



Universidade Federal de Goiás
Instituto de Ciências Biológicas
Programa de Pós-Graduação em Ecologia e Evolução



Avaliação de potenciais estratégias de conservação para onça-pintada na Mata Atlântica

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Milena Fiuza Diniz

Dissertação apresentada à Universidade Federal de Goiás como parte das exigências do Programa de Pós-graduação em Ecologia e Evolução para a obtenção do título de *Magister Scientiae*

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Milena Fiuza Diniz

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“Você é capaz de mais do que você pensa. Escolha um objetivo que parece certo para você e se esforce para ser o melhor, por mais difícil que seja o caminho. Comporte-se honrosamente. Prepare-se para ficar sozinho às vezes e para suportar o fracasso. Persista! O mundo precisa de tudo o que você pode dar.”

E. O. Wilson

A minha amada família.

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ESTRUTURA DA DISSERTAÇÃO

Essa dissertação está organizada em dois capítulos com abordagens complementares que possuem como objetivo geral estruturar e avaliar a viabilidade de redes de áreas protegidas para manutenção de populações e metapopulações de onça-pintada (*Panthera onca*, Linnaeus 1758) na Mata Atlântica e, então, explorar a efetividade de potenciais estratégias de manejo. Esse trabalho surgiu da necessidade de integrar duas abordagens, até então, efetuadas de maneira isoladas: a análise de conectividade funcional e análise de viabilidade populacional, para uma avaliação mais completa do potencial conservacionista de fragmentos florestais e estratégias de manejo.

A onça-pintada é o terceiro maior felino do mundo e um dos símbolos mais marcantes da biodiversidade brasileira. Além da importância no cenário conservacionista, atuando como espécie bandeira, a onça-pintada potencialmente atua no equilíbrio dos ecossistemas como predador de topo (Ripple et al. 2014). Embora apresente uma ampla distribuição geográfica, desde o México até a Argentina, perfazendo 18 países e os cinco biomas brasileiros, em alguns locais o status de conservação da espécie é bastante preocupante (de Paula et al. 2010). Na Mata Atlântica e Caatinga, por exemplo, a espécie está classificada como Criticamente em Perigo (de Paula et al. 2010). As pressões antrópicas colocaram a onça-pintada na lista das 20 espécies de mamíferos de grande porte que sofreram as maiores reduções na área de distribuição original desde 1500 (Morrison et al. 2007).

A onça-pintada tem requerimento por grandes extensões de habitat e, principalmente, de boa qualidade ambiental, evitando áreas dominadas por humanos (Cullen et al. 2005; Cullen et al. 2013). Considerando essas características, a persistência da espécie na Mata Atlântica é crítica, pois a floresta atualmente encontra-se fragmentada em centenas de milhares de manchas, das quais cerca de 80% são menores do que 0,5 km² (Ribeiro et al.

2009). Além disso, estudos recentes têm estimado densidades inferiores a 1 onça-pintada/100km² para maior parte do bioma (Beisigel et al. 2012).

Apesar da conservação da onça-pintada na Mata Atlântica depender principalmente da manutenção de grandes áreas protegidas, todas as unidades de conservação do bioma possuem populações inviáveis no longo prazo (Sollmann et al. 2008). A redução e o isolamento demográfico, provocados pela fragmentação e perda de habitat em larga escala, tem resultado na perda de diversidade genética das populações de onça-pintada na Mata Atlântica (Haag et al. 2010). Portanto, a estruturação de rede de áreas protegidas, através do re-estabelecimento da conectividade entre áreas, torna-se fundamental para restaurar estruturas metapopulacionais e, possivelmente, aumentar a probabilidade de persistência da espécie.

Diante de um mundo fragmentado, a conectividade deve ser um elemento essencial para guiar o planejamento e a gestão de áreas protegidas (Minor & Urban 2008; Pascual-Hortal & Saura 2006). Corredores eficazes possibilitam o aumento da variabilidade genética através do fluxo de indivíduos entre subpopulações, evitando a depressão endogâmica e perda de flexibilidade evolutiva (e.g. Lowe & Allendorf 2010). Portanto, estudos que explorem o potencial de diferentes estratégias de conservação que visam restaurar a dinâmica metapopulacional, como a implementação de corredores, são de grande importância para guiar tomadores de decisão e futuras pesquisas que possibilitem avanços na conservação de espécies ameaçadas.

Portanto, no primeiro capítulo, intitulado *Identifying key sites for connecting jaguar populations in the Atlantic Forest*, empregamos a teoria de grafos para estruturar metapopulações de onça-pintada para Mata Atlântica. Utilizamos índices baseados nessa abordagem para ranquear as unidades de conservação e os demais remanescentes florestais segundo sua importância para conectividade da paisagem através da perspectiva da espécie e,

então, avaliamos o grau de proteção deles. Esse capítulo foi escrito em inglês e de acordo com as normas da revista *Landscape Ecology* para ser submetido posteriormente à defesa.

No segundo capítulo, *Management of jaguar populations in the Atlantic Forest should focus on connecting existing populations or establishing new ones?*, avaliamos a viabilidade das metapopulações, propostas pelo primeiro capítulo, de forma comparativa as estruturas populacionais encontrada na literatura científica para onça-pintada na Mata Atlântica. Posteriormente, exploramos o potencial de algumas estratégias de manejo incluindo a criação de corredores entre as subpopulações e reintrodução de diferentes tamanhos populacionais em fragmentos chave para a conectividade funcional, identificado também em nossa abordagem no Capítulo 1. Esse capítulo foi escrito em inglês e de acordo com as normas da revista *Journal for Nature Conservation* também para ser submetido após a defesa. Os elementos restantes dessa dissertação foram escritos em Português.

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CAPÍTULO 1

IDENTIFYING KEY SITES FOR CONNECTING JAGUAR POPULATIONS IN THE ATLANTIC FOREST

Title: Identifying key sites for connecting jaguar populations in the Atlantic Forest

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ABSTRACT

It is expected that networks of protected areas (NPAs) play a key role in conservation of several carnivores species, as jaguar, since habitat fragmentation and population isolation are strong threats. Therefore, the identification and establishment of connector structures, such as corridors and stepping-stones, are essential to ensure the population persistence of these species. Here, we used graph approach and the habitat availability metrics to design NPAs for jaguars in Atlantic Forest and ranking protected areas and other forest fragments according to their importance for landscape connectivity. Our results indicate that the protected jaguar areas (PJAs) are important to functional connectivity, mainly the state parks located in the Serra do Mar. The potential stepping-stone network, formed by 564 fragments with higher levels of importance for connectivity, increased the number of connections in landscape and reduced the amount of isolated PJAs. Only 15 fragments of this network, located in the south of the Atlantic Forest, contributed with 88% of interpatch connectivity, being considered as potential sites for jaguars reintroduction. Most of these connector areas are under the less restrictive protection of sustainable use protected areas. The approach used here has simple data requirements and provides a valuable initial guide to planning NPAs, can be applied to many other species.

KEYWORDS: Atlantic Forest, corridor, habitat availability metrics, networks of protected areas, *Panthera onca*, stepping-stones

INTRODUCTION

Recent indicators suggest that the rate of decline of species has not reduced (Butchart et al. 2010), and the major causes of such declines are loss and fragmentation of habitats (IUCN 2014a). Nowadays, one way to block the advance of these processes is establish and maintain protected areas (Lindenmayer et al. 2006), because this strategy is perhaps the most promising answer to the challenges faced by contemporary conservation (IUCN 2014b). However, the creation of protected areas does not guarantee the long-term persistence of native wild life populations (e.g. Crooks and Sanjayan 2006). For example, in highly fragmented landscapes, the existing protected areas rarely have sizes large enough to maintain viable populations in isolation (e.g. Brito et al. 2008; Sollmann et al. 2008). In such landscapes, the effective implementation of networks of protected areas (NPAs) is a more interesting conservation strategy, because its structure reduces isolation between protected areas through increasing the availability of habitat areas (Crouzeilles et al. 2011).

The patches isolation results of habitat fragmentation (Fahrig 2003), restricting landscape connectivity and consequently the animal movement, which is critical to population persistence (Taylor et al. 1993). Landscape connectivity can be defined as “the degree to which the landscape facilitates or impedes movement among resource patches” (Taylor et al. 1993). In the short and medium term, connectivity is responsible for the maintenance of seasonal migration, recolonization of patches and metapopulation persistence (Hanski and Glinpin 1991; Hanski 1998). In the long run, the flow of individuals between habitat patches increases the resistance of populations to environmental disturbance, giving greater capacity for species to change their range due to climate change (Crooks and Sanjayan 2006). Therefore, connectivity is a critical factor to guide the planning and management of protected areas (Minor and Urban 2008; Pascual-Hortal and Saura 2006). Connectivity can be studied

from two perspectives: structural and functional. Structurally, connectivity refers to the spatial arrangement of the elements that comprise the landscape (Tischendorf and Fahrig 2000). However, there is consensus in the scientific literature that connectivity should be analyzed from a functional perspective (Saura and Torne 2009), considering the responses of species in relation to the elements of the landscape (Tischendorf and Fahrig 2000).

The functional connectivity may be analyzed by the graph theory (Urban and Keitt 2001), which is gaining popularity among studies of landscape ecology and conservation (Rayfield et al. 2011). Some of these studies have applied this tool for the evaluation of networks of protected areas (e.g. Goetz et al. 2009; Gurrutxaga et al. 2010; Crouzeilles et al. 2011). The use of graph theory allows to maximize the flow efficiency or connectivity of networks or circuits (Gross and Yellen 1999), making it a promising tool when applied in the metapopulation context (Bunn et al. 2000), analysis of landscape connectivity and the assessment of ecological flows in general (Urban and Keitt 2001). In applied landscape ecology, a graph is a diagram that represents habitat patches as nodes or vertices, which are connected by edges. The connections indicate the existence of some ecological flow between vertices, and they are determined by biological data such as dispersal distance or perceptual ability (Urban and Keitt 2001). Among the indices derived on graph-based approaches, habitat availability indices have shown high sensitivity to several types of changes in the landscape, overcoming some serious limitations found in other indices (Pascual-Hortal and Saura 2006, Saura and Pascual-Hortal 2007). Besides the traditional definition of connectivity, which focuses on inter-patch metrics, the habitat availability concept considers that connectivity also exist within habitat patches (intrapatch connectivity) (Pascual-Hortal and Saura 2006).

Recently, the application of the habitat availability indices in some Atlantic forest regions has resulted in important theoretical advances in conservation of this severely

fragmented biome (Crouzeilles et al. 2011; Crouzeilles et al. 2013; Crouzeilles et al. 2014). The joint effect of deforestation, forest fragmentation and other pressures has threatened the mammal fauna and caused the extirpation of large forest mammal species of some areas of this biodiversity hotspot (Canale et al. 2012). Among these species, the jaguar (*Panthera onca*, Linnaeus 1758) has suffered significant reductions in its population across the whole Atlantic Forest, which driven some of these populations to local extinction (Mazzolli 2008) and has given to the species the status of Critically Endangered in the biome (de Paula et al. 2010). Beisiegel et al. (2012) suggests that the extension of occurrence of jaguar in the Atlantic Forest is divided in only eight polygons, which also represent the jaguar subpopulations, currently isolated. Although the habitat loss is cited among the leading causes of the isolation and reduction of jaguar populations, a recent study showed that the fragmentation is a greater threat to jaguar populations (Zanin et al. 2014). Additionally, the protected areas in Atlantic Forest cannot alone ensure the long-term jaguar persistence (Sollmann et al. 2008). Therefore, the landscape connectivity becomes an essential element to maintain populations of this top predator in biome. The jaguar requires large expanses of habitat and a high degree of conservation, features which make the species a landscape detective, important to design and manage networks of protected areas (Cullen et al. 2005).

In this study, we used graph approach and habitat availability indices to design a network of protected areas for jaguar in Atlantic Forest. We identified the most important forest fragments to maintain functional connectivity and we evaluated their degree of protection. In spite of we used the jaguar as a focal species in Atlantic Forest, the approach used in our study requires relatively simple data and can be applied to any species or group of species that have them, making it possible analyze important aspect of functional landscape connectivity.

MATERIAL AND METHODS

Study area and database

The Atlantic Forest originally covered an area of 1,315,460 km² being considered one of the largest tropical forests of the Americas (Ribeiro et al. 2009). Currently, it is considered one of the most threatened biomes in the world and received the status of biodiversity hotspot (Mittermeier et al. 2005). Its history of fragmentation began with the colonization of Brazil and crawls to the present day, with the most recent annual rate of deforestation estimated as 235 km² (2011-2012) (SOS Mata Atlântica and INPE 2012). Currently, 11.4% of the original vegetation is distributed in 232,939 fragments (SOS Mata Atlântica and INPE 2012), of which 80% have area less than 0.5 km² (Ribeiro et al. 2009).

We evaluated in analysis of landscape connectivity all the national protected areas, state protected areas and indigenous lands of the Atlantic Forest with at least one record for jaguars; these areas are named as protected jaguar area (PJAs) and described in Sollmann et al. (2008). We obtained a total of 54 PJAs, with mean area of 35,234.46 ha (being the minimum area 10,603.59 ha and the maximum area 185,262 ha) of which 25 are state parks, 19 national parks and 10 are indigenous lands (Sollman et al. 2008).

We also included in our analysis all the forest fragments with an area greater than 1,000 ha, which is the approximate threshold area in which there is a 50% chance of jaguar occurrence (Calaça 2009). Even when they were structurally connected to each other, we did not consider the PJAs as a single area, since they are managed independently. After using the criteria, we took into account 1270 forest fragments throughout Atlantic Forest (Figure 1). The data on the remaining forest remnants came from SOS Mata Atlântica and INPE (2012) and is derived from TM / Landsat-5, ETM +/- 7 and CCD/CBERS-2 images on a scale of 1:

50,000 in vector format from 2011-2012. We used geographic information system South American Datum 1969 and the projection was converted to Albers using as linear unit the meter, to allow calculation of the distance between the forest remnants.

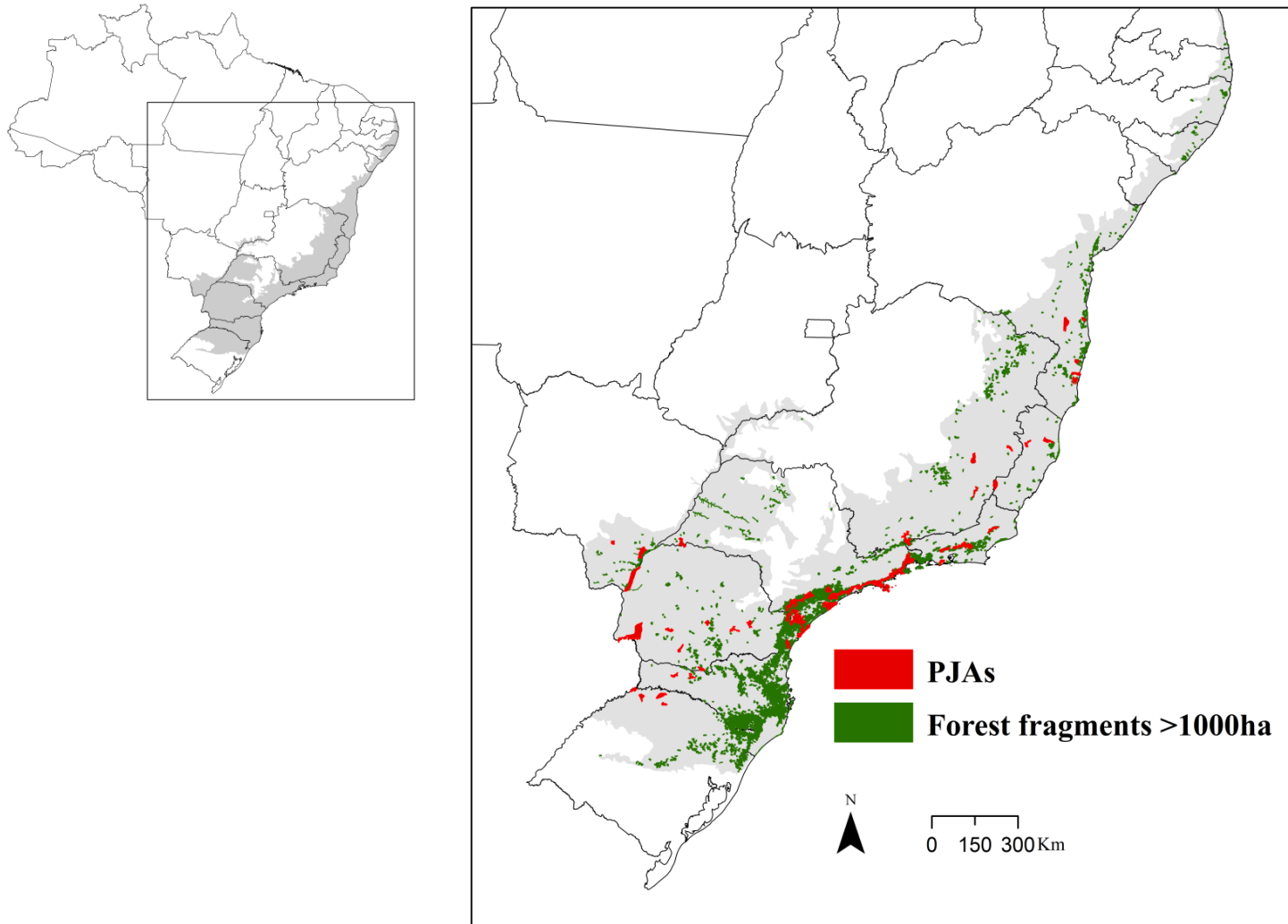


Figure 1. Localization of protected jaguar area (PJAs) and forest fragments greater than 1,000 ha in Atlantic Forest used in analysis of functional connectivity.

Analysis of functional connectivity

We used the Probability of Connectivity index (PC), a habitat availability index based on graph structures that quantifies functional connectivity. PC is defined as ‘the probability that two animals randomly placed within the landscape fall into habitat areas that are reachable from each other (interconnected) given a set of n habitat patches and the connections among them’ (Saura and Pascual-Hortal 2007). PC is calculated as follows:

$$\frac{\sum_{i=1}^n \sum_{j=1}^n a_i \cdot a_j \cdot p_{ij}^*}{A_L^2}$$

where a_i and a_j are the areas (or other attribute, such as carrying capacity) of the habitat patches i and j , p_{ij}^* is the maximum product probability of all possible paths between patches i and j and A_L is the total landscape area attribute (maximum attribute). The PC values range from 0 to 1, and greater values indicate greater landscape connectivity (Saura and Pascual-Hortal 2007). The importance of each patch can be computed in relative terms (dM) or in absolute terms ($varM$):

$$dM(\%) = 100 \cdot \frac{M - M_{after}}{M}$$

$$varM = M - M_{after}$$

where M is the overall connectivity index (metric) with all patches that constitute the landscape and M_{after} is the overall index value after removal of a given patch or set of patches (Saura and Torné 2012).

Recently, the partition of habitat availability indices in three fractions was proposed in order to improve the comprehension of how each element contributes to landscape functional connectivity (Saura and Rubio 2010):

$$dPC = dPC_{intra} + dPC_{flux} + dPC_{con}$$

where PC_{intra} is related to intrapatch connectivity and is independent of the patch topological position and the dispersal distance; PC_{flux} measures how well patch is connected to other patches, but not their contribution to interpatch connectivity of remnant patches, and PC_{con} corresponds to the contribution of the patch, as a connecting element, to maintain interpatch connectivity (Saura and Rubio 2010).

We computed the PC using a probability $p_{ij}= 0.05$ corresponding to maximum dispersal distance to compute the direct dispersal probabilities as a negative exponential function of the distance between patches. The area of forest remnants and PJAs were used as the patches attribute and edge-to-edge Euclidean distance as the connection attribute. Data about jaguar dispersal are scarce in literature, being mostly sporadic observations of the movement of some individuals which vary between 15, 30 and 64 km in different areas of Brazil (de Almeida 1990; Crawshaw and Quigley 1991; Crawshaw 1995). However, Cullen (2006) monitored for seven years with radio-collared 10 adult individuals in two protected areas (Morro do Diabo State Park and Ivinhema State Park) in the Atlantic Forest and obtained a maximum annual movement between consecutive locations averaged 13.18 km. We opted to evaluate the connectivity using a range of dispersion thresholds distances to cover the variations in existing empirical dispersal data: 10km, 20km, 30km, 40km, 50km and 60km. We computed Euclidean distance between forest remnants using the dispersion distance as threshold, i.e. we only calculated the distances between forest patches equal to or less than the threshold distance.

We used mean values of varPC and its fractions for all dispersal distances as a criteria to rank the PJAs and the other forest fragments (Crozeilles et al. 2013) and then classify them within five levels of importance according with decimal places: 1st level (10^{12} - 10^{11}), 2nd level (10^{10} - 10^9), 3rd level (10^8 - 10^7), 4th level (10^6 - 10^5) and 5th level (10^4 - 10^3). The number and the areas of fragments were computed without considering the PJAs. The forest remnants with the highest values of varPC_{con} (1st, 2nd and 3rd levels) were classified as important connecting elements and selected to constitute a potential stepping-stone network.

In order to assess the impact of the potential stepping-stone network in functional connectivity between the PJAs, we constructed two scenarios. In the first scenario, we evaluated only the connectivity between PJAs. The second scenario included the stepping-stone network identified by ranking and prioritization of PC_{con} of the forest remnants. We computed the Equivalent Connected Area (ECA), which is calculated by the square root of the numerator of the PC index and its unit is given in area, which facilitates the measurement and interpretation when dealing with changes in connectivity (Saura et al. 2011). We calculated the relative variation of ECA (dECA) between the two scenarios mentioned above, and compared with the difference in available habitat area (dA). If dECA is greater than the dA, the added forest remnants are connected to previously existing habitats, acting as corridors and stepping-stone.

To examine the network topology in more detail, in each scenario we computed some graph-based indices: total number of links (NL), number of components in the landscape (NC) and number of isolated nodes (NIN). Components are groups of nodes in which a node is connected to at least one other node of the same component but has no connection with other nodes outside the component. The total number of links refers to the number of connections within the landscape. The number of isolated nodes

measures the quantity of forest remnants unconnected to any other node, becoming itself a component. All functional connectivity analyses in the landscape were performed using the command line Conefor Sensinode (CS) executable in R software (R Core Team 2012). We used the ArcGis 9.x extension Conefor inputs to create the inputs file in the format required by CS.

To check the degree of protection of forest fragments ranked by PC_{con} , we evaluated the area percentage of these fragments covered by the Atlantic Forest network of protected areas, including strictly protected areas (SPAs) and sustainable use protected areas (SUAs) at the national, state and municipal levels. Spatial analyses were performed in ArcGIS 9.3 software (ESRI 2008).

RESULTS

The analysis of network formed by 1270 forest remnants, including the PJAs, showed that the number of components decreases as the dispersal distance increases (Figure 2). Until the dispersion threshold of 30 km (Figure 2a-c), the landscape showed many components ($NC_{10km} = 227$, $NC_{20km} = 139$, $NC_{30km} = 70$) and only the forest fragments of ecoregion of Serra do Mar were well connected with the fragments further south in Brazil. For the dispersion thresholds higher than 30km (Figure 2d-f), few components ($NC_{40km} = 39$, $NC_{50km} = 20$, $NC_{60km} = 13$) were formed, and in the most optimistic scenario (60km) of them no PJAs remains completely isolated (Figure 2f).

The 54 PJAs were ranked according to the mean value of PC for the six dispersal distances and 19 of them were included within 1st level of importance, all located only in Serra do Mar ecoregion, 26 within the 2nd level, with about 50% in Alto Paraná Atlantic Forest and Araucaria Moist Forests ecoregions, and only 9 within 3rd level of

importance (Figure 3). No PJA was classified within the 4th or 5th level of importance (Table 1). Of the PJAs classified in the 1st level of significance, 85% are state parks and 15% are national parks. At the 2nd level, 54% are national parks and at the 3rd level 55% are indigenous lands. All Serra do Mar cores were classified at the first level of importance and four of them are among the 10 PJAs with higher mean values of PC, highlighting the Serra do Mar State Park - N. Cutatão, the PJA with the highest importance for connectivity (Table 1). Although the Iguazu National Park has the largest area among PJAs, this protected area occupied only the 25th rank (Figure 3). Table 2 shows the amount of PJAs distributed between PC fractions. For PC_{intra} criterion, all PJAs were classified within the 2nd and 3rd levels. In turn, for PC_{flux} 98% of PJAs were in the three first levels of importance and for the PC_{con} criterion, the PJAs were distributed in all levels of importance, of which approximately 74% were included in the last three levels of importance.

The remaining forest remnants composed of 1216 fragments, excluding PJAs, was also ranked based on PC and its functions (PC_{intra}, PC_{flux} and PC_{con}) and the remnants were classified into five levels of importance (Table 1). For all criteria, the higher the level of importance, the greater the mean area of forest remnants included in the group. More than 90% of the remnants classified in the PC and PC_{flux} criteria were included in 2nd and 3rd levels. No forest remnant was classified in the 5th level of importance according to the PC and PC_{intra} criterions. For PC_{con} criterion, about 83% of the forest remnants were classified in the last three levels of importance. Without considering PJAs, the largest forest remnant (371,580.33 ha) found in the landscape was classified in the 1st level of importance and the smallest forest remnant (1,000.06 ha) was in the 4th level of importance in all criteria.

The 536 forest remnants classified in the 1st, 2nd and 3rd levels of importance were chosen to form a potential stepping-stone network, with approximately 40% of fragments located in Serra do Mar ecoregion. The addition of the stepping-stone network to isolated PJAs network greatly increased the number of connections in the landscape and reduced the amount of isolated PJAs (Table 2). As expected, increases in dispersal distance resulted in a decrease in the number of components and an increase in the number of links in both scenarios (Table 2). The changes in the degree of connectivity due to the addition of the stepping-stone network were similar for the all dispersal distance scenarios, with mean value dECA of 412.86% (SD=4.45), this value was much larger than the dA (189%). The relative contribution of the remnants with higher values of PC_{con} as a function of the total area of forest remnants was similar in all dispersal distance analyzed (Figure 4). On average, approximately 22% of the total area of forest remnants, and about 88% of key connecting remnants were conserved (Figure 4). In all the scenarios, the set of top remnants that contributed with 88% of the total PC_{con} values in all the study area consisted of only 15 out of the 1270 fragments, with a total area of 11,319 km², and only one of these forest remnants was a PJAs (Serra do Mar State Park - N. Cutatão) (Figure 5).

The Atlantic Forest has approximately 62% of its area covered by protected areas at the federal, state and municipal levels; about 17% under coverage of SPAs and 45% under coverage of SUAs (Table 3). For the PC_{con} criterion, in average 44% of connector areas are not protected (Table 3). The fragments classified in the last four levels of importance are more protected by SPAs (Table 3). On the other hand, for the 1st level of importance the SUAs cover a larger area (34.77%) in relation to SPAs (20.84%) (Table 4).

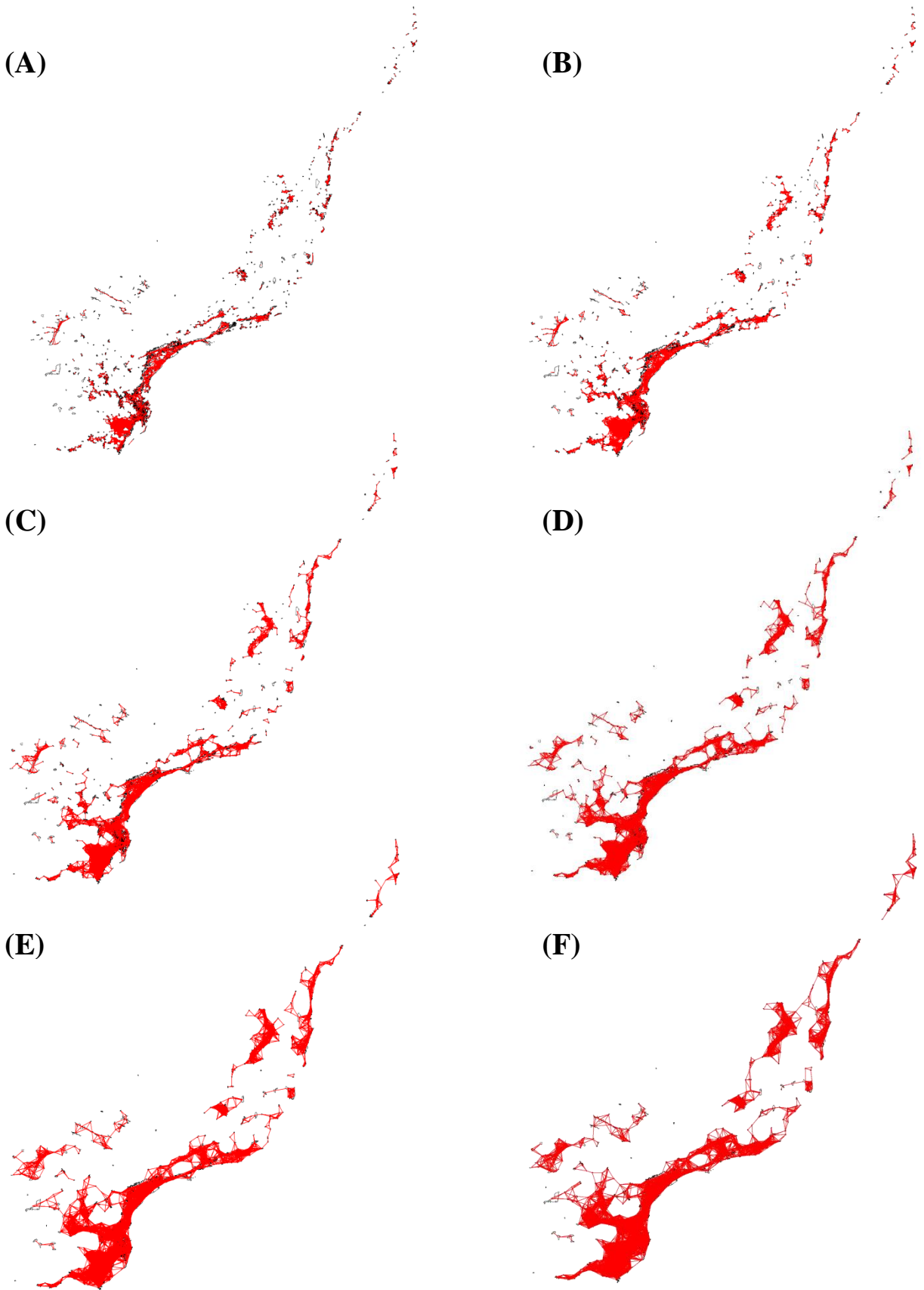


Figure 2. Network structure for jaguar according to thresholds dispersion of 10 km (A), 20 km (B), 30 km (C), 40 km (D), 50 km and 60 km for forest fragments of the Atlantic Forest with area larger than 1000 ha.

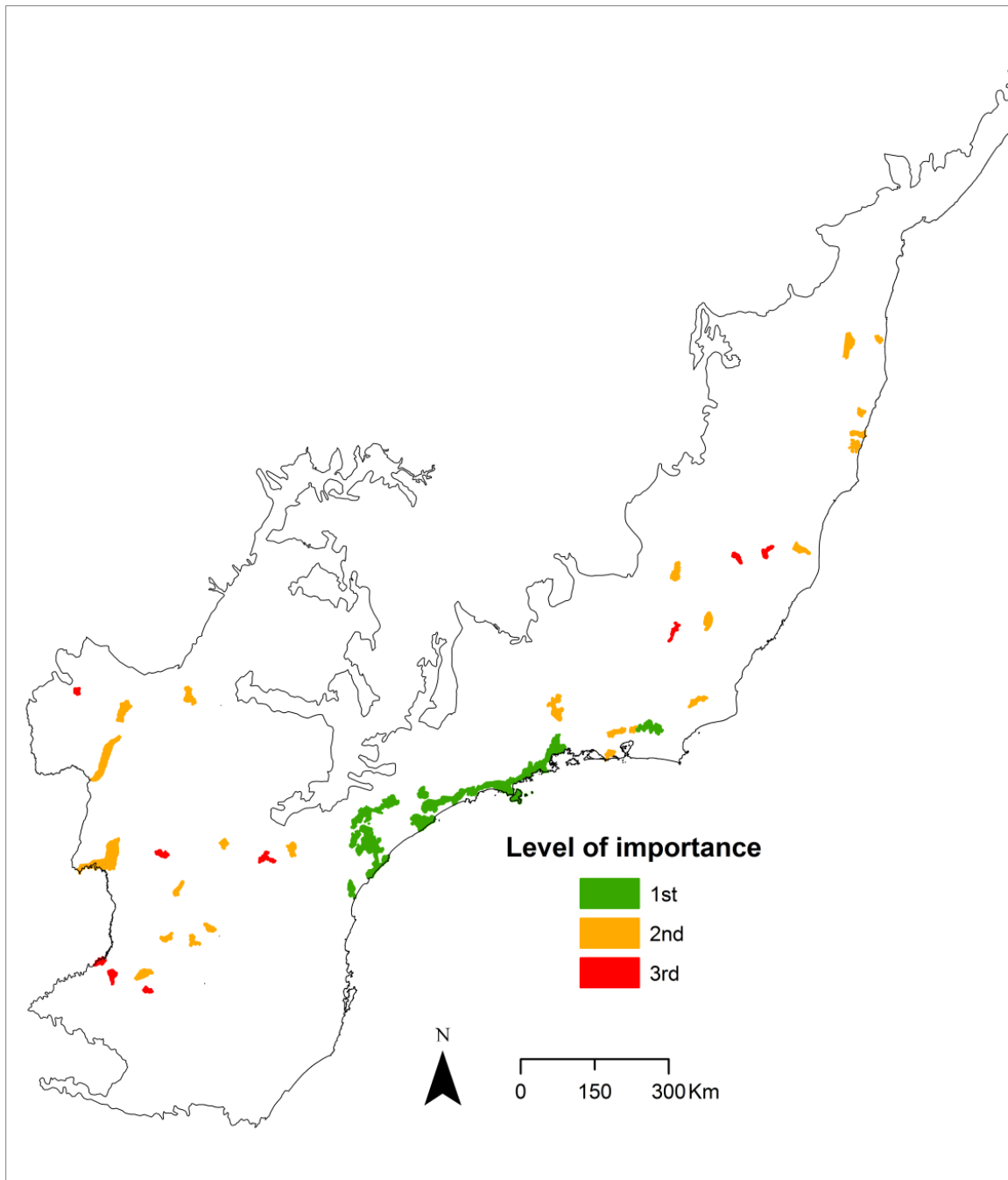


Figure 3. Level of importance for PJs in Atlantic Forest ranked according to their PC value, calculated by mean varPC for all dispersion thresholds (10, 20, 30, 40, 50 and 60 km).

Table 1. Total amount of forest remnants and PJAs in each level of importance ranked according to the PC criterion and its fractions (PC_{intra} , PC_{flux} , PC_{con}). The areas of smallest and largest remnants forest and mean area were identified excluding the PJAs.

Criteria	Forest remnant importance	Remnants N°	PJAs	Smallest remnant (ha)	Largest remnant (ha)	Mean remnants (\pmDP)(ha)
PC	1st	60	19	2,576.73	371,580.33	51,358.91 (77,801.29)
	2nd	684	26	1,001.13	25,712.52	3,175.30 (2,930.84)
	3rd	466	9	1,000.76	10,154.63	2,130.34 (1,475.60)
	4th	61	0	1,000.06	2,991.75	1,267.77 (326.74)
	5th	0	0	-	-	-
PCintra	1st	1	0	371,580.33	371,580.33	371,580.33
	2nd	32	19	33,141.75	267,141.96	104,386.09 (72,053.98)
	3rd	335	35	3,164.36	28,943.78	6,763.91 (4,472.31)
	4th	903	0	1,000.06	3,151.74	1,660.34 (568.52)
	5th	0	0	-	-	-
PCflux	1st	46	19	13,397.29	371,580.33	72,402.23 (88,340.28)
	2nd	667	18	1,001.13	25,712.52	3,244.58 (3,043.04)
	3rd	470	16	1,000.76	15,038.07	2,290.85 (1,884.70)
	4th	81	1	1,000.06	4,730.13	1,424.44 (571.37)
	5th	7	0	1,004.21	2,991.75	1,497.24 (693.43)
PCcon	1st	28	2	2,576.73	371,580.33	66,563.82 (91,768.79)
	2nd	191	12	1,005.75	50,228.40	4,695.74 (6,115.99)
	3rd	347	15	1,000.76	25,712.52	3,193.49 (3,024.43)
	4th	229	9	1,000.06	12,100.07	1,982.31 (1,458.55)
	5th	476	16	1,001.13	18,059.47	2,365.92 (1,971.32)

Table 2. Basic characteristics of the PJAs isolated and PJAs added to stepping-stone network (PJAs+NSS) for different thresholds dispersion modeled.

Dispersal distances (km)	Number of links		Number of components		Number of isolated PJAs	
	PJAs	PJAs+NSS	PJAs	PJAs+NSS	PJAs	PJAs+NSS
10	25	1133	34	83	28	13
20	31	1984	32	43	25	8
30	43	3007	27	28	19	7
40	52	4104	22	22	15	6
50	65	5304	18	15	8	2
60	72	6590	17	11	6	2

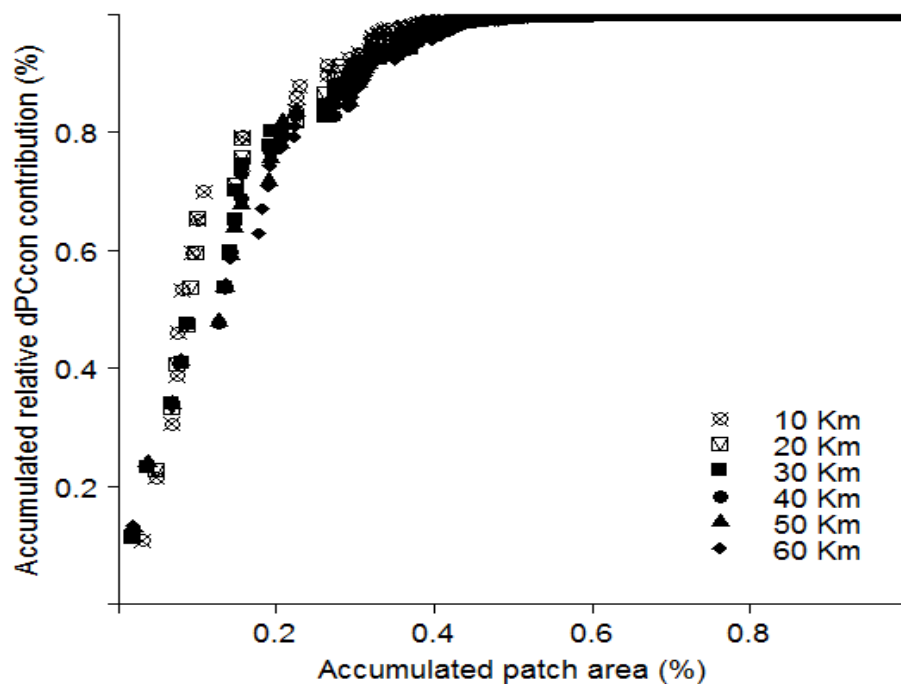


Figure 4. Relative contribution of forest remnants ranked according the increasing order of PC_{con} values in function of the accumulated areas of the forest remnants for the six thresholds dispersion modeled (i.e. a 10% in the x axis corresponds to a set of patches resulting from selecting first those with the highest dPC_{con} values until a 10% of total landscape area is attained).

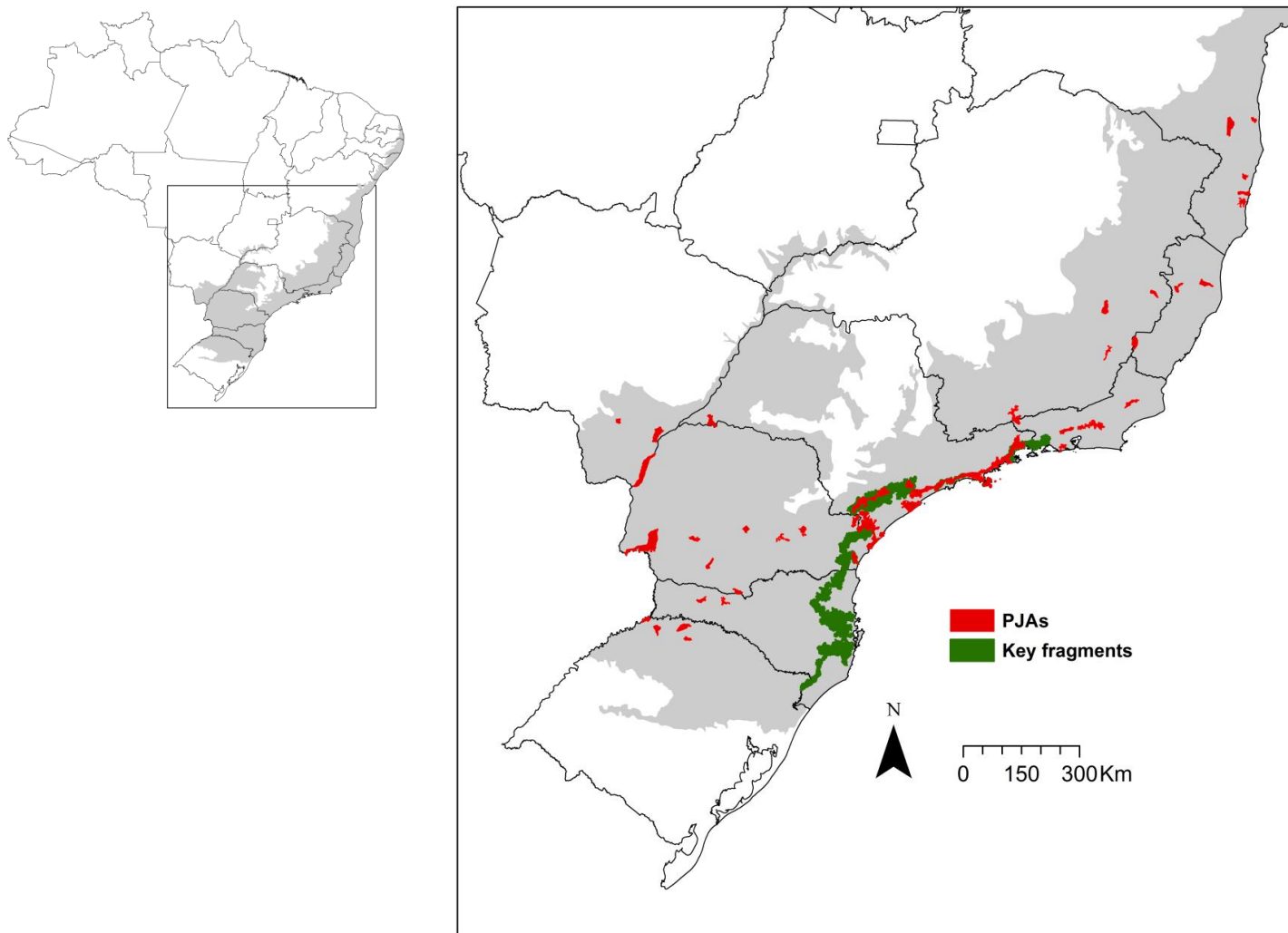


Figure 5. Location of 15 forest remnants, with a total area of 11,319 km², responsible for 88% of the total PC_{con} values in all the study area.

Table 3. Proportion of total area of forest remnants, ranked through PC_{con} criterion, covered by strictly protected areas (SPAs), sustainable protected areas (SUAs) and non-protected in the five levels of importance (1st, 2nd, 3rd, 4th and 5th).

Forest remnants importance (PC_{con})	SPAs%	SUAs%	NP%
1 st	20.84	34.77	44.39
2 nd	43.54	37.77	18.70
3 rd	27.54	23.76	48.70
4 th	26.32	17.43	56.26
5 th	37.38	10.61	52.00
Mean	31.12	24.87	44.01
Atlantic Forest	16.81	44.97	38.22

DISCUSSION

The current loss and fragmentation of habitats are among the main causes of local extinction, demographic isolation and the loss of genetic variation of jaguar populations in the Atlantic Forest (Mazzoli 2008; Haag et al. 2010). In the face of the increase in deforestation rates (SOS Mata Atlântica and INPE 2012) and the inefficiency of protected areas in maintaining viable populations of jaguars in the long term (Sollmann et al. 2008), it is expected that re-establishment of metapopulation dynamics through connector structures, such as wild corridors, will play a key role in the conservation of the species in the Atlantic Forest. The connectivity between areas for jaguars was first explored by Sanderson et al. (2002), for prioritization of jaguar conservation units. Since then, several studies have applied different approaches to identify connector structures for jaguars throughout its distribution (Rabinowitz and Zeller 2010; Rodríguez-Soto et al. 2013; Silveira et al. 2014). However, only recently, dispersal data have been incorporated to the models (Bernal-Escobar et al. 2015).

Our analysis showed that the dispersion threshold strongly affects the results, since the number of components across the Atlantic Forest ranges from 227 to only 13 components for dispersal distances of 10 km and 60 km, respectively. Considering all the 1,270 forest fragments and scenarios of dispersal threshold equal to 10, 20 and 30 km, the subpopulations were structured similarly to the scenario proposed by Beisiegel et al. (2012). Published data confirm that jaguars in dispersal can reach these distances in the Atlantic Forest. For example, Crawshaw et al. (2004) monitored dispersing subadult males and observed a distance of 33 km for one of them in Iguazu National Park. In the Atlantic Forest of Alto Paraná, Cullen (2006) showed that adult jaguars can move up to 30 km in 3-4 days, crossing open pastures and gallery forests. Therefore, we believe that the scenarios built with dispersal thresholds up to 30 km are more consistent with the biology of the species in the Atlantic Forest. Although we used the average index for all dispersal thresholds in the ranking of fragments, this value was very close to derived from the dispersal threshold of 30 km. Up to this threshold, the largest component formed was located in the Serra do Mar Coastal Forests and part of the Alto Paraná Atlantic Forest and Araucaria Moist Forests ecoregions. This component covers most PJAs, making it possibly the main metapopulation structure of jaguars in the Atlantic Forest. The smaller and more isolated components are located in the ecoregions of Bahia Coastal and Interior Forests. The conservation status of southern Bahia's population is very worrying, because in addition to isolation, shown in our results, it is estimated that its size is only 3-9 individuals (Leite et al. 2002).

We showed that the PJAs had a key role for connectivity because 40% of them are included within the 1st level of importance (mean varPC), which represented more than 30% of fragments included in this level. Most of these PJAs are state parks and are located in the Serra do Mar ecoregion. In addition to the key connectivity role for jaguars, the Serra do Mar State Park is also important for the viability of jaguar populations, because it is the only PJA

that has area large enough to promote some perspective for jaguar conservation (Sollmann et al. 2008). In spite of the spatial extent, the two largest PJAs (Iguaçu and Ilha Grande National Parks), both located in the ecoregion of Alto Paraná Atlantic Forest, were included only in the 2nd level of PC. Probably due to the fact that the habitat availability indices are based on intrapatch and interpatch connectivity (Pascual-Hortal and Saura 2006), and although these PJAs had potentially great habitat availability (high intrapatch connectivity), they are highly isolated from other forest fragments (low interpatch connectivity). We should emphasize that our analysis is limited to the Brazilian Atlantic Forest, excluding areas such as the Green Corridor and their connections, including the connection between Iguaçu National Park and Turvo State Park.

With the continued modification of the landscape by human actions, stepping-stone networks have a crucial role for species persistence by reducing the isolation of large habitat blocks (e.g. Leidner and Haddad 2011; Saura et al. 2014). The increasing connectivity and the comparison between the changes in ECA (dECA) and in area size (dA) demonstrated that the addition of key connectors, identified by PC_{con} criterion, to PJAs network significantly increased landscape connectivity, stressing that the fragments added are acting as stepping-stones or corridors. Although it is not possible to expand the network of protected areas to cover all the key elements for landscape connectivity (536 forest fragments), our results indicated that 15 fragments (Figure 5) could significantly improve the network effectiveness. Our analysis revealed that most of these 15 forest fragments are located in the states of Rio Grande do Sul, Santa Catarina and Paraná. The jaguar disappeared from these fragments between the decades of 1960 and 1990 (Mazzolli 2008). However, in addition to their importance for connectivity, these fragments have a considerable area, capable of providing habitat for a small population of jaguars, becoming potential sites for future reintroductions.

Our analysis showed that forest remnants ranked in 1st level of importance according to PC_{con} criterion, are more protected by SUAs, most of them APAs (IUCN category V). The protection of biological diversity and sustainable use of natural resources are among the goals of APAs (MMA SNUC 2014). However, the supposed sustainable exploitation of resources in Brazilian SUAs does not necessarily obey this criterion (Fernandez et al. 2012). Additionally, these areas presented a certain degree of human occupation (MMA SNUC 2014) limiting their use by jaguars (Cullen et al. 2013). This result stresses that part of the network currently categorized as APAs, should be included in more restrictive categories, a suggestion also made by Crouzeilles et al. (2013) for key fragments to improve connectivity in the Atlantic Forest of Rio de Janeiro.

Many work are converging to similar results, showing connections spatially compatible to the jaguar in the Atlantic Forest (Rabinowitz and Zeller 2010; Silveira et al. 2014). Therefore, we believe that the evaluation of connectivity must be at the forefront of conservation strategies for the species. We are aware that the design of corridors is a very complex activity and their establishment very expensive. However, the approach presented in this study has simple data requirements and may be used for an initial screening of important areas for jaguar functional connectivity. Additional analyses that incorporate the effects of the matrix, for example, should be performed, since that we considered only the Euclidean distance between fragments. Although jaguars used anthropogenic habitat, they avoid disturbed and developed habitats (Colchero et al. 2011; Cullen et al. 2013). For example, the presence of agriculture is a critical factor to selection of corridors because it severely limits the presence of jaguars and prey species (Petracca et al. 2014).

The Serra do Mar ecoregion have great value for landscape connectivity. In addition to these areas, most forest fragments in the least restrictive protection category of sustainable use (APAs) also act as important connector areas for jaguars in the Atlantic Forest. Given this

assessment, the low population density of jaguars in Atlantic Forest (Beisiegel et al. 2012) and increasing rates of deforestation (SOS Mata Atlântica & INPE 2012), we recommend strongly that conservation actions to increase the effectiveness of the network of protected areas should be made quickly for the long-term maintenance of jaguars in the biome. The approach of this study can be used as an initial guide for the design and management of networks of protected areas, promoting the selection of potential fragments to integrate the network and identification of reserves that need of special attention from managers by the important role played in landscape connectivity.

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CAPÍTULO 2

MANAGEMENT OF JAGUAR POPULATIONS IN THE ATLANTIC FOREST SHOULD FOCUS ON CONNECTING EXISTING POPULATIONS OR ESTABLISHING NEW ONES?

Title: Management of jaguar populations in the Atlantic Forest should focus on connecting existing populations or establishing new ones?

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ABSTRACT

Based on habitat loss and fragmentation, and numerous other threats, the conservation status of jaguars (*Panthera onca*) in the Atlantic Forest is very critical. In this study, we evaluated the potential of network of protected areas in the Atlantic Forest in ensure the long-term persistence of metapopulations and isolated subpopulations of jaguar. We explored the relative effectiveness of two conservation strategies: establishment of different corridors and population reintroductions in key fragments for functional connectivity of landscape. Using population viability analysis, we employed controlled simulations to evaluate the species persistence in a series of scenarios based on current spatial distribution and potential management strategies. The current network of protected areas of Atlantic Forest is not able to maintain viable jaguar metapopulations or isolated subpopulations in the long-term. Although the implementation of good ecological quality corridors has reduced the probability of extinction of the population structures, they were not sufficient to ensure the species persistence for the next 200 years. Reintroduction scenarios of a minimum 20 jaguars in the fragment in south of Atlantic Forest, near Serra do Mar subpopulation, presented the population structures with lower probabilities of extinction. We recommend that this strategy should be explored in order to reverse the critical conservation status of the jaguar in the Atlantic Forest.

KEYWORDS: Corridor, *Panthera onca*, population viability analyses, network of protected areas, reintroduction

INTRODUCTION

Habitat loss and fragmentation are the main causes of the current species extinction crisis (IUCN, 2014). One of the many consequences of these processes is the formation of small and isolated populations (Fahrig, 2003). Population decline and isolation, in turn, are accompanied by an increase in the probability of extinction, due to greater vulnerability to stochastic factors (Caughley, 1994; Caughley & Gunn, 1996). However, habitat loss and fragmentation do not affect species in the same way, because extinctions do not occur randomly and are also not driven by the same factors across different taxa (Purvis et al., 2000; Johnson et al., 2002). While for small mammals the risk of extinction is mainly determined by environmental factors, for large mammals it is directed by intrinsic biological traits in addition to environmental factors (Cardillo et al., 2005). Among the intrinsic biological traits, body size has a strong correlation with the risk of extinction (Cardillo et al., 2005; Fritz et al., 2009; Forero-Medina et al., 2009) and this has resulted in a predictable size-selective defaunation gradient for mammal species (Dirzo et al., 2014). Due to greater vulnerability to extinction, large mammals that occur in highly disturbed habitats should receive special attention by conservationists

In tropical forests, fragmentation has threatened large mammals by reducing their abundances and geographic ranges (Canale et al., 2012; Kosydar et al., 2014). In scenarios like this, landscape connectivity is a key element in restoring and maintaining metapopulation dynamics and, consequently, the persistence of species (Hanski, 1998). One of the ways to ensure connectivity is through the establishment of wildlife corridors, a conservation tool that has become very useful in the face of an increasingly fragmented world (Beier & Noss 1998; Hilty et al., 2006). Well-designed corridors allow the dispersal of individuals and, consequently, gene flow between subpopulations, avoiding inbreeding depression and the

loss of evolutionary flexibility (Keyghobadi, 2007; Lowe & Allendorf, 2010). However, when the connectivity established is not sufficient to ensure the long-term viability of populations, other management strategies, such as reintroduction, become necessary. According to IUCN (2013), reintroduction is the movement and intentional release of organisms within its indigenous range after local extinction for the re-establishment of a viable population. The number of species that has become focus of this conservation practice has increased in recent decades (Seddon et al., 2014). Reintroduction projects have become an important tool mainly for conservation of rare, threatened species and/or locally extinct species (e.g., Simón et al., 2012; Ripple & Beschta, 2012).

Because the conservation funds are limited, the implementation of management strategies, such as corridors and reintroductions, are generally very expensive. Therefore, a framework to previously assess the costs and benefits of these strategies is desirable. One approach that allows this very effectively is the Population Viability Analysis (PVA) (e.g., Tian et al., 2011; King et al., 2014). PVA has become an important tool for conservation studies, since it allows the identification of key factors that influence population persistence based on species-specific data and allows to evaluate the impact of in population dynamics of focal species, showing the likely future of the modeled population (Akçakaya & Sjögren-Gulve, 2000; Morris & Doak, 2002; Shaffer, 2009).

In this context, we evaluated how various conservation scenarios affect population viability for the largest carnivore in South America, the jaguar (*Panthera onca*, Linnaeus 1758), in one of the most threatened biomes of world, the Brazilian Atlantic Forest (Mittermeier et al., 2005). As fragmentation consists of a major threat, maybe even more serious than habitat loss (Zanin et al., 2014), studies aiming to evaluate population persistence in fragmented scenarios, providing a guide for future research and management actions, are essential to promote advances in jaguar conservation. In the Atlantic Forest, the conservation

status of the jaguar is classified as Critically Endangered and it is estimated that total number of adults does not exceed 250 individuals (Beisiegel et al., 2012). The extent of occurrence of the jaguar is currently fragmented in eight isolated polygons, totaling 44,487 km² (Beisiegel et al., 2012). There are 49 areas, among state and federal reserves, as well as indigenous lands, with jaguar presence (PJAs) in the Atlantic Forest. However, only Serra do Mar State Park has individual potential to ensure long term viability for an isolated jaguar population (Sollmann et al., 2008).

The Atlantic Forest is one of the richest and most threatened biome globally (Mittermeier et al., 2005). With an extensive fragmentation history due to anthropogenic pressures, the forest currently exists as 232,939 fragments of native vegetation above three hectares totaling 11.4% of the original biome (SOS Mata Atlântica & INPE, 2012). Despite the increasing fragmentation rates (239 km² 2012-2013, the highest since 2008), (SOS Mata Atlântica & INPE 2012), resulting in multiple levels of fragmentation and loss of habitat along the biome, only 9% of the remaining forest are legally protected, representing 1% of the original forest (Ribeiro et al., 2009).

Therefore, the main objectives of our study were: (1) to analyze the potential of the network of protected areas in the Atlantic Forest (see Chapter 1) to maintain viable metapopulations of jaguars, and to compare with the viability of the population structures proposed by Beiseigel et al. (2012); and (2) to explore the effectiveness of management strategies to improve the conservation status of the species: (i) to implement corridors between subpopulations and (ii) to reintroduce different population sizes in a set of fragments considered key for landscape connectivity maintenance (see Chapter 1).

MATERIAL AND METHODS

Landscape scenarios

We evaluated the persistence probability of jaguar metapopulations through population viability analysis. Metapopulations were structured as detailed in Chapter 1, through functional connectivity analysis, contrasting the Euclidean distance between forest fragments and data on jaguar dispersal distance. To account for the variation shown in the literature, six dispersion distance values were used, resulting in six potential metapopulation structures formed by PJAs linked by other forest fragments. Here we selected only the four structures derived from the four smaller values of dispersal distance, which we believe to be closer to the reality of the species in the Atlantic Forest. In order to model the metapopulations, the number of PJAs and their areas were considered surrogates for subpopulation number and size, respectively. The other forest fragments were only used for connectivity, disregarding their potential to keep populations. We used the population density for estimating the subpopulations size in each PJA. However, in the published literature there are different estimates for jaguar population densities to some landscapes in the Atlantic Forest (Table 1) and therefore we created two scenarios. In the first scenario, named “pessimistic scenario”, we used real population density data for PJAs where this data was available, and for those where data was unavailable, we used the average of these values (1.0 ind. /100 km²) (Table 1). In the second scenario, “optimistic scenario”, to estimate the initial population sizes, we used the highest density value found, 2.22 ind. / 100 km² (Cullen et al 2006), and used by Sollmann et al. (2008) to analyze the viability of individual PJAs.

Subsequently, we compared the viability of metapopulations mentioned above with the population structure suggested Beisiegel et al. (2012) (Figure 1). For this, we used the

eight extent of occurrence polygons (EEO polygons, from now on) that represent present jaguar subpopulations and its estimates. We also simulated the effect of potential ecological corridors between these subpopulations according to proximity of the polygons EEO. We used the dispersers mortality rate as surrogate for the ecological quality of corridors and built five hypothetical scenarios for each connection with dispersers mortality rate ranging from 10% to 50%. In both analyses, we used population estimates presented by Beisiegel et al. (2012) as initial populations. If the subpopulation presented more than one value, we considered the average.

We also evaluated potential reintroduction scenarios of individuals in the fragments that showed high importance to connectivity (Figure 2), called from now on “key fragments to connectivity”. Jaguar populations were extirpated from these fragments between 1960 and 1990 (Mazzoli, 2008), but their spatial extent and topology make them important for landscape connectivity, even when the shortest distance dispersal is considered (Chapter 1). Because of the spatial proximity to the Serra do Mar polygon (P3), we created reintroduction and connection scenarios between this polygon and the key fragments to connectivity. In spite of the apparent spatial connection, we do not consider the reintroduced population as part of the subpopulation of Serra do Mar, but that a metapopulation structure was formed. The reintroduced population sizes ranged from 10 to 50 individuals and for each of the five population sizes, the connectivity quality was also modeled following the same methodology of the corridors described above.

Table 1. Estimates of population density of jaguar (*Panthera onca*) for protected areas in Atlantic Forest found in the scientific literature.

Population density (ind./100km²)	Study areas	References
2.22	PE Morro do Diabo	Cullen et al., 2006
0.78	PE das Varzeas do Rio Ivinhema	Sana, unpubl. Data
0.71	PN Iguazu, Argentina	Paviolo et al., 2008
0.31	PE Carlos Botelho	Beisiegel & Oliveira, unpub. data
1.00	Mean	-

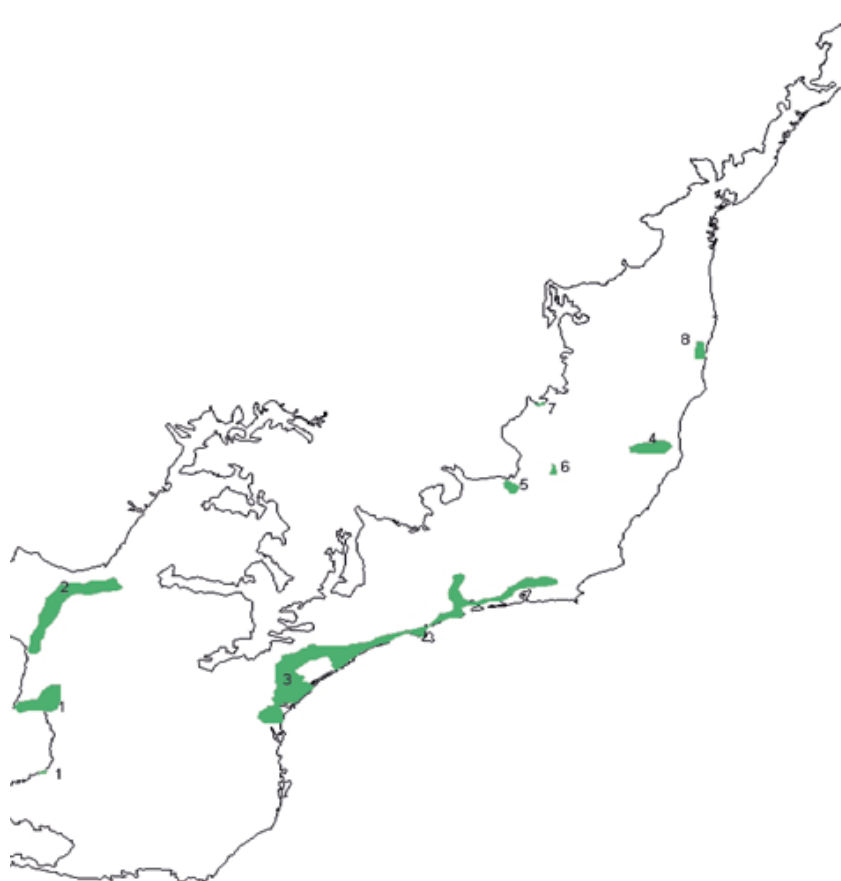


Figure 1. Polygons (subpopulations) representing the extent of occurrence of the jaguar in the Atlantic Forest. Figure extracted from Beisiegel et al. (2012).

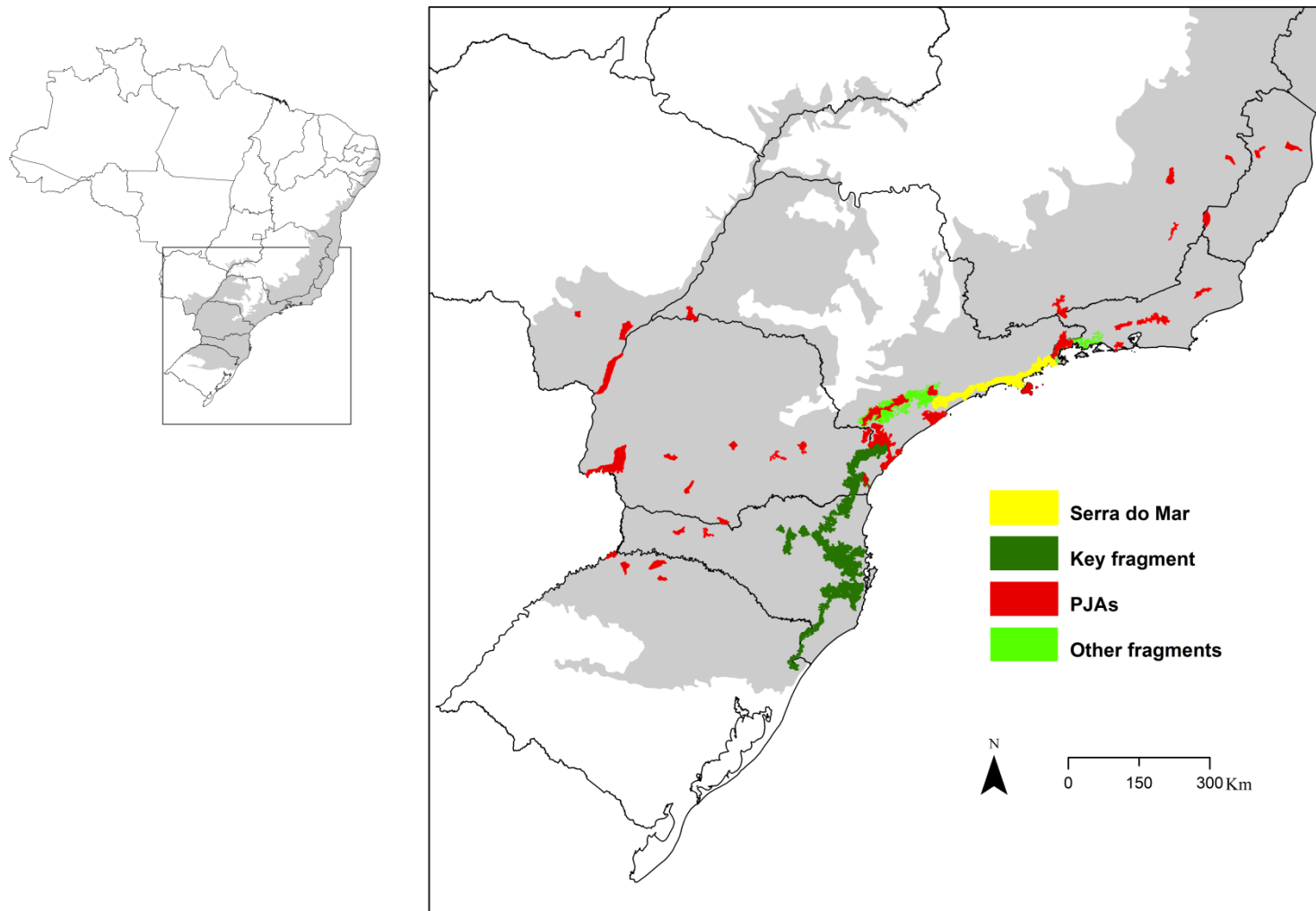


Figure 2. Key fragments to functional landscape connectivity, potential areas for reintroduction of jaguar populations in Atlantic Forest.

Population Viability Analysis

We used VORTEX version 9.99 (Lacy, 2012) to evaluate the population and metapopulation dynamics. VORTEX is a software based on Monte Carlo simulations that follow each individual in the population independently, simulating the effects of combining deterministic and stochastic factors on population persistence, allowing also to assess the viability of metapopulation structures (Lacy, 2000). The software is well suited to model the population dynamics of jaguar because it was originally designed to model populations of long-lived species with low fecundity (Lacy, 2000).

There are no specific data in the literature on jaguar mortality, dispersion or reproduction for most Atlantic Forest landscapes, so the life history parameters required as input data in VORTEX were obtained from the "Brazilian Action Plan for Jaguars" (de Paula et al., 2010) (Table 2). In the analysis of the resulting metapopulations of the PJAs network, we considered the carrying capacity equal to the initial population of each protected area. For the analysis of individual subpopulations and the analysis of potential corridors used as carrying capacity the higher estimate suggested by Beisiegel et al. (2012). Finally, for the restoration scenarios used the lower density shown in Table 1 to calculate the carrying capacity of the fragments key to connectivity. A total of 1,000 interactions were conducted for each scenario, and population persistence was assessed during the period of 200 years. We assumed that both males and females disperse as subadults (20%), (Funston et al 2003), the same approach adopted by Zanin et al. (2014). In our study, we considered as viable those populations that showed a probability of persistence $\geq 95\%$ during the period modeled.

Table 2.Life history parameters of the jaguar used in the population viability analysis.

Parameter	Value
Breeding system	Polygynous
Age of first offspring for females	3
Age of first offspring for males	4
Maximum age of reproduction	15
Sex ratio at birth (%)	50:50
Progeny/brood	4
Density dependent reproduction	Yes
Allee parameter	0.5
Steepness parameter	2
% female breeding	$(P0((P0-K)*((N/K)^2)))*(N/(A+K))$
EV in % breeding	12.5
% male breeding pool	90
% mortality rate age 0-1 (♂:♀)	42(7)/ 42(7)/
% mortality rate age 1-2 (♂:♀)	17(3.5)/ 17(3.5)
% mortality rate age 2-3 (♂:♀)	20(5)/ 20(5)/
% mortality rate age 3-4 (♂:♀)	25(6)/ 6(1.5)
% mortality rate age 4-10 (♂:♀)	10(2)/ 8(1.5)
% mortality rate age 10-15 (♂:♀)	increasing the mortality rate of 5% / year
SD carrying capacity	5% of N(0)
Migration rate	20%
Dispersers surviving	50%-90%

RESULTS

There were no viable metapopulations during 200 years for both the pessimistic and optimistic scenarios for the four dispersion distances evaluated, with mean time to extinction of not more than 70 years for all of them (Figure 3). The Serra do Mar metapopulation (M1) had a mean time to extinction, considering the average between four dispersal distances, of only 33.52 ± 1.26 years in the pessimistic scenario and 65.82 ± 1.18 years in the optimistic scenario. There was an average of 4.6 subpopulations added in the metapopulation structure of M1 among dispersion scenarios, with an average population size of 2.95 ± 3.01 , and 10.10 ± 7 individuals for the pessimistic and optimistic scenarios, respectively. The second metapopulation with longer mean time to extinction, 23.4 ± 2.20 years for pessimistic scenario and 60.97 ± 2.85 years for the optimistic, was formed by the Upper Paraná PJAs (PARNA Ilha

Grande, PE Ivinhema and PE Morro do Diabo) (M2) (Figure 3). The mean time to extinction of other metapopulation did not exceed 25 years for all scenarios (Figure 3).

The evaluation long term viability for the eight EOO polygons suggested by Beisigel et al. (2012) showed that individually, none of these areas are able to persist in the next 200 years (Table 3). The polygon stretching from Pontal do Paranapanema to PARNA da Ilha Grande(P1), which has the highest estimated number of adults ($N = 52$) showed a probability of 90% of extinction in 200 years and the highest mean time to extinction, 139.6 year, among the eight subpopulations (Table 3). The subpopulation of Serra do Mar (P2) ($N = 41$) showed 92% of chance of being extinguished during the study period, with a mean time to extinction of 135.6 years (Table 3). The other subpopulations had probability of extinction of 100% in 200 years with a mean time to extinction lower than 100 years (Table 3).

The creation of hypothetical corridors between isolated subpopulations (EOO polygons) had a positive impact on the probability of persistence of connected subpopulations (Figure 4). Only connectivity between the four smaller sub-populations of the Atlantic Forest showed no positive effect. Although corridors presented low dispersal mortality rates, i.e. high ecological quality, the probability of extinction for this metapopulation (M4) would be 100% in 200 years (Figure 4). For the remaining metapopulations (M1, M2, and M3) even with high mortality rate for dispersing individuals (30%) we observed a reduction in the probability of extinction (Figure 4) and an increase in genetic diversity (Figure 5) compared to the isolated subpopulations (Table 3). As expected, the establishment of good quality corridors (dispersers mortality equal to 10%) among the three largest subpopulations (P1, P2 and P3) resulted in a population structure (M3) with probability of extinction of only 8% (Figure 4) and genetic diversity of 75% (Figure 5). However, a decrease of 10% in corridors quality resulted in a mean increase of approximately 20%, 10% and 5% in the probability of extinction in M3, M1 and M2, respectively (Figure 4).

The reintroductions scenarios in key fragments near the Serra do Mar polygon (P3) resulted in metapopulations with lower probability of extinction than those formed between EOO polygons, except for M3, when runners with low dispersers mortality (10%) are considered (Figure 6). However, decrease in the corridors quality resulted in more pronounced increases in probability of extinction than the scenarios of connections between EOO polygons (Figure 6). The metapopulation formed by adding 20 individuals reintroduced showed 25% chance to be extinct in 200 years. There was low variation of probability of extinction and genetic diversity this metapopulation compared to those formed by reintroduction of 30 and 40 individuals (Figure 6 and 7).

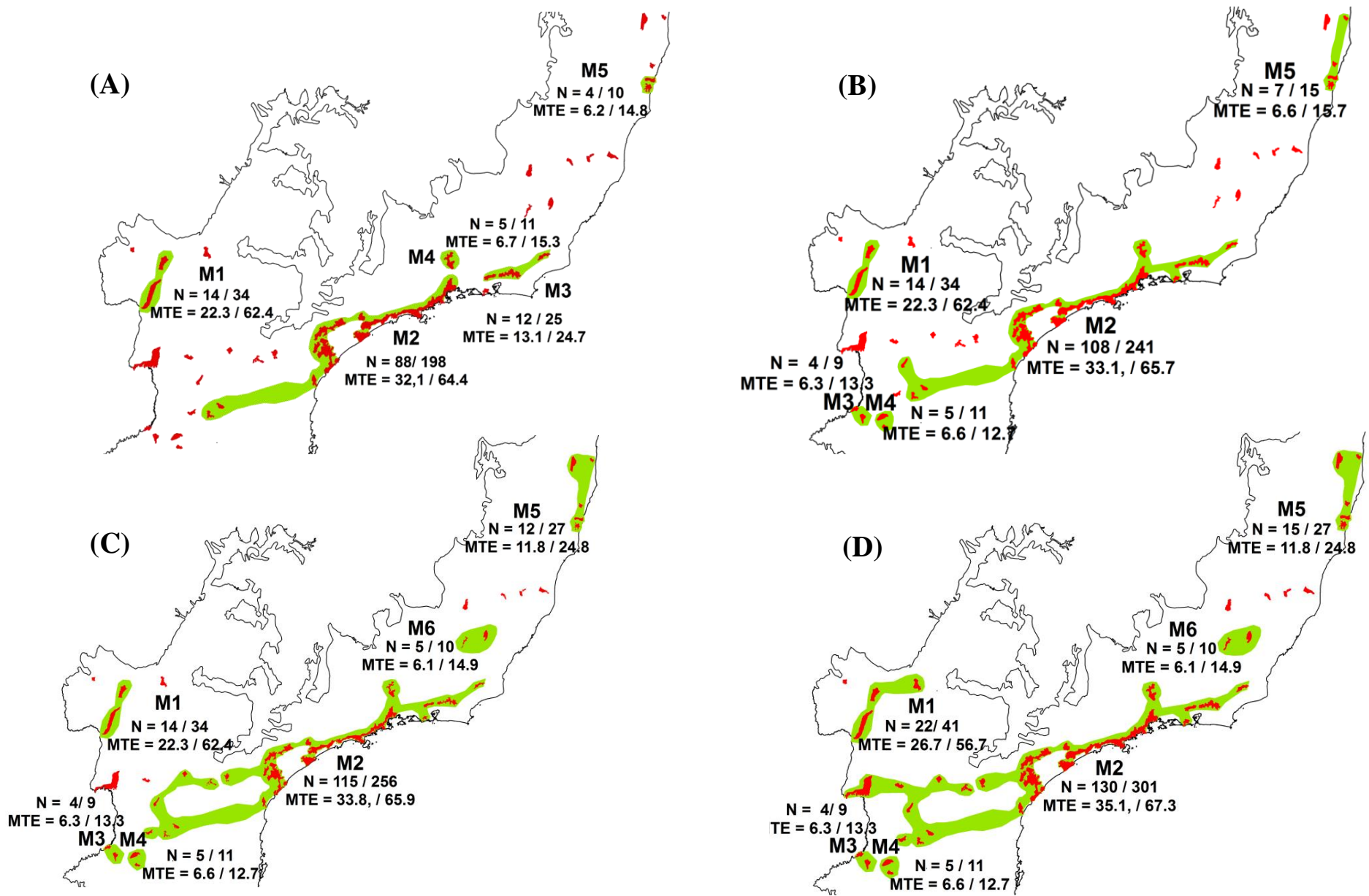


Figure 3. Mean time to extinction in years (MTE) and population size (N) considering the pessimistic/optimistic scenario for metapopulations (M) of PJAs network (in red) structured by functional analysis connectivity (Chapter 1) for dispersion thresholds of (A) 10km, (B) 20km, (C) and 30km (D) 40 km.

Table 3. Population size (N), mean rate of stochastic population growth (stoc-r), probability of extinction (PE), mean time to extinction in years (MTE) and mean population size (N-all) of the isolated subpopulations suggested by Beisiegel et al. (2012) at the end of 200 years of simulations.

Subpopulation	Polígono	N	stoc-r (SD)	PE	MTE	N-all (SD)
P1	PARNA Iguazu ao PE do Turvo	32	-0,01 ± 0,158	1	88,8	0
P2	Pontal do Paranapanema ao PARNA da Ilha Grande	52	-0,01 ± 0,135	0,9	139,6	1,41 ± 5,66
P3	Serra do Mar	41	-0,01 ± 0,136	0,92	135,6	1,03 ± 4,37
P4	Sooretama/Reserva Vale	20	-0,02 ± 0,183	1	53	0
P5	Mantiqueira	6	-0,01 ± 0,257	1	13,3	0
P6	Rio Doce	12	-0,02 ± 0,217	1	31,1	0
P7	Espinhaço	1	0	1	1	0
P8	Monte Pascoal e Pau Brasil	3	-0,01 ± 0,265	1	6	0

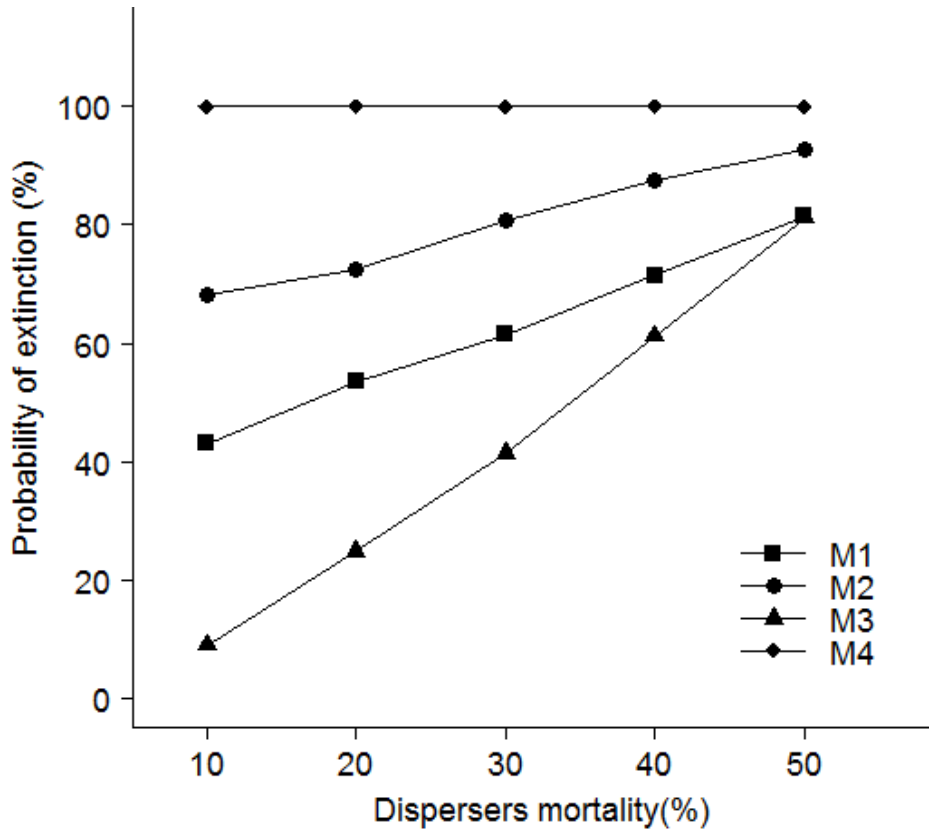


Figure 4. Probability of extinction of metapopulations (M) formed by the corridors establishment of different ecological quality, represented by percentage of dispersers dead, among subpopulations of the EOO polygons (Table 3). M1= P1+P2; M2= P1+P3; M3= P1+P2+P3; M4= P4+P5+P6+P7+P8.

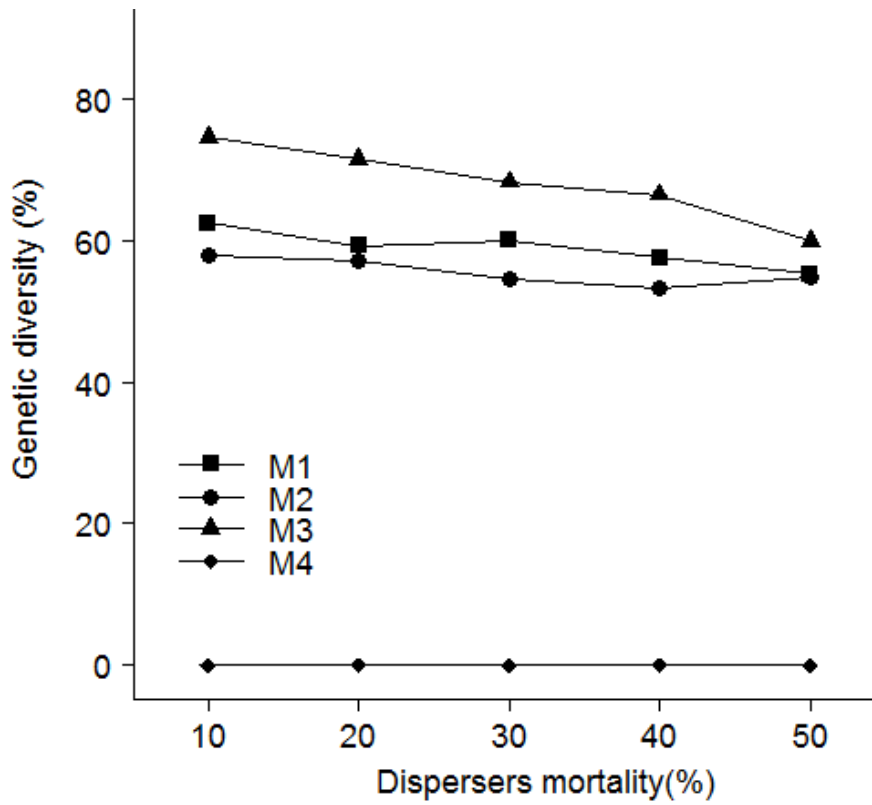


Figure 5. Genetic diversity of metapopulations (M) formed by the corridors establishment of different ecological quality, represented by percentage of dispersers dead, among subpopulations of the EOO polygons (Table 3). M1= P1+P2; M2=P1+P3; M3=P1+P2+P3; M4=P4+P5+P6+P7+P8.

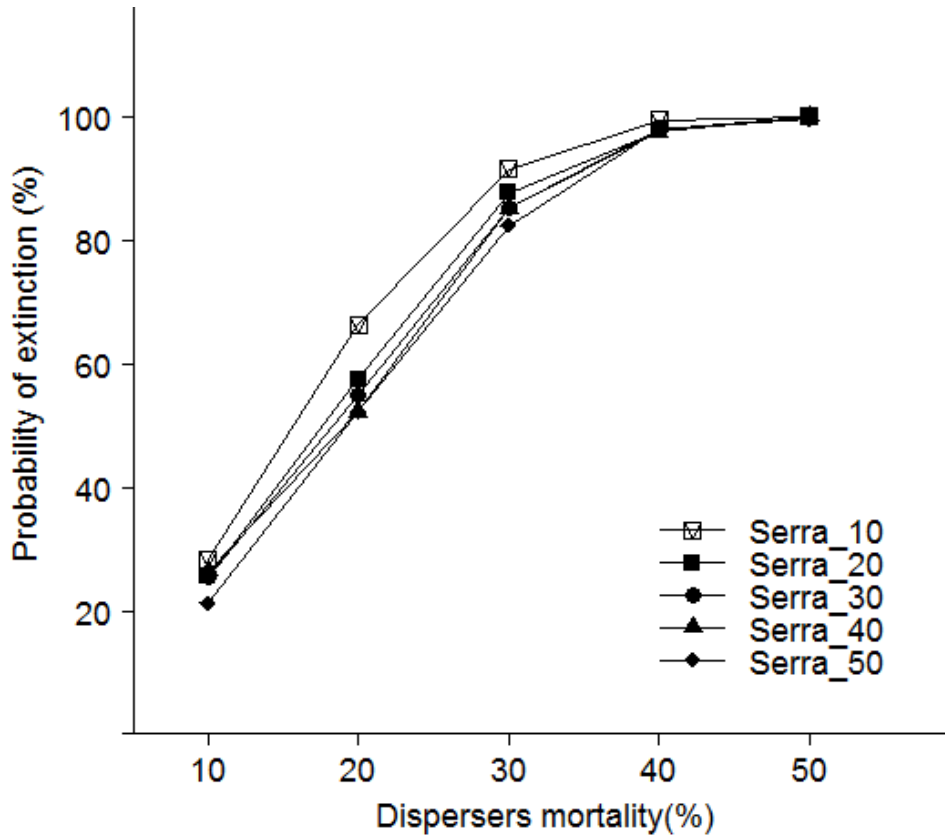


Figure 6. Probability of extinction of metapopulation formed between the polygon of the Serra do Mar (P3) and different population sizes reintroduced into the key fragments to connectivity according ecological quality of corridors. Serra_10= Serra do Mar population + 10 jaguars reintroduced; Serra_20= Serra do Mar population + 20 jaguars reintroduced; Serra_30= Serra do Mar population + 30 jaguars reintroduced; Serra_40= Serra do Mar population+ 40 jaguars reintroduced; Serra_50= Serra do Mar population+ 50 jaguars reintroduced.

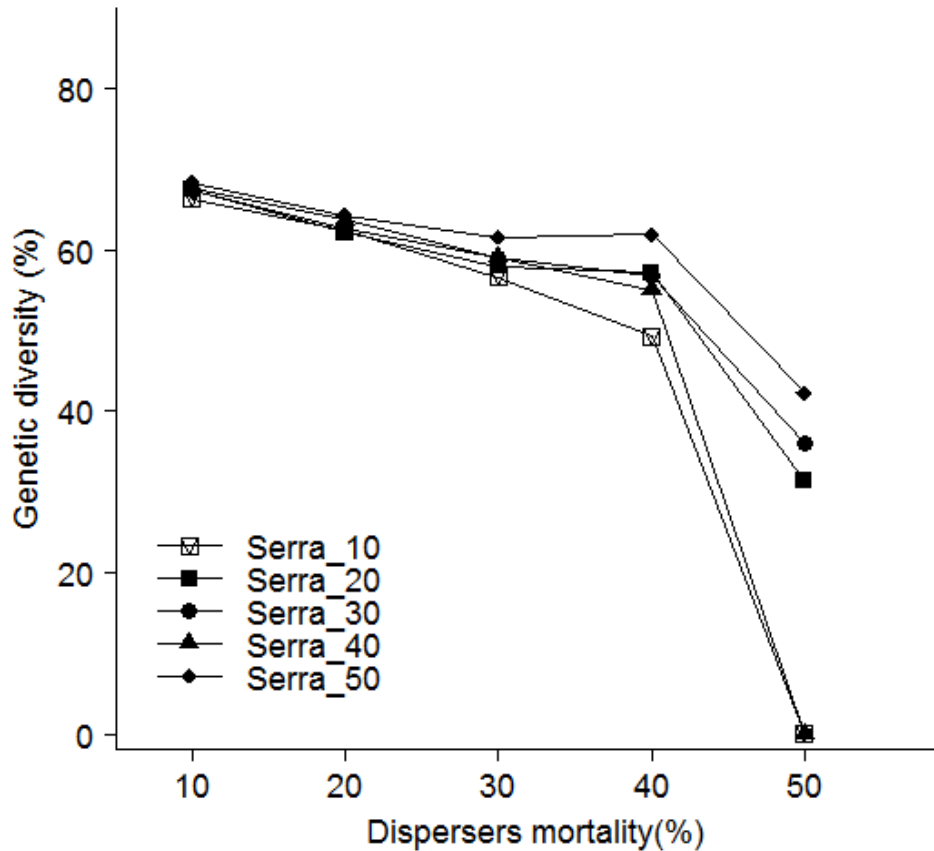


Figure 7. Genetic diversity of metapopulation formed between the polygon of the Serra do Mar (P3) and different population sizes reintroduced into the key fragments to connectivity according ecological quality of corridors. Serra_10= Serra do Mar population + 10 jaguars reintroduced; Serra_20= Serra do Mar population + 20 jaguars reintroduced; Serra_30= Serra do Mar population + 30 jaguars reintroduced; Serra_40= Serra do Mar population + 40 jaguars reintroduced; Serra_50= Serra do Mar population + 50 jaguars reintroduced.

DISCUSSION

It is estimated that jaguars are confined to an area less than 50% of its original range (Sanderson et al., 2002). In the Atlantic Forest, the status of the species is very worrying, since fragmentation is a serious threat (Zanin et al., 2014) and the annual deforestation rates have increased considerably (SOS Mata Atlântica & INPE, 2012). Because protected areas alone cannot guarantee the persistence of the jaguar in the long term in the Atlantic Forest (Sollmann et al., 2008), it is expected that the structure of a network between them play a key role in future species conservation. However, our analysis highlight the critical status of jaguar conservation in the Atlantic Forest, for not even the current network of protected area is able to maintain viable populations of the species in the next 200 years.

Our model PVA showed that most metapopulations, located in the Atlantic Forest, would be extinct between 33-66 years. In spite of the growing number of subpopulations between the dispersion scenarios, there were no great changes in the average time of extinction. This probably occurred because the added PJAs did not have, in general, sufficient area to sustain significant subpopulations of the species, in both scenarios. The metapopulation size of the pessimistic scenario for the Atlantic Forest, 89-135 individuals, is within the range estimated by Leite et al. (2002), of 200 ± 85 jaguars adult for this area. However, most of the region is not well conserved and preliminary analyzes have estimated population densities below $0.5 \text{ ind.} / 100 \text{ km}^2$ (Beisiegel et al., 2012), much smaller than that used in our analysis. The region of Serra do Mar forms the largest extent of occurrence polygon for jaguars in the Atlantic Forest, but not the largest population (Beisiegel et al., 2012). If considered the formation of a single subpopulation in the region, as discussed by Beisiegel et al. (2012), the mean time to extinction nearly doubles, although it is still not be

viable in 200 years. These results stress the strong threat that fragmentation represents to jaguars (Zanin et al., 2014).

Considering the trends of subpopulation reduction and isolation, Cullen et al. (2006) estimated an average of 88 years to the extinction of jaguars the Upper Paraná region. This estimate was higher than that found by our analysis, even in the optimistic scenario, probably due to different mortality rates and areas considered by the two studies. PVA models for jaguar are very sensitive to changes in reproductive parameters and mortality rates, especially of adult females (de Paula et al., 2010; Zanin et al., 2014). In addition to the protected areas in Brazil (Morro do Diabo State Park, Ivinhema State Park Region and Ilha Grande National Park), Cullen et al. (2006) included a subpopulation in Eastern Paraguay along the Paraná River, not evaluated in our study. It is estimated that the population reduction in the largest jaguar population of Upper Paraná may have reached 87-90% in the last 10-15 years (Beisiegel et al., 2012). Nevertheless, our simulations showed that one of subpopulation of this region (P2) had the highest mean time to extinction among all others, about 140 years. However, the other subpopulation of Alto Paraná (P1), formed by the Green Corridor (PN Iguazu to PN Turvo connected by areas in Missones, Argentina) could be extinct in less than 100 years. Although the region has sufficient potential habitat available, low population densities have been estimated, revealing a strong population decline (Paviolo et al., 2008). These subpopulations reductions of Alto Paraná, mainly due to habitat loss and fragmentation, have resulted in loss of genetic variability and caused enough isolation to promote differentiation induced by genetic drift (Haag et al., 2010).

Because the current population structures of jaguars in the Atlantic Forest, both in the form of metapopulation as suggested by our study, and in the form of isolated subpopulations as proposed by Beisiegel et al. (2012), had highly likely to be extinct in less than 200 years, the connectivity between them should be considered. Our PVA model showed that although

the implementation of good quality corridors would benefit the coastal subpopulations and the Upper Paraná, reducing the probability of extinction in relation to isolated subpopulations, the formed metapopulations are not viable. In addition, a recent evaluation showed that about 80% of potential corridors between PJAs in the Atlantic Forest are lowest quality corridors due to human pressure, making the implementation of a jaguar corridor very expensive and maybe prohibitive (Silveira et al., 2014). Although the metapopulation formed by subpopulations of Alto Paraná with the coastal subpopulation has presented a low probability of extinction, we believe that the great effort, both financial and logistical, makes it unlikely the establishment of conservation actions. Another factor to be considered is that the distribution of the jaguar in the Atlantic Forest has different socioeconomic and ecological characteristics in relation to the Upper Paraná, factors should be considered when corridors linking these two regions are thought (de Paula et al., 2010).

Due to the low efficacy possibly presented by potential corridors (Silveira et al., 2014), our results suggest that perhaps the reintroduction is the best strategy for the conservation of the jaguar in the Atlantic Forest. The jaguar was extinguished from key fragments for connectivity, which are potential sites for reintroduction, between the 1960s and 1990s, one of the main causes was illegal poaching (Mazzolli, 2008). The results of our model suggests that at least 20 animals must be released on the fragment to structure with subpopulation of Serra do Mar one metapopulation with 25% probability of extinction in 200 years. This result is consistent with carnivore reintroduction projects which indicate that at least 20 individuals must be released so that the project does not suffer a higher risk of failure (van Wieren, 2006). Although the literature lacks information about jaguar reintroduction studies and projects, with the few cases resulting in failures (Hunter & Rabinowitz, 2009), the jaguar has the potential to become a focus species of reintroductions programs (Kelly & Silver, 2009). We are aware that before the execution of a reintroduction program in a

candidate site, many studies and efforts are still necessary, for example, the evaluation of environmental suitability, eradication of causes that led to the extinction of jaguar and prey base viability.

The predictions derived from our simulations are considered optimistic, even in the scenario here entitled “pessimistic”, for the following reasons. The lower density used in our study to assess the metapopulation viability was 1 ind. /km², but studies have predicted and estimated jaguar population densities below this value to various locations in the Atlantic Forest (Paviolo et al., 2008; Bernal-Escobaret al., 2015). Although there are many threats to the jaguar in the Atlantic Forest, which go far beyond the habitat destruction and fragmentation, such as illegal poaching and loss of prey base, they were not considered in our model. Moreover, various parameters used in our study, as the mortality rate, were derived from the PVA model of the "Brazilian Action Plan for Jaguars" which is a general baseline model for jaguar (de Paula et al., 2010), which may be underestimated, as in the case of mortality, or overestimated values to the Atlantic Forest.

In spite of our models presents some limitations, we believe that our results can provide an initial guide for selecting management strategies in a near future to improve the jaguar conservation status in the Atlantic Forest. This study confirms that the current network of protected areas is not able to maintain viable metapopulation of the species in Atlantic Forest in the long term. Although the implementation of effective corridors, which is perhaps unlikely to Atlantic Forest, reduces probability of extinction of subpopulations, the metapopulations still have a high probability of extinction in 200 years. Therefore, the reintroduction in the south of Atlantic Forest is perhaps, given the weights, the best candidate management strategy to save the most majestic field of New World.

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CONCLUSÃO

Nossos estudos mostraram que a maioria dos fragmentos florestais que atuam como importantes áreas conectoras na Mata Atlântica para onça-pintada estão sob a proteção menos restritiva das unidades de conservação de uso sustentável. Entre as áreas protegidas como presença inferida ou confirmada de onça-pintada (PJAs), o Parque Estadual da Serra do Mar, principalmente o N. Cutatão, também possui grande valor para conectividade da paisagem. Nossos estudos também mostraram que a rede de áreas protegidas é incapaz de garantir a persistência de metapopulações de onça-pintada a longo prazo. Mesmo as potenciais metapopulações formadas através da dispersão de indivíduos utilizando corredores de boa qualidade ecológica teriam grandes chances de serem extintas em menos de 200 anos. A reintrodução da espécie em fragmento-chaves para conectividade se mostrou a melhor estratégia de manejo para melhorar o crítico status de conservação da onça-pintada na Mata Atlântica. Mostramos com esse estudo que a integração da análise de conectividade funcional e da análise de viabilidade populacional constitui uma poderosa ferramenta conservacionista, permitindo a exploração de aspectos diferentes, mas complementares da conservação de espécies focais.