaxaca, (E) Chapulhuacan to Tamiahua, (F) Tamiahua to Tamaulipas.

is important for the viability of the species populations. The results of this study can produce guidelines to take action on the protected sites to connect jaguar conservation areas (Beier et al., 2006; Theobald 2006). The goal of this study is to identify the corridors between jaguar conservation and management areas (JCMA) in Mexico (Rodríguez-Soto et al. 2011) and to analyze the viability of the corridors, considering human activities (roads, human settlements, agriculture and livestock rearing). In addition, in two areas of potential corridors we identify "stepping stones" that can help the jaguar movement between large fragments.

Study zone

Mexico covers almost 2 million km^2, from 32°43′ to 14°32′. The topography is very complex, with more than 65% of the country's area above 1000 m.a.s.l. (De Alba & Reyes 1998). These characteristics have contributed to make Mexico one mega-diverse country (Ramamoorthy, Bye, & Lot 1993) and one of the most important biodiversity hotspots (CBD 2009). The terrestrial ecosystems of Mexico are tropical deciduous forest (33.51 million ha, 11.26% of the national extension), evergreen tropical forest (17.82 million ha, 9.1%), montane forest (0.87 million ha), temperate coniferous forests and hardwoods (43.96 million ha, 16.45%), xerophytic scrub (70.49 million ha, 29.7%), grassland (18.68 million ha, 6.38%), and wetlands (770 000 ha, 0.66%; INEGI 2003, 2005).

Methods

A useful method of determining corridors is through the development of least-cost paths (Kautz et al. 2006; Larkin et al. 2004; Meegan and Maehr 2002; Penrod et al. 2006; Schadt et al.2002). This technique models the relative cost for an animal to move between two areas of suitable habitat (Penrod et al. 2006). The cost distance is the prerequisite for finding the least cost path or corridor. The cost distance functions are similar to Euclidean functions, but instead of calculating the actual distance from one point to another, the cost functions determine the shortest weighted distance (or accumulated travel cost) from each cell to the nearest cell in the set of source cells. The weighted distance functions apply distance in cost units, not in geographic units. All weighted-distance functions require a source raster (end of each habitat patch) and a cost raster (permeability map).

The ensemble model of jaguar distribution in Mexico (Rodríguez-Soto et al. 2011, Fig. 1) was considered as cost raster or permeability map. Considering the same ensemble model of jaguar distribution in Mexico (Rodríguez-Soto et al. 2011; Fig. 1); jaguar conservation and management areas (JCMA) were identified with the module "create habitat patch" of Corridor Designer in ArcGis 10 (Beier, Majka, & Spencer 2008). We used the ending points of these JCMA as habitat patches or source raster. A habitat patch is a cluster of pixels that are good enough, big enough, and close enough together to support breeding by a particular species. In a GIS context, modeling patches requires a moving window size that reflects perceptual range and landscape effects on habitat quality. A minimum threshold of habitat quality required for breeding and a minimum area to support breeding. In these case, we used 5-kilometer wide moving window, considering 25 km^2 that is the minimal value of home range for the jaguar (Núñez, Miler, & Lindzey 2002), a minimal habitat quality of 45% as threshold (Rodríguez-Soto et al. 2011). A minimal patch size 900 km^2 were used (considering that these is the smallest continuous area necessary to preserve a viable jaguar population; Rodríguez-Soto et al. 2011).

Considering these two attributes (permeability map and habitat patches) the corridors between the JCMA were produced utilizing "creating corridor" by Corridor designer (ArcGis 9.2). Corridor

Table 1
Variables analyzed to identify the anthropic and environmental viability of the corridors between JMCA.

ID	Variable	Source	Author	Year
1	Vegetation cover	National Forest Inventory	SEMARNAT et al.	2001
2	Human disturbance	Agriculture	SEMARNAT et al.	2001
		Road network	CONABIO	2008
		Human population density	FAO	2005
3	PNA	Protected natural areas	CONANP	2007
4	Elevation	Digital elevation model	USGS	2007

designer uses the inverse of habitat suitability as a permeability map and the starting and ending points of each patch to model the corridor. From this, the module calculates the cost-distance of each pixel and chooses an appropriate layer of the distance cost maps as a corridor.

There are no data on the minimal necessary width for a corridor functional, nevertheless, in this model the corridors with more than 10 km in width were considered viable (Colchero et al. 2010; Rabinowitz & Zeller 2010); while those with a smaller width at any point along them were considered potential.

We analyzed anthropic (roads, localities, agriculture and livestock rearing) and environmental (altitude and vegetation) variables between JMCA's to explore the viability of the corridors (Table 1). Besides the protected natural areas were compared (Table 1).

The corridors between Could Forests in Sierra Madre Oriental (CFSMO) and the Sierras in Northern Mixe Oaxaca (SNMO) and between the South of the Pacific Coast (SPC) and Northern Olinala (NO) are the largest and narrowest corridors. These corridors may hinder the passage of jaguars. To solve this, we apply additional analysis for these zones (Hilty et al. 2006). Other smaller patches were identified, although do not allow the establishment of jaguar populations may facilitate dispersal through the corridor. The smallest habitat patches (areas between 10 and 900 km^2)were called "stepping stones" were identified with the habitat "create patch module" (Corridor Designer, ArcGIS 9.2).

Results

Thirteen habitat corridors between JCMA were identified; out of them, seven were viable and six potential (Tables 2 and 3; Fig. 1), together they comprise an area of 32 695 km^2 (20 173 km^2 viable and 12 512 km^2 potential). There were Protected Natural Areas (PNA, 3296 km^2 that correspond to 16.33% of the corridors) in five viable corridors and in five potential corridors (Tables 2 and 3; supplementary data). Exist records of jaguar in six of the viable corridors and in five of the potential corridors (supplementary data).

The minimal width of the viable corridors is 14.25 km and the maximal length is 230 km (Table 2). The minimal width of the potential corridors is 2.43 km and the maximal length is 320 km. The viable and potential corridors characteristics are shows in the supplementary data.

Twenty-three stepping stones between the Could Forests of Sierra Madre Oriental and the northern Mixe Oaxaca were identified, with extensions between 17 and 1020 km^2 (total area: 2596 km^2); the shortest distance between these patches is 1 km and the longest 23 km (Fig. 2).

Six stepping stones from southern Pacific coast to the north of Olinalá were identified, with extensions from 92 to 1020 km, which account for a surface of 2770 km^2. The shortest distance between these is 1 km and the longest is 11 km (Fig. 3).

Discussion

This study shows a solid analysis to identify the main areas to connect the JCMA's, in order to influence on the guidelines for conservation and restoration projects in Mexico. This is the first study in Mexico that proposes corridors at national level (2 000 000 km^2) for the management and conservation of jaguar considering environmental and anthropic variables. This study can be a model for others country's and guidelines for conservation strategies of jaguar in the Americas.

The principal Government Mexican effort in biodiversity conservation is the PNA's, this strategy is very poor and insufficient due to logistic and economics problems in the operation and a few representation of biodiversity and principally several top predators (Domínguez-Vega et al. 2012; Rodríguez-Soto et al. 2011).

Comparing the JCMA identified in these study and the identified by Rodríguez-Soto et al. (2011) in these analyses found two new areas in northeastern Mexico and only one area in the center and south pacific coast. An applicable challenge of the study it

Table 2
The seven viable corridors for jaguar in Mexico are shown and their characteristics described.

Id	Corridor	Localization	Area (km^2)	Minimal width (km)	Maximal lenght (km)	Habitat[a] (%)	Protected natural areas
1	North to south of the Pacific Coast	Western Tepic	2057	30	72	80.5	Sierra San Juan and Feeding basin of the 043 watering district of the State of Nayarit
2	North of Olinala to south of Pacific Coast	East of Chilapa	2137	14	105	71.4	No PNA
3	South Pacific coast to southern Chiapas	From Tehuantepec Isthmus to Sepultura	2183	25	78	82.4	Sepultura and Selva Zoque
4	Lacandona to Yucatan Peninsula	South of el Trebol	2060	20	79	76.3	Usumacinta Canyon
5	Southeast of Pacific Coast to Lacandona	From Tehuantepec Isthmus to Lacandona	7642	16	230	45.3	Palenque, Cascadas de Agua Azul, Sierra de Tabasco and Agua Blanca
6	Sierra Madre Oriental to Chapulhuacan	Xilitla and west of Temazunchale	2025	37	62	76.7	Sierra Gorda
7	Sierra Madre Oriental to Tamaulipas Sierra	West of El Cielo and Xicotencatl	2069	26	61	88.9	No PNA

[a] Habitat is the percentage of jaguar suitable habitat inside each corridor.

Table 3
The six potential corridors for jaguar in Mexico are shown and their characteristics described.

Id	Corridor	Localization	Area (km^2)	Minimal width (km)	Maximal length (km)	Habitat[a] (%)	Protected natural areas
A	Pacific South Coast to Olinala North	Mexcala	1368	2.5	164	90.5	No PNA
B	Olinala North to Mazateca Sierra	Sn Miguel Amatitlan North and Tehuacan South	2207	3	229	44.9	Tehuacán-Cuicatlan, Zapotitlan and Valley of Cuicatlan
C	South of Chiapas to Montes Azules	El Triunfo to la Concordia	2170	8	131	61.5	Lagunas de Montebello
D	Could Forests of Sierra Madre Oriental to Sierras of Northern Mixe Oaxaca	East of Cordoba and west of Xalapa	2484	3	320	69.8	Cofre and Perote, Necaxa River, San Pedro en el Monte and San Juan del Monte
E	Chapulhuacan to Tamiahua	Huautla, Amatlan and Cerro Azul	2119	28	72	70.0	Otontepec Sierra
F	Tamiahua to Tamaulipas	Sierra Lakes of San Andres	2174	9	132	74.6	No PNA

[a] Habitat is percentage of jaguar suitable habitat inside each corridor.

is that the spatial connectivity in two spatial scales (regional and landscape scale) was analyzed, it allows a comprehensive planning and a more feasible application (Noss & Daly 2006). With these two modeling scales, a similar modification was reported (Zeller et al. 2011). We propose that modeling the corridors in regional scale shows a more real approach and before of the validation fieldwork allow distribute resources.

The corridors identified in this study differ from others proposed for Mexico (Rabinowitz & Zeller 2010). The main difference is that in the present study no exits corridor, in the north, between northeast and northwest Mexico. Such a corridor is unlikely to occur, the jaguar potential habitat in that zone have very low suitability and there are too long (670 km straight in line between Sierra Madre Oriental and Sierra Madre Occidental). Furthermore, in these zones the climate is arid with extreme temperatures (annual thermal amplitudes of 20 °C and a peak temperature of 45 °C) and low precipitation (50–380 mm annual precipitation; Challenger 1998). It is the largest deserts in Mexico. Besides, there are few potential preys, such as deer and other vertebrates (Patterson et al. 2007) and nine federal roads travel across it, some of these are highways.

In contrast, our new identified corridors have zones with high potential habitat values are sorter and in several of them, exist jaguar presence. In this study, the connection between the West and East Jaguar populations is for the Central-south of Mexico over River Balsas Basin.

At a local level, in some regions of Mexico there are approaches that try to identify and preserve habitat corridors for this and other species. As example, Grigione et al. (2009) agrees with this work on identifying the area between El Cielo Reserve and Tamaulipas Sierra as potential corridor. Also in almost all of the corridors, the presence of jaguar has been registered (Cruz et al. 2007).

The next step of these research it is to explore the functional connectivity in each corridor identified (Taylor et al., 1993; Wiens 2001). Mostly, the main threats for jaguars along the possible

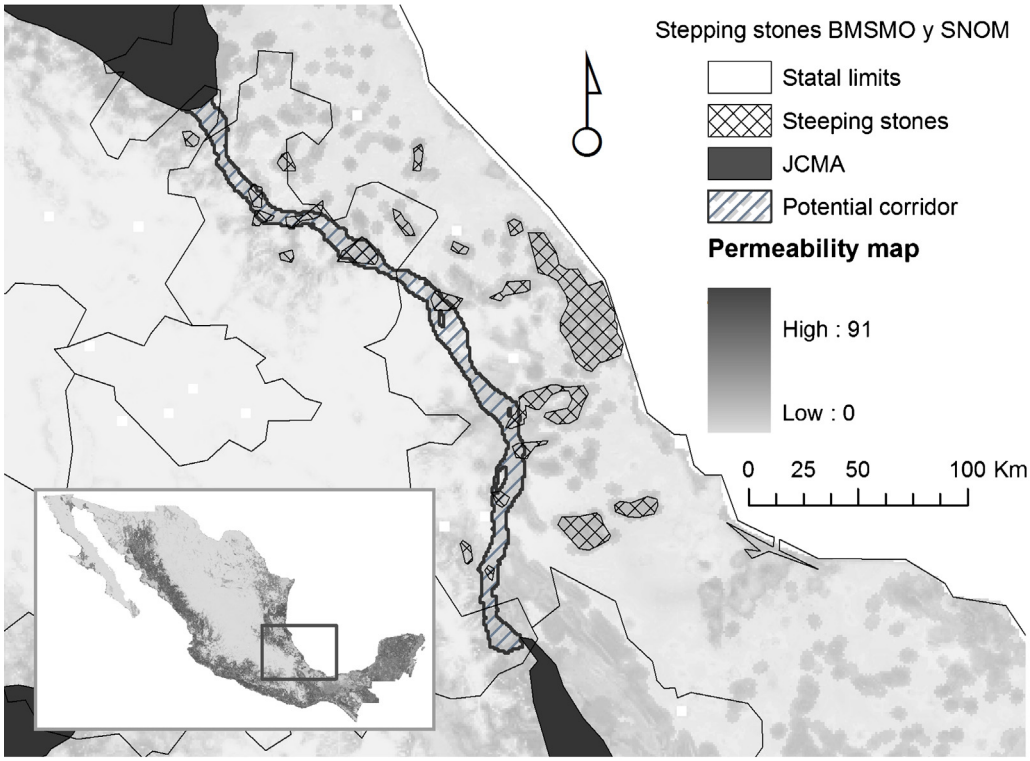

Fig. 2. Stepping stones between could forests of Sierra Madre Oriental (BMSMO) and the Northern Mixe Oaxaca Sierras (SNOM) for jaguar in Mexico.

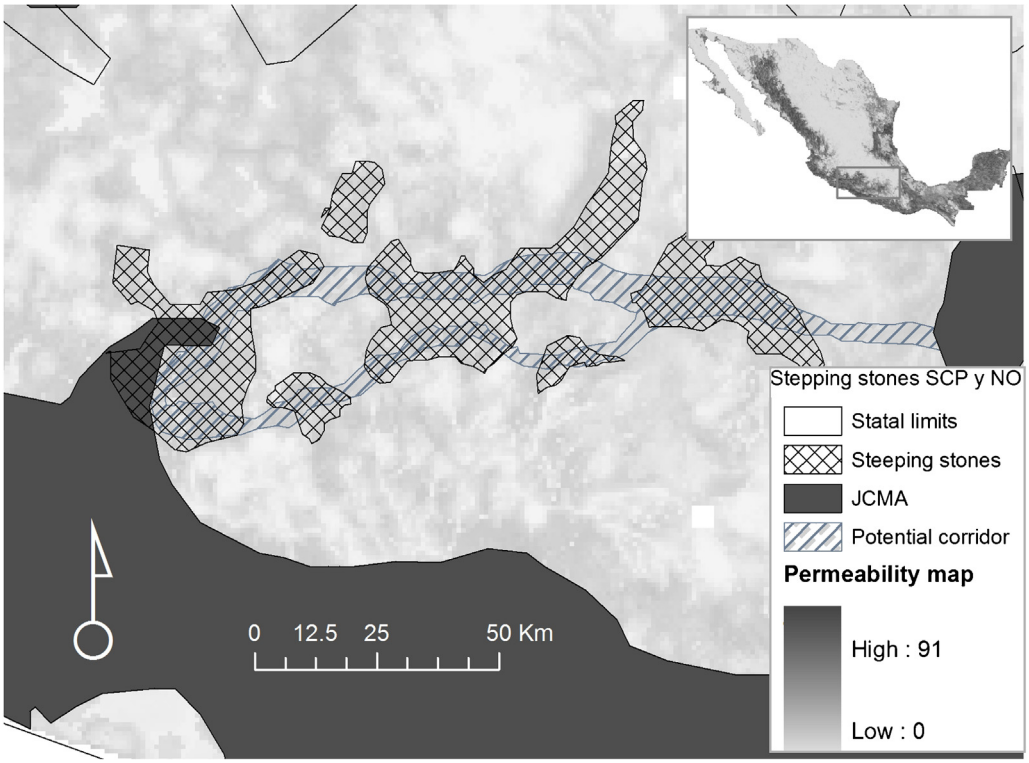

Fig. 3. Stepping Stones between Southern Pacific Coast (SCP) and north of Olinala (NO) for jaguar in Mexico.

corridors identified in this study are roads and highways); this is documented for other carnivores (Beier 1993; Carroll et al. 2001; Colchero et al. 2010; Mace et al., 1996; Singleton et al. 2002; Woodroffe & Ginsberg 1998). Other threat is the potential conflict with livestock holders (Zarco-González, Monroy-Vilchis, & Alaníz 2013).

Scientific data on jaguar dispersion across vast land extensions are few; for big carnivores report lengths of 1213 km (LaRue & Nielsen 2008), also in Calakmul, it was registered that a jaguar moved inside an area of 1000 km^2 in a year (Ceballos et al., 2005). In other way, the width of corridors is very important and only two studies mention this data, minimum 4 km for cougars and jaguars (De Angelo, Paviolo, & Di Bitetti 2011). In this study, the maximum length of viable corridors is 230 km, and for potential corridors is 320 km, and the minimum width for viable corridor was 14 km and for potential corridor 2.5 km was suggested. The fact that the proposed corridors in this study are shorter and wider increases highly the likelihood of movement of jaguars among corridors. Also in almost all the corridors there are PNA's and were recorded the jaguar presence. Nevertheless, as distances between nucleus or reproductive populations of jaguar increase, those relatively small habitat patches become more important (Rabinowitz & Zeller 2010).

Most of the areas identified as potential corridors shows minimal widths of 1.3 km and maximal lengths of 320 km, characteristics of risk for jaguar displacements; governmental support, environmental education and ecological restoration actions are required in these zones. All corridors are in predation risk zones, and is important add effort for jaguar conservation (Zarco-González et al. 2013).

Habitat patches that can facilitate the displacements of jaguars identified with the stepping stones exercise. Even though some of them are small (17 km^2) their separation is short (23 km at most) according to the reports of the displacements for this species in Mexico (20 km/night; Núñez et al. 2002). The connectivity and restoration of the habitat patches in the could forests of Sierra Madre Occidental – Sierra of Northern Oaxaca is possibly the only ways to maintain the genetic flow with population toward the northeast of Mexico. This population represents the northern most distribution of jaguar in the American continent.

The results from this study can provide the bases to take actions on the protection of connecting JCMA's and allow the genetic flow in these areas (Beier et al. 2006; Theobald 2006).

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jnc.2013.07.002.

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