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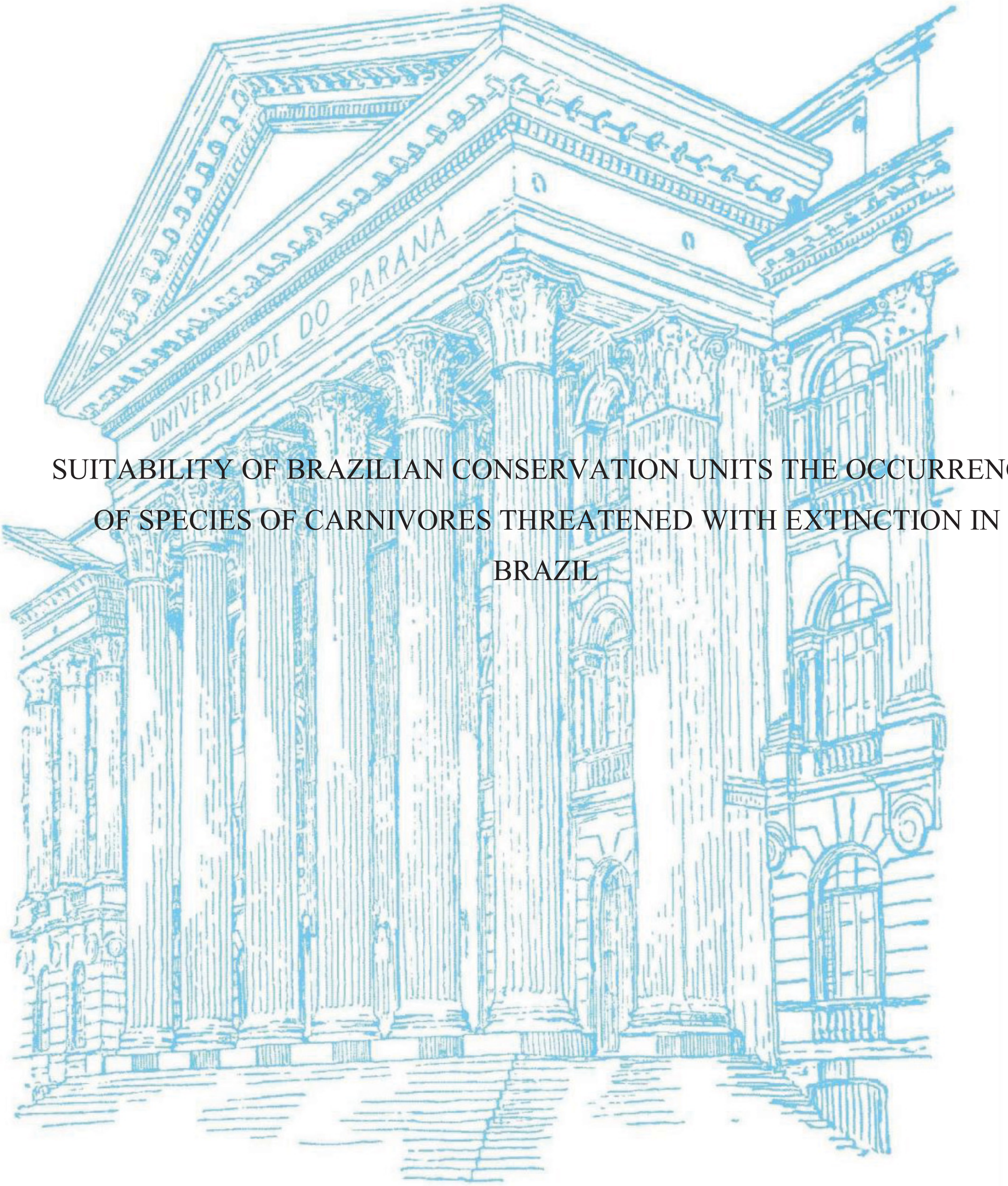

SUITABILITY OF BRAZILIAN CONSERVATION UNITS THE OCCURRENCE OF SPECIES OF CARNIVORES THREATENED WITH EXTINCTION IN BRAZIL

CURITIBA, PR

2021

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Dissertação apresentada como requisito parcial à obtenção do título de Mestre em Ecologia e Conservação, no Curso de Pós-Graduação em Ecologia e Conservação do Setor de Ciências Biológicas da Universidade Federal do Paraná.

Orientador: Prof. Dr. Fernando de Camargo Passos
Co-orientadora: Dr.ª Fernanda Thiesen Brum

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ATA DE SESSÃO PÚBLICA DE DEFESA DE MESTRADO PARA A OBTENÇÃO DO GRAU DE MESTRE EM ECOLOGIA E CONSERVAÇÃO

No dia vinte e tres de junho de dois mil e vinte e um às 14 horas, na sala https://meet.google.com/yuu-tooc-fsg?authuser=0, MODALIDADE PARECER, foram instaladas as atividades pertinentes ao rito de defesa de dissertação da mestranda **FABIELLE PEREIRA DOS SANTOS**, intitulada**: Suitability of Brazilian Conservation Units the occurrence of species of carnivores threatened with extinction in Brazil.**, sob orientação do Prof. Dr. FERNANDO DE CAMARGO PASSOS. A Banca Examinadora, designada pelo Colegiado do Programa de Pós-Graduação em ECOLOGIA E CONSERVAÇÃO da Universidade Federal do Paraná, foi constituída pelos seguintes Membros: FERNANDO DE CAMARGO PASSOS (UNIVERSIDADE FEDERAL DO PARANÁ), MÁRCIO LEITE DE OLIVEIRA (UNIVERSIDADE EST.PAULISTA JÚLIO DE MESQUITA FILHO), ROBERTO FUSCO COSTA Pós-Doc (UNIVERSIDADE FEDERAL DO PARANÁ). A presidência iniciou os ritos definidos pelo Colegiado do Programa e, após exarados os pareceres dos membros do comitê examinador e da respectiva contra argumentação, ocorreu a leitura do parecer final da banca examinadora, que decidiu pela APROVAÇÃO. Este resultado deverá ser homologado pelo Colegiado do programa, mediante o atendimento de todas as indicações e correções solicitadas pela banca dentro dos prazos regimentais definidos pelo programa. A outorga de título de mestre está condicionada ao atendimento de todos os requisitos e prazos determinados no regimento do Programa de Pós-Graduação. Nada mais havendo a tratar a presidência deu por encerrada a sessão, da qual eu, FERNANDO DE CAMARGO PASSOS, lavrei a presente ata, que vai assinada por mim e pelos demais membros da Comissão Examinadora.

CURITIBA, 23 de Junho de 2021.

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CONSERVAÇÃO - 40001016048P6

TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em ECOLOGIA E CONSERVAÇÃO da Universidade Federal do Paraná foram convocados para realizar a arguição da dissertação de Mestrado de **FABIELLE PEREIRA DOS SANTOS** intitulada: **Suitability of Brazilian Conservation Units the occurrence of species of carnivores threatened with extinction in Brazil.**, sob orientação do Prof. Dr. FERNANDO DE CAMARGO PASSOS, que após terem inquirido a aluna e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.
A outorga do título de mestre está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

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“O correr da vida embrulha tudo.
A vida é assim: esquenta e esfria,
aperta e daí afrouxa,
sossega e depois desinquieta.
O que ela quer da gente é
coragem.”

Guimarães Rosa

RESUMO

Conhecer a área de ocorrência das espécies e compreender os fatores subjacentes às suas distribuições são essenciais para tratar da sua conservação. Mudanças no clima e no uso da terra estão entre as principais ameaças a muitas espécies de mamíferos. As espécies ameaçadas de carnívoros brasileiros, se não forem efetivamente protegidas, podem sofrer grandes consequências em sua distribuição e até mesmo desaparecer de algumas regiões, piorando seu estado de conservação. Este estudo teve como objetivos: 1) avaliar o impacto das mudanças climáticas e do uso da terra na distribuição de 11 espécies de carnívoros ameaçados no Brasil; 2) avaliar o grau de proteção das espécies em Áreas Protegidas tanto no cenário atual quanto no futuro; e 3) realizar a priorização espacial de áreas no Brasil, buscando selecionar áreas prioritárias complementares para conservação. Para isso, usamos modelos de nicho ecológico e dados de uso da terra atuais e futuros para estimar as distribuições atuais e futuras. Combinamos modelos de distribuição de espécies com os dados de áreas protegidas para obter o grau de proteção. Por fim, foi realizada a priorização espacial para a conservação das espécies incluídas no estudo. Nossos resultados mostraram que todas as espécies de carnívoros ameaçados no Brasil devem apresentar uma contração em sua distribuição nos próximos anos. Além disso, o nível de proteção das áreas protegidas mostrou-se extremamente baixo para garantir a persistência das espécies em uma perspectiva de longo prazo. Além disso, nossa análise de priorização indicou a região central do Brasil como a de maior prioridade quando se trata de implementar áreas complementares às áreas protegidas já existentes no país. Os resultados aqui encontrados mostram a vulnerabilidade das espécies ameaçadas de carnívoros no Brasil às mudanças climáticas e de uso do solo, além de mostrar a importância da implantação de um maior número de áreas protegidas, que devem ser pensadas como de alta eficiência para garantir a longevidade das espécies. persistência.

Palavras-chave: Conservação, Mamíferos, Modelagem de nicho ecológico, Priorização espacial.

ABSTRACT

Knowing the area of occurrence of the species and understanding the factors underlying their distributions are essential to address their conservation. Climate and land use changes are among the main threats to many species of mammals. The threatened species of Brazilian carnivore, if not effectively protected, can suffer large consequences in their distribution and even disappear from some regions, worsening their conservation status. This study aimed: 1) to assess the impact of future climate and land use changes on the distribution of 11 threatened carnivore species in Brazil; 2) evaluate the degree of protection of species in Protected Areas (PA) both in current and future scenarios; and 3) perform spatial prioritization of areas in Brazil, seeking to select priority complementary areas for conservation. For that, we used ecological niche models and current and future land use data to estimate current and future distributions. We combined species distributions models with the PA data to acess the protection degree. Finally, we carried out the of spatial a prioritization for the conservation of species included in out the study. Our results showed that all threatened carnivore species in Brazil are expected to have a contraction in their distribution in the coming years. Also, the protection level of PAs proved to be extremely low to guarantee the persistence of species in the long-term perspective. Also, our prioritization analysis indicated the central region of Brazil as having the highest priority when it comes to implementing areas complementary to the PAs that already exist in the country. The results found here show how vulnerable the threatened carnivore species in Brazil are to climate and land use changes, in addition to showing the importance of implementing a greater number of PAs, which must be thought as of high effictiveness to guarantee the long-term species persistence.

Keywords: Conservation, Ecological Niche Modeling, Mammals, Spatial prioritization.

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Sumário

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The worrying fate of brazilianThreatened Carnivores: negative impacts climate and land use changes and conservation priorities

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Running Header: The worrying fate of brazilian Threatened Carnivores

Abstract

Knowing the area of occurrence of the species and understanding the factors underlying their distributions are essential to address their conservation. Climate and land use changes are among the main threats to many species of mammals. The threatened species of Brazilian carnivore, if not effectively protected, can suffer large consequences in their distribution and even disappear from some regions, worsening their conservation status. This study aimed: 1) to assess the impact of future climate and land use changes on the distribution of 11 threatened carnivore species in Brazil; 2) evaluate the degree of protection of species in Protected Areas (PA) both in current and future scenarios; and 3) perform spatial prioritization of areas in Brazil, seeking to select priority complementary areas for conservation. For that, we used ecological niche models and current and future land use data to estimate current and future distributions. We combined species distributions models with the PA data to acess the protection degree. Finally, we carried out the of spatial a prioritization for the conservation of species included in out the study. Our results showed that all threatened carnivore species in Brazil are expected to have a contraction in their distribution in the coming years. Also, the protection level of PAs proved to be extremely low to guarantee the persistence of species in the long-term perspective. Also, our prioritization analysis indicated the central region of Brazil as having the highest priority when it comes to implementing areas complementary to the PAs that already exist in the country. The results found here show how vulnerable the threatened carnivore species in Brazil are to climate and land use changes, in addition to showing the importance of implementing a greater number of PAs, which must be thought as of high effictiveness to guarantee the long-term species persistence.

Keywords: Conservation, Ecological Niche Modeling, Mammals, Spatial prioritization.

1. Introduction

Approximately 61% of the world's Carnivores (mammal species of the order Carnivora) are currently threatened with extinction risks due to the increasing impact of the human species in the earth's surface (Ripple *et al.*, 2014). The conservation of this group is essential because it has great ecological importance considering the role it plays as predators and, consequently, regulators of natural preys populations, in addition to acting as umbrella species (Cardillo *et al.*, 2004). Many species of this order are experiencing population declines and are among the animals most affected by habitat loss and fragmentation (Ripple *et al.*, 2014; Di Minin, Leader-Williams & Bradshaw, 2016a). Also, the degree of protection of these species is considered low (DiMinin *et al.*, 2016b; Zanin, Palomares & Albernaz, 2021). According to DiMinin *et al* (2016), only 10% of carnivore species are globally protected. When selecting new areas to protect is important to take into account the inclusion of specific priorities for some target species (Jones *et al.*, 2016), as the carnivores themselves. In Brazil, one of the richest countries in the world in terms of biodiversity (Senna *et al.*, 2013), 39% of the carnivores are threatened mainly by habitat loss and fragmentation resulting from agricultural activities, and hunting (ICMBio, 2018).

The knowledge on species distribution is primal for conservation planning (Araújo & Peterson, 2012; Ferraz *et al.*, 2012; Di Minin *et al.*, 2016b), specially for assessing the impact of threats on biodiversity, such as climate change and habitat loss (Virkkala *et al*., 2008; Meyer, Pie & Passos, 2014; Sales *et al*., 2017). According to the 2018 Intergovernmental Panel on Climate Change (IPCC), global temperatures are expected to rise between 1.5°C and 4.5°C during the 21st century. As a result, these future climate changes will have a significant impact on biodiversity (Pearson & Dawson, 2003; Bellard *et al*., 2012), since species distribution is largely determined by climate (Thomas, 2010). In this context, there is an increasing awareness among the scientific community that for conservation strategies to be effective in ensuring biodiversity persistence, it is necessary to anticipate the impacts of climate change (Araújo & Rahbek, 2006). In addition to climate change, another issue that deserves special attention is related to land use. Activities such as agricultural expansion, logging, urbanization, road construction, among others, are leading to habitat loss and degradation, which are the main threats to biodiversity (Seki *et al*., 2017; Coelho *et a*l., 2018; Bueno & Peres, 2020). Studies have shown that the increased intensity of land use is responsible for a significant change in the structure of habitats, causing changes in the distribution of species and even in your behavior (Blaum *et al*., 2007, Miranda *et al*., 2013; Brehm *et al*., 2019; Gallego-Zamora *et al*., 2020). Also, the change in land use has a direct effect on the reduction and isolation of populations through the loss and fragmentation of the species habitat (Haag *et al*., 2010; Balkenhol *et al.*, 2014; Zanin, Palomares & Brito, 2015a; DiMinin *et al.*, 2016b; Powers & Jetz, 2019).

Another important factor that must be considered when we talk about climate change and land use is the dispersion capacity of the species. Studies indicate potential changes in species distribution in response to climate change and land use (Pearson & Dawson, 2003, Faleiro, Machado & Loyola, 2013; Zanin *et al*., 2021). However, most of these studies do not consider that the species ability to follow these changes depends on their dispersion skills. Dispersion is important because it regulates the species ability to track change and access more suitable areas (Midgley *et al.*, 2006; Schloss *et al.*, 2012). Therefore, it is essential to consider the dispersion capacity of species to assess not only the effects of both climate change but also of land use on it.

Studies have shown that climate change can affect carnivore species in different ways, such as with population reduction, loss of adequate habitat, change in distributional range, genetic isolation, and extinctions (Thomas *et al*., 2004; Carroll, 2007; Warren *et al*., 2013, Ariaz-Alzate *et al*., 2017, 2020; Zanin *et al*., 2020). Also, the change in land use is an aggravating factor for the species decline, being considered one of the main threats to most species of carnivores mammals (Morrison *et al*., 2007; Zanin, Palomares & Brito, 2015b). Thus, more studies are needed to indicate priority areas for the conservation of carnivores mammals taking into account both climate change and land-use change.

In conservation biology, there are several ways to deal with the threats that surround biodiversity and the main strategy involves the creation of Protected Areas (PA) (Lawler *et al*., 2009; Dawson *et al*., 2011; Loyola *et al*., 2012). The implementation of these PAs is essential for the persistence of the species. Systematic conservation planning was designed to assist in the creation of new PAs (Margules & Pressey, 2000). This framework proposes criteria for the definition of where, why, and how conservation efforts should be directed to obtain maximum benefits in protecting species (Margules & Pressey, 2000; Margules & Sarkar, 2007). In Brazil, 18% of the territory is estimated to be under protected areas (MMA, 2020). However, it is known that PAs do not cover all of the biodiversity (Venter *et al*., 2014; Pouzols *et al*., 2014; Butchart *et al*., 2015) and do not even protect all fauna and flora that are threatened in Brazil (Oliveira *et al.*, 2017; Ribeiro *et al.*, 2018). Thus, success in biodiversity conservation depends, mainly, on the establishment of coordinated and well-developed strategies and actions, structured in a system of PAs (Pimm *et al*., 2014; Watson *et al*., 2014; Di Minin & Toivonen, 2015).

In this context, this study aims: (1) to assess the impact of future climate and land use change on the distribution of threatened carnivores in Brazil; (2) to evaluate the degree of protection of threatened carnivore species in PAs current and future; and (3) to perform spatial prioritization of areas in Brazil, seeking to select complementary to existing PAs for protection.

2. Materials and Methods

2.1.Species selection and occurrence data

We selected for this study Brazilian species belonging to the Carnivora mammalian order that are threatened with extinction. According to the Red Book of threatened Brazilian Fauna (ICMBio, 2018) 13 species of carnivores mammals are classified as threatened considering the national territory: *Lycalopex vetulus, Atelocynus microtis,* *Speothos venaticus, Chrysocyon brachyurus, Leopardus guttulus, Leopardus tigrinus, Leopardus geoffroyi, Leopardus colocolo, Leopardus wiedii, Puma yagouaroundi, Puma concolor, Panthera onca* and *Pteronura brasiliensis.* Among the selected species, only one, *Leopardus tigrinus*, was classified as Endangered, the other species have been calssified as Vulnerable. Due to specificities in the modelling of aquatic species, as *P. brasiliensis*, we opted to leave it out of the present work. The specie *P. concolor* has not been included in the analysis because it has a very wide distribution on the continent. This fact made the analysis of the species very heavy and not supported by the computer that performed them.

We assessed species distributions by using Ecological Niche Modeling (ENM). The models are built upon the correlation between species records and environmental variables and are used to predict species distributional shifts in response to changes in climate and other variables (Peterson et al. 2011). These data reflect the ecological requirements of the species, thus providing information on which areas best correspond to the ecological niche of each species. ENM's approach is involved with the construction of a model that relates the current distribution of species to the climate, to estimate a potential future range based on future climate projections (Pearson and Dawson, 2003). For this, we compiled the occurrence record data for each species using the geographical coordinates of occurrence points. These data were obtained from the GBIF (https://www.gbif.org/), SpeciesLink (http://splink.cria.org.br/), Portal da Biodiversidade (https://portaldabiodiversidade.icmbio.gov.br/portal/) databases and the datapaper "Neotropical carnivores: a data set on carnivores distribution in the Neotropics" (Nagy-Reis *et al*., 2020). After the compilation of the occurrence data, with the aid of the Coordinate Cleaner package (Zizka *et al*., 2018), points of localities that, according to the literature and historical distribution of the species, did not appear as occurrences were removed from the analyzes, to avoid any kind of bias. Also, to reduce the autocorrelation in the species' occurrence data and a possible sampling bias, we used the thinning technique from a minimum distance of 10km between the occurrence points.

We estimated an accessible area for each species, that is, a study area in which the model was calibrated and projected. We take into consideration the biogeographical regions where the distribution points of each species are distributed (Barve *et al.,* 2011). For this, we use biogeographic regionalization for the

Neotropical region (Morrone, 2014) for all species, except *Panthera onca*. For *P. onca* we use terrestrial ecoregions of the World (Olson *et al*., 2001). This difference consists in the fact that this species has a distribution that goes beyond the Neotropical region.

2.2.Current and future climatic variables

Nineteen bioclimatic variables (derived from temperature and precipitation measurements) were used, averaging for the period 1950-2000 from the WorlClim database version 2.0 (Fick & Hijmans, 2017). We also used topographic data referring to altitude and slope from the EarthEnv database (Amatulli *et al*, 2018). To control for multicollinearity in the predictors dataset, we used a Principal Component Analysis (PCA). The three first PCA axes encompassed 95% of the variation in these variables and we therefore retained them as new variables representing the original ones to run our models.

Future climate models were built using climate projections from global climate models (GCM) for the period 2041-2060 (hereafter 2050). We used two shared socioeconomic paths (SSP): SSP2-4.5 and SSP5-8.5. SSPs have a connection with Representative Concentration Pathways (RCP). The RCPs are trajectories of concentration of greenhouse gases adopted by the IPCC. This connection between SSPs and CPRs allows the impact, adaptation, and vulnerability community to use information from SSPs in conjunction with climate projections from RCPs (Riahi *et al*., 2017). Thus, SSPs provide descriptions of relevant future conditions by analyzing both emissions and mitigation strategies and social vulnerability to climate change (O'Neill *et al*., 2017). SSP245 describes moderate challenges for adaptation and mitigation and represents a future in which development trends are not extreme in any sphere, but follow intermediate paths (O'Neill *et al*., 2017, Kc & Lutz, 2017, Riahi *et al*., 2017). SSP585, on the other hand, foresees accelerated globalization and the rapid development of human capital, thus the energy demand grows rapidly and the system continues to depend heavily on fossil fuels, making mitigation a major challenge (O'Neill *et al*., 2017, Kc & Lutz, 2017, Riahi *et al*., 2017). In summary, the SSP585 scenario is more environmentally pessimistic compared to the SSP245 scenario. All the analysis were performed using spatial data with 2.5 x 2.5 arc-minutes of resolution (approximately 5km at the equator). We selected four GCMs (BCC-CSM2, CanESM5, IPSL-CM6A and MIROC-ES2L). For the selection of GCMs we used the environmental variables bio1 and bio12 of the available models (BCC-CSM2, CanESM5, CNRM-CM6-1, CNRM-ESM2-1, IPSL-CM6A, MIROC-ES2L, MIROC6 and MRI-ESM2-0). The environmental variables bio 1 and bio12 represent average annual temperature and average annual rainfall, respectively, and because they are the most general variables for temperature and rainfall, we use them for the selection of GCMs. We performed a PCoA for each variable (bio1 and bio12) by each SSP (245 and 585) and analyzed which GCMs were more different from each other, that is, which were more external in the first two axes of PCoA (Fig. S1). We selected the most dissimilar GCMs to reduce the redundancy between them. To project species distribution into future scenarios, we used the PCA covariance structure (from current variables) to predict future PCA axes, combining the future climatic variables with the data on altitude and slope.

2.3.Modeling procedures

We used six algorithms to model species distributions: Maxent (Phillips *et al*., 2006); Support Vector Machine (Cortes & Vapnik, 1995); Gaussian Process (Golding & Golding, 2014); Generalized Linear Model (Nelder & Wedderburn, 1972); Generalizes Additive Model (Buja, Hastie & Tibshirani, 1989; Hastie & Tibshirani, 1990); Random Forest (Breiman, 2001). As all the chosen algorithms needed background/pseudo-absences points, we used the environmental restriction method to select them, based on the areas of least suitability predicted by the climate envelope model (Andrade, Velazco & De Marco, 2020). Subsequently, we submited our occurrence data to a random partition by the bootstrap method five times, each with 70% for model training (calibration) and 30% for model testing (validation). Model performance was evaluated using the Area under the ROC curve (AUC) and True Skill Statistic (TSS) metric. AUC is a commonly used measure of model performance, so models with AUC values from 0.7 to 0.9 are considered good, while values greater than 0.9 are considered models with excellent discrimination skills or high predictive power (Lobo, Jiménez-Valverde & Real, 2008). The TSS metric takes into account errors of omission and commission and success as a result of random guessing and ranges from -1 to +1, in which +1 indicates perfect agreement and values of zero or less indicate no better than random performance (Allouche, Tsoar & Kadmon, 2006).

To deal with the differences between the selected algorithms, we created an ensemble model (Araújo & New, 2007) using the upper average method. In this method, the average of the best models is used, so that the average value of the metric chosen for all models is calculated and only the models that have values above the average are used in the ensemble. We used the AUC metric to select the above-average models. For the creation of binary maps, we selected the MAX_TSS limit, this limit maximizes the sum of sensitivity and specificity. The ecological niche models were generated using the ENMTML package (Andrade, Velazco & De Marco, 2020), in the software R version 4.0.2 (R Core Team 2020). After the construction of the models, we created an a posteriori spatial restriction using the MSDM package (Mendes *et al*., 2020). We used the occurrence-based constraint method. After the model has been binarized, the study area was divided into suitable and unsuitable patches. This method assumes that suitable patches overlapping occurrences are a part of species distributions in contrast to suitable patches that do not intercept any occurrences. The edge-edge distance of occurring patches to non-occurring patches is calculated and reclassified as unsuitable for patches that have exceeded a species-specific distance limit. This limit is calculated as the longest distance from the nearest neighbor between occurrence pairs.

2.4. Land use data

For the analysis of the current land use, we used the 2019 land use map of from MapBiomas Project 5.0 (https://mapbiomas.org). These maps are produced from the pixel-by-pixel classification of satellite images and the entire process is carried out with machine learning algorithms through the Google Earth Engine platform. For the future land use projections (2050), we use the data provided by Soares-Filho *et al* (2016). This projection was built with a spatially explicit model, which uses climatic suitability for annual crops and probabilities of loss of native vegetation, based on historical trends and the environmental law. The data used were resampled to the same resolution as the models. We searched on the literature which habitat types each species could potentially use, to after constrained their distributions to habitat availability (see Table S1). After that, we overlaid each species distribution model with the map of land use, and constrained the distribution areas to places where the habitats for each species were available. We followed the same procedure for current and future land use maps. By doing this, we were able to assess the current and future distribution of the threatened Canivores, based on environmental suitability and habitat availability.

2.5.Dispersion Rate

In order to evaluate future distribution shifts due to climate and land use changes, while taking account each species dispersal capacity, we consider the dispersal rate for species according to the calculations made by Schloss *et al* (2012). They estimated the dispersion rate based on body mass, type of diet, and generation size. Also, these authors estimated the frequency of natal dispersal events from the successive period between generations, determined by the duration of pregnancy, age at sexual maturity, and the period until the next reproductive season. All threatened carnivore species in Brazil used in this work had their dispersion rates based on the rates calculated by Schloss *et al* (2012), except *Leopardus guttulus*. In 2013, Trigo *et al* (2013) found evidence of hybridization in *Leopardus tigrinus*, which was later identified as two distinct species: *Leopardus tigrinus* and *Leopardus guttulus*. Thus, to estimate the dispersion rate of *Leopardus guttulus*, we averaged the dispersion rates of the species of felids of the *Leopardus* genus included in this work.

The dispersion rate was estimated by Schloss *et al* (2012) in km/year, so to calculate the species dispersion rate for the year 2050 we calculated the species dispersion rate per year multiplied by 31, which is the number of years to go until 2050, considering 2019 as the baseline.

2.6.Protected areas (PA)

To verify the protection degree of the current PA network in the protecting carnivores threatened with extinction in Brazil, we made a spatial overlap of PA and the current and future distribution of species. Then, we computed the proportion of the current and future distributions of the species that are covered with the existing PAs in Brazil. Spatial data for PA in Brazil were obtained from the National Registry of Protected Areas (CNUC, 2020).

2.7.Spatial Prioritization

To select spatial priorities for threatened carnivore conservation in Brazil, we use the Zonation software (Moilanen *et al*., 2005). This software identifies locations that are important for maintaining high-quality, connected habitats for species to occur, providing a quantitative method for increasing long-term biodiversity persistence. Zonation works by establishing a hierarchical classification of conservation priorities, which is based on the complementarity of priority sites throughout the studied region (Moilanen *et al*., 2005). The zoning method works with the removal of cells with less conservation contribution to the total conservation value of the region. This removal of cells refers to the marginal loss value, which is calculated taking into account how much the removal of a cell negatively affects species representation. The cell with the least marginal loss is removed from the analysis (Moilanen, 2007). We use the basic core-area Zonation (CAZ) method, in which the removal of cells was done in a way that minimizes biological loss, choosing the cell that has the lowest occurrence for the most valuable characteristic.

To obtain the best result for prioritizing areas for the threatened carnivore species considered in this work and thinking about the main threats for these species, we used the following primary data as input for the spatial prioritization analysis: maps of species distributions (with suitability values)for the current and future (SSP245 and SSP585); vegetation cover map of current and future Brazil's natural habitats (forests, savanna, mangove, wetland and field); and a map of human population density of Brazil. We opted for the use of human population density with a negative weight in the analysis since the species tend to avoid areas with high population density. Thus, the software prioritized areas with high species representation, high native vegetation cover and the low human population. We also included in the analysis of spatial conservation the PAs already established. Then Zonation built conservation priorities to complement the composition of the current Brazilian PA network. Also, we used the zoning interactions component, aiming to connect the current and future distribution for each species, by identifying important areas to maintain connectivity between both distributions. Since we have the current distribution and two future scenarios of climate change, we performed the prioritization considering only current distribution, and for the SSP245 and SSP585 scenarios separately. Because conservation targets aim representation of different ecosystems, and the uneven protection degree of the Brazilian biomes (Vieira *et al.,* 2019), we performed the prioritization considering the different biomes as separate administrative units. By doing that, we ensure that we are keeping good levels of species representation for each biome individually.

At the time of presenting the results, we considered the percentage of 17% and 30% of the most priority areas. The percentage of 17% refers to one of the Aichi Targets, which foresaw the expansion of the coverage of the PAs to 17% of the terrestrial areas by the year 2020 (CBD, 2021). And the percentage of 30% refers to the current discussion that points to a new target of 30% by 2030 (Dinerstein *et al*., 2019). This new target will be discussed at the Conference of the Parties (COP15) of the Convention on Biological Diversity, later this year (CBD, 2021).

3. Results

The modeling procedure provided good results for all species, with AUC values ranging from 0.907 to 0.996 (the complete table can be viewed in the supplementary material in Table S2). The distribution data generated from the combination of ecological niche models with the availability of adequate habitat showed that the areas of distribution for all species will decrease by the year 2050 (Fig. 1).

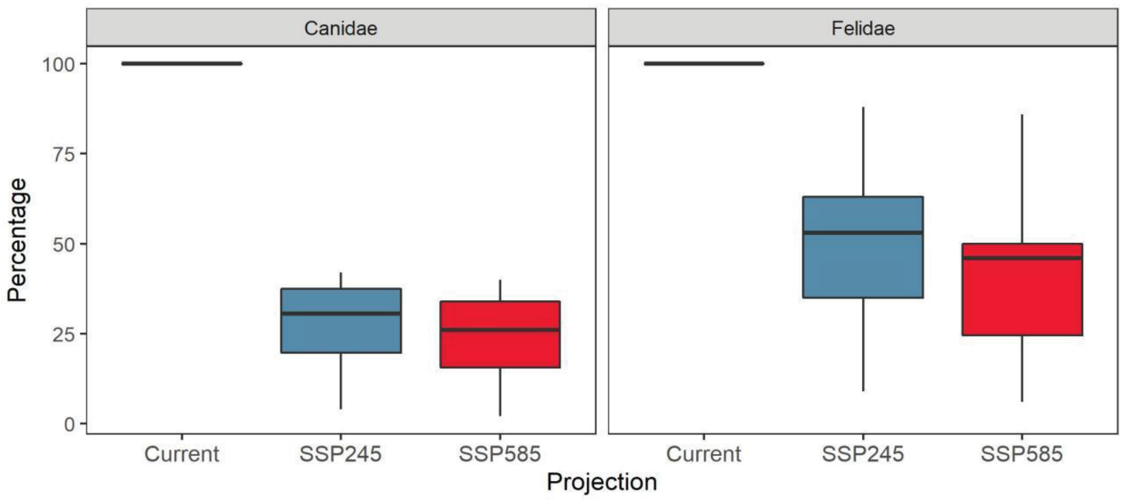

Figure 1. Proportional reduction in the distribution of the species of Canids and Felids due to climate change and land use for the two scenarios analyzed for the year 2050.

Regarding the analysis of the two future scenarios, most species exhibited a decreasing trend in their distributions even more in SSP585 when compared to SSP245, except *L. vetulus*. Our models predicted a more severe loss of area for *S. venaticus* (-96% in 2050 with SSP245 and -98% with SSP585, Table S3), while *P.*

onca was the species that had the least area reduced (-12.3% in 2050 with SSP245 and -13.8% with SSP585). The *L. vetulus* species was the only one that showed less loss of area in the SSP585 scenario than in the SSP245 scenario (from -75.1% in 2050 with SSP245 to -68.3% with SSP585, Table S3). In figure 2 we have a species richness map for the current and future scenarios, SSP245 and SSP585, and we can see the reduction in the number of species in the northern region of Brazil for both future scenarios.

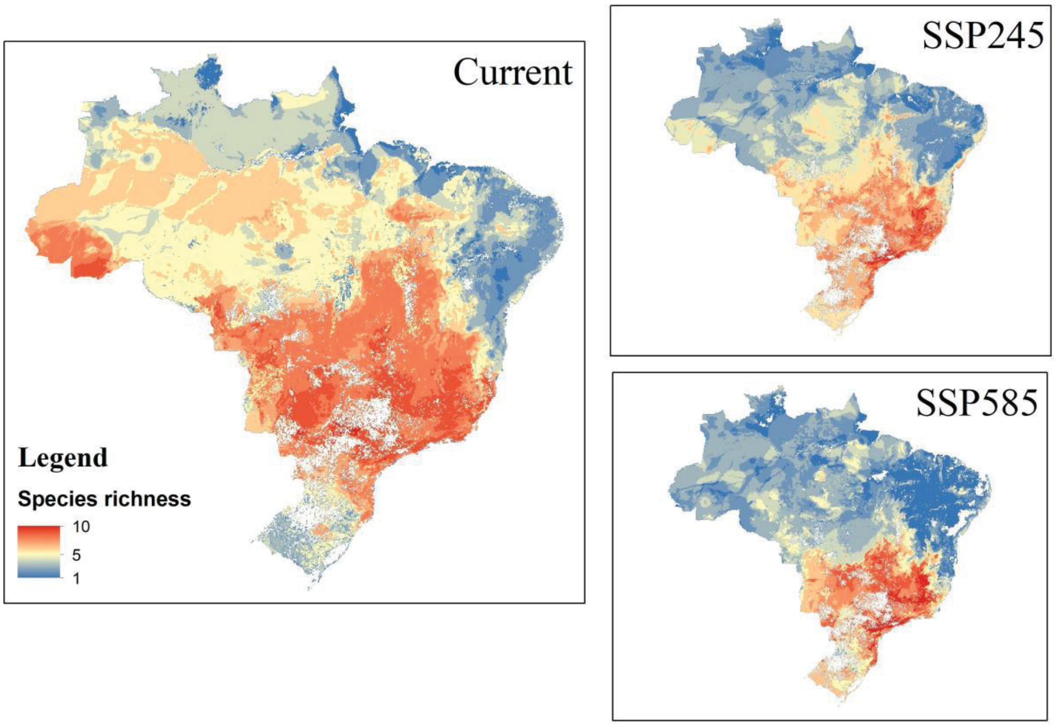

Figure 2. Richness map of threatened carnivore species in Brazil for the current and future scenarios, SSP245 and SSP585.

Our results also showed that the SSP585 scenario predicts a greater loss of area and less stability for the species (Fig. 3). The group of canids has a small increase in area gain in the SSP585 scenario compared to SSP245, probably due to the increase in area presented by the species *L. vetulus*. The map with the differences between the areas of gain, loss and stability for each species can be seen in the supplementary material (Fig. S2).

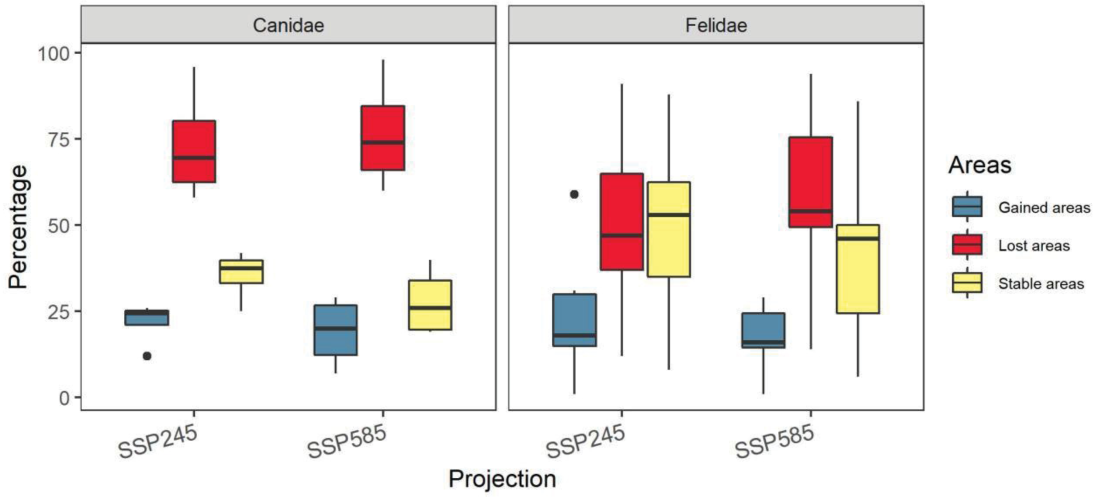

Figure 3. Difference between the areas gained, lost and stable in the two scenarios analyzed for the year 2050.

Current species distributions have been partially covered by the current network of PAs (Table 1), with the protection degree ranging from 5.1% for *L. geoffroyi* to 15.6% for *L. wiedii*. Future projections showed that the species that had the highest protection degree in PAs were *P. onca* and *A. microtis*, with 12% for SSP245 and 11.9% for SSP585 and 8.7% for SSP245 and 8% for SSP585, respectively. For the other species, the percentage of future areas under protection ranged from 0.5% to 5.3% for SSP245 and from 0.3% to 5.2% for SSP585. The degree of protection will be lower in the future for all species. When comparing the SSP245 and SSP585 scenarios, we also found a reduction in the PA coverage for all species in the SSP585 scenario, except for *L. wiedii*. This species showed an increase in its protection coverage from 3.2% in 2050 with SSP245 to 5.1% with SSP585.

Table 1. Area in km² and percentage referring to the predicted occurrence of species in PAs in Brazil today and for the year 2050 in the two scenarios analyzed, SSP245 and SSP585. Percentage based on the current area of PAs in Brazil.

Specie	Current (km^2)	SSP245 (km^2)	SSP585 (km²)
Atelocynus microtis	364.917 (14.5%)	217.623 (8.7%)	201.369 (8.0%)
Speothos venaticus	1.223.460 (12.1%)	52.458 (0.5%)	29.526 (0.3%)
Chrysocyon brachyurus	317.037 (7.5%)	117.957 (2.8%)	85.764 (2.1%)
Lycalopex vetulus	238.245 (6.1%)	109.074 (2.8%)	116.802 (3.0%)
Leopardus guttulus	114.702 (7.4%)	83.412 (5.3%)	80.913 (5.2%)

Leopardus tigrinus	1.056.300 (10.6%)	102.543 (1.1%)	82.194 (0.8%)
Leopardus colocolo	213.234 (5.2%)	150.906 (3.7%)	123.270 (3.0%)
Leopardus geoffroyi	21.609 (5.1%)	13.503 (3.2%)	4.053 (1.0%)
Leopardus wiedii	1.290.618 (15.6%)	263.088 (3.2%)	422.982 (5.1%)
Puma yagouaroundi	1.222.872 (14.5%)	202.083 (2.4%)	170.688 (2.0%)
Panthera onca	1.161.909 (12.2%)	1.143.177 (12.0%)	1.135.155 (11.9%)

The spatial prioritization analysis indicated that the areas of highest priority for conservation are mainly in the central and southern regions of Brazil (Fig. 4). The maps show 17% and 30% of the highest priority areas in Brazil. The performance curves of spatial prioritization showed that by protecting 17% of the landscape in each biome, an average of 14.5% of threatened carnivore species will be being protected in the current scenario, 14.1% in the SSP245 scenario and 13.8% in the SSP585 scenario. By protecting 30% of the landscape, the species representation more than doubles up, presenting an average protection for the analyzed species of 41.6%, 35.4% and 34.8% for the current scenarios, SSP245 and SSP585, respectively. The table with the average percentage of protection per family can be seen in the supplementary material, as well as the map with all the values of the current and future conservation prioritization analysis in Brazil (Table S4 and Fig. S5).

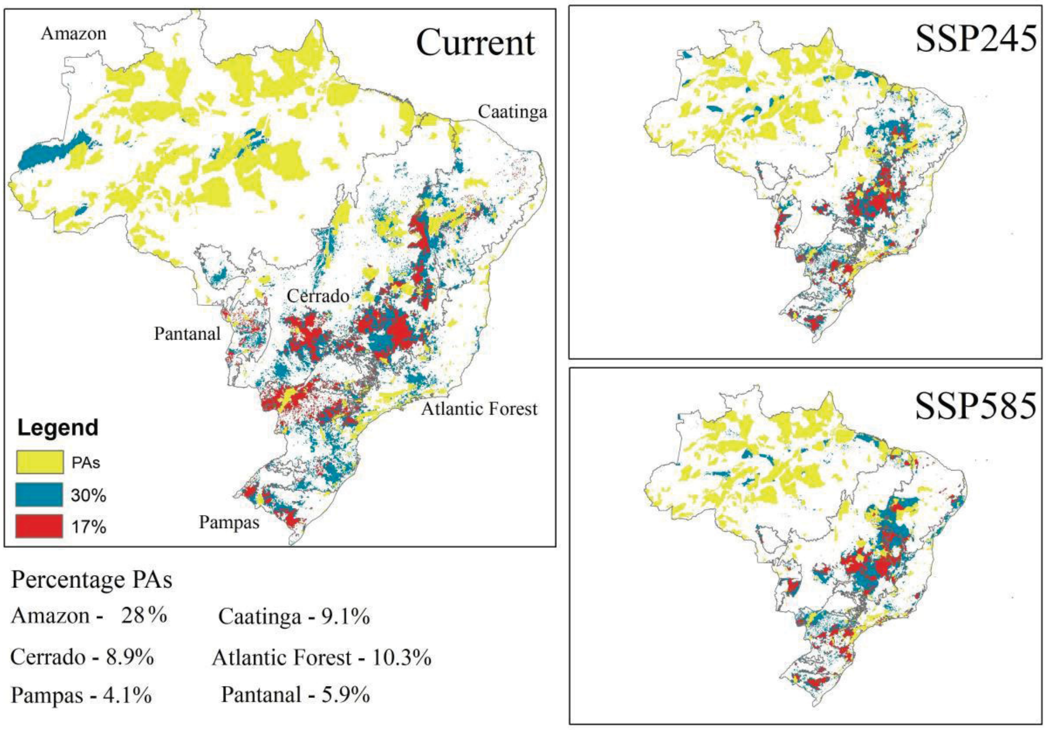

Figure 4. Priority areas for the conservation of threatened carnivore species in Brazil that best complement existing PAs in each biome. In red 17% of highest priority for conservation, in blue 30% of highest priority and yellow the PAs in Brazil.

4. Discussion

Understanding the distributions of carnivore species and what can lead to a possible change in this distribution has received greater attention in recent years (Carroll, 2007; Ripple *et al*., 2014; Caruso *et al*., 2016; Zanin *et al*., 2021). Our results showed that all species analyzed showed a reduction in their distributions due to climate change and land use. Understanding how threatened carnivore species in Brazil respond to climate change and land use provide important information for the biodiversity conservation. Also, we showed that, by only relying on the current PA network, the protection level of threatened carnivores distribution would mostly decrease. Fortunately, by selecting priority areas based on current and future species distribution for these species, we show how conservation for this group can be highly improved. It is known that species considered as the top of the chain are strongly affected by fragmentation, loss of habitat, and degradation of the environment, as well as by climate change (Brook, Sodhi & Bradshaw, 2008; Ripple *et al*, 2014; Salek, Drahníková & Tkadlec, 2015). However, smaller species are also impacted by these changes (Zanin *et al*, 2021). Our results support these previous findings, indicating that both larger and top of the chain species, such as *P. onca*, and smaller species, such as *P. yagouaroundi*, are expected to have their distribution reduced by climate and land use changes (Fig. S2). A very worrying result is related to the reduction in the distribution of *L. tigrinus*. This is the only species in our study with endangered status and is the second species that loses the most area in both scenarios (91.5% in SSP245 and 94.1% in SSP585), behind only *S. venaticus* (Table S3). The main threat to *L. tigrinus* is habitat loss and fragmentation (Oliveira *et al*., 2013; Trigo *et al*., 2018a). Also, its occurrence is strongly associated with the Cerrado and Caatinga regions (Trigo *et al*., 2013, 2018a; Payan & Oliveira, 2016), biomes that are quite degraded and poorly protected (Overbeck *et al*., 2015, Vieira *et al*., 2019). The loss of remnants in the species' occurring biomes is estimated at around 10% over the next 15 years, and *L. tigrinus* populations are presumed to decrease at an equivalent rate (Trigo *et al*., 2018a). For these reasons, it may be that the species will suffer a greater loss of its distribution until 2050.

The species that showed the greatest reduction in its distribution in our study was *Speothos venaticus* (96% in SSP245 and 98% in SSP585), also known as bush-dog. This species, despite currently having a good distribution in the country, has a low population density (Jorge *et al*., 2013, 2018). According to Oliveira (2009) the PAs in the Amazon region are more extensive than the PAs in the other regions of Brazil and, even so, they are not sufficient to guarantee the survival of subpopulations of the species in the region. This study corroborates our results, which indicate a drastic reduction in the distribution of the species in the Amazon biome. Historically, *S. venaticus* is considered to be a predominantly forest species and restricted to little disturbed environments (DeMatteo & Loiselle, 2008; Jorge *et al*., 2013). This fact may explain the reduction in its distribution, considering the changes in land use and, consequently, the loss of its habitat, which is one of the main threat to the species (Jorge *et al*., 2018).

Comparing the two future scenarios analyzed, SSP245 and SSP585, our results showed that one species had an expansion in its distribution for the scenario SSP585, *L. vetulus*. This canid is the only one that presents greater distribution in the future scenario SSP585 compared to SSP245. This can happen due to the species using more open environments (Dalponte, 2009; Lemos *et al*., 2018). Climate change and land use are making the climate warmer and drier, conditions that favor habitats like savanna (Franchito, Rao & Fernandez, 2012; Nobre *et al*., 2016; Sales, Galetti & Pires, 2020) and, consequently the persistence and expansion of this species. The other species, on the other hand, as they frequent more forest habitats, will suffer even greater reductions in the SSP585 scenario. Besides, this species is associated with pasture environments (Dalponte, 2009; Lemos, Facure & Azevedo, 2011), a fact that also favors the expansion and persistence of the species in the scenario foreseen for the SSP585 projection. Despite the expansion of the distribution of the species from the SSP245 scenario to the SSP585, it is important to remember that the species tends to suffer a reduction in its distribution for the year 2050 (Table S3) and that one of the main threats to the species is also the destruction of its habitat (Lemos *et al*., 2011, 2018). The fact that the species occurs predominantly in the Cerrado region, which is poorly protected and presents a great degradation due to the advance of commercial and industrial borders (Overbeck *et al*., 2015, Lemos *et al*., 2018; Vieira *et al*., 2019), makes it susceptible to reducing its distribution.

The impact of the reduction of the species' distribution areas can be exacerbated by the low percentage of coverage of PAs. Currently, the ranges of distribution of the analyzed species overlap to a very small extent with the current network of PAs. This fact emphasizes the importance of protecting larger portions of the species' distribution areas under current and future conditions. These findings also confirm the relevance of assessing whether climate change and land use can drive threatened species out of current PAs (Araújo *et al*., 2011), compromising its role in maintaining species persistence.

Previous studies already indicate the existing deficit in the efficiency of PAs in Brazil in the protection of threatened carnivore species in the country (DeMatteo & Loiselle, 2008; Sollmann, Torres & Silveira, 2008). This is because even with the increasing number of PAs, most of them do not fulfill the conservation function because they do not support viable populations of carnivore species in the long term (Sollmann *et al*., 2008). Also, Brazil's non-Amazonian biomes suffer from under-protection. According to Vieira *et al* (2019), the Amazon biome has almost 30% of its territory as PAs, while the percentage of PAs in the Atlantic Forest, Cerrado, Caatinga, Pantanal and Pampas is 10.1%, 8.6%, 7.7%, 4.6% and 2.7%, respectively (Vieira, Pressey & Loyola, 2019). We know that the Amazon is extremely important for species. Sollmann *et al* (2008) showed that only in the Amazon biome *P. onca* species is truly protected and have their viable permanence.

Consequently, the PA system in the Amazon plays a fundamental role in the conservation of this species and others with fewer environmental requirements. In contrast, the other regions of the country have great difficulties in guaranteeing the permanence of this species (Sollmann *et al*., 2008), as a result of the under-protection of these regions.

The creation of new PAs must consider spatial and species-specific priorities to ensure their representativeness over space and time (Jones *et al*., 2016). Studies show that when PAs are allocated appropriately and consciously there is a high chance of interrupting threatening processes that cause the decline of mammal species (Watson *et al*., 2014; Coad *et al*., 2019; Pacifici, Di Marco & Watson, 2020). It is important to remember that some PAs may play a more critical role in the conservation of species than others, so it is essential to be clear about conservation objectives when developing and implementing a new PA (Visconti *et al*., 2019; Coad *et al*., 2019; Pacifici *et al*., 2020). PAs can maintain the representativeness of species and are a valid answer for conservation in the face of climate change and changes in land use (Hannah *et al*., 2007; Araújo *et al*., 2011). Furthermore, the implementation of dispersion corridors to connect PAs is the main strategy recommended by researchers and conservation managers to reinforce populations of threatened species (Rabinowitz & Zeller, 2010; Rodríguez-Soto, Monroy-Vilchis & Zarco-González, 2013; Jorge *et al*., 2018; Morato *et al*., 2018). Thus, actions are also needed to maximize the size of the PAs, as well as the connectivity between them, in addition to efforts to mitigate the persecution and confrontations of humans with the large carnivores (Jorge *et al*., 2018; Queirolo *et al*., 2018; Almeida *et al*., 2018a; Trigo *et al*., 2018a).

Our study highlights important regions in which the conservation of threatened carnivores in Brazil should be focused. We indicate priority areas for the conservation of these species, which represent regions with high climatic and habitat suitability for these species. The spatial prioritization analysis indicated that the areas of highest priority for conservation are mainly in the central and southern regions of Brazil, regions that cover the Pantanal and Pampa biomes, which have the smaller UCs in Brazil (Vieira *et al*., 2019). As it is an analysis that complements existing PAs in the country, this result again emphasizes the protection deficiency in non-Amazonian regions.

Our prioritization results are important because they show the top 17% and 30% of the most priority areas for the conservation of threatened carnivores in Brazil.

Looking at figure 4 it is possible to see that the highest concentration of these priority areas is at the central region of the country. To achieve the Aichi target, many PAs were established in Brazil, but not equally between the different biomes (Vieira *et al*., 2019). By considering the areas indicated here as priorities for the establishment of new PAs, the viability of existing PAs can be increased. The inclusion of these complementary areas creates a network of PAs that is much more effective in conserving the species of carnivores that are threatened. Venter *et al* (2018) showed that if the PAs created in recent years had been strategically planned for the real conservation of species, the protection would be 30 times greater than it is today. Besides, incorporating future distribution projections for species protection is important to improve conservation actions. The success of these actions depends on the ability to anticipate possible impacts generated by climate change and land use to try to reduce them.

Establish effective protection in the areas of greatest suitability for carnivore species is a logical way to protect a significant number of species that, in the absence of protection, would likely be lost. It is important to emphasize that modeling the occurrence of carnivore species is extremely complex since they are affected not only by the changes analyzed here but also by species-specific biological characteristics, resources availability, habitat quality, in addition to a variety of anthropic activities (Cardillo *et al*., 2004; DiBitetti, Paviolo & De Angelo, 2006; Long *et al*., 2011; Sarmento *et al*., 2011; Gálvez *et al*., 2013; Pia *et al*., 2013; Jorge *et al*., 2018; Queirolo *et al*., 2018; Almeida *et al*., 2018a; Trigo *et al*., 2018a).

5. Conclusion

Future climate and land-use changes may negatively affect the potential geographic distribution of threatened carnivore species in Brazil. The effects of climate and land use on the distribution of species are fundamental when developing strategies in conservation planning. The consideration of some priority areas mentioned here is a viable alternative to decrease climate change and land use change effects on species distributions and conservation. Considering the areas pointed by our results as of high priority would allow a large number of species, not only threatened carnivores, to persist in suitable areas over time given the changes planned for the next 30 years. Besides, understanding habitat requirements and anthropogenic effects on species occurrence are essential steps for effective conservation practice. We hope our study to provide a solid and initial basis for implementing these conservation strategies to ensure species protection in such a large and biodiverse country.

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7. Supporting information

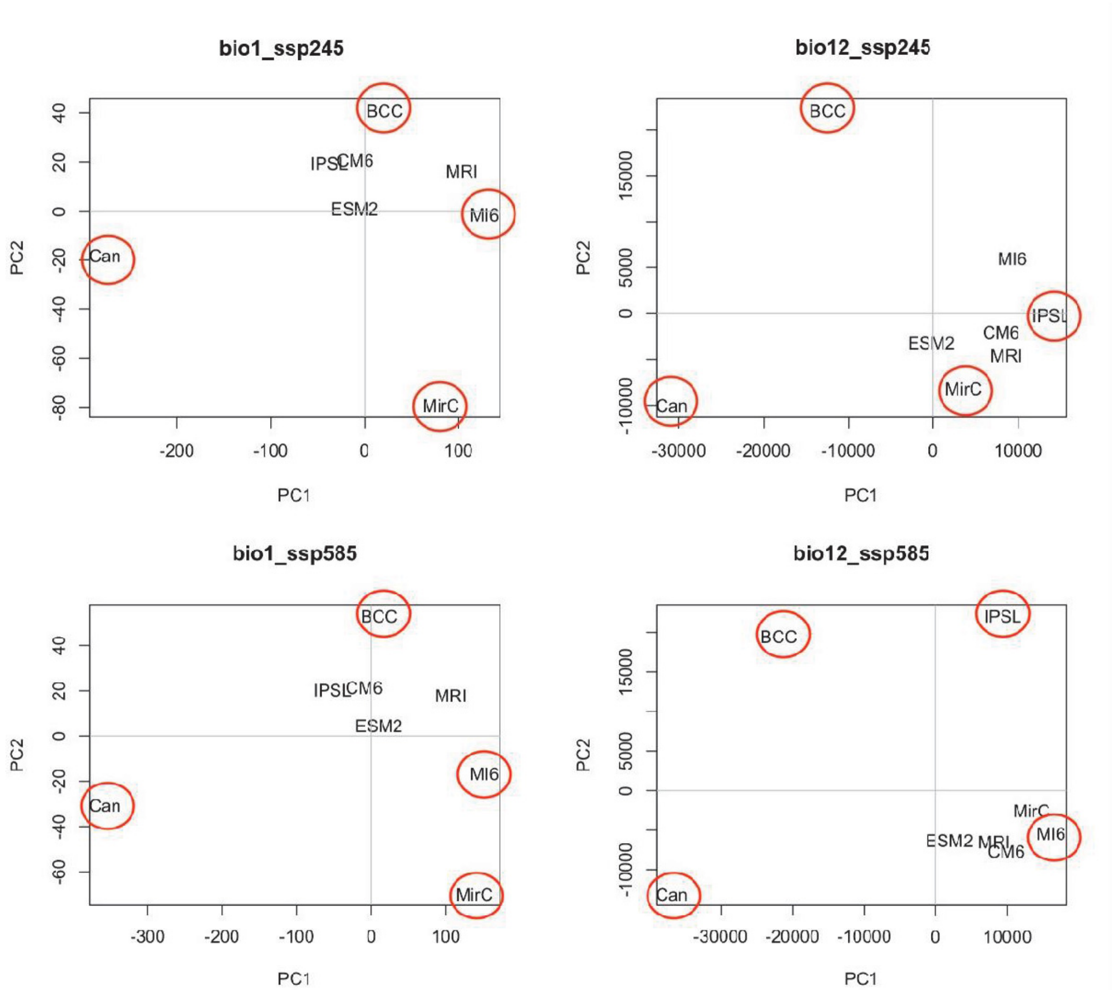

Figure S1. PCoA analysis for the selection of GCMs used in ENM. Bio1 is the bioclimatic variable referring to the average annual temperature and Bio12 is the bioclimatic variable referring to the average annual rainfall.

Table S1. Habitat used by each species.

Specie	Habitat	Reference
Atelocynus microtis	Forest, Savanna, Wetland, Field	Pitman & Beisiegel, 2013; Pitman & Beisiegel, 2018.
Speothos venaticus	Forest, Savanna, Wetland,	Jorge *et al*., 2013; Jorge *et al*.,

	Field	2018.
Chrysocyon brachyurus	Forest, Savanna, Wetland, Field	Paula *et al*., 2013; Paula *et al*., 2013
Lycalopex vetulus	Forest, Savanna, Field	Lemos *et al*., 2013; Lemos *et al*., 2018.
Leopardus guttulus	Forest, Savanna, Wetland, Field	Oliveira *et al*., 2016; Trigo *et al*., 2018b.
Leopardus tigrinus	Forest, Savanna, Wetland, Field	Oliveira *et al*., 2013a; Trigo *et al*., 2018a.
Leopardus colocolo	Forest, Savanna, Wetland, Field	Queirolo *et al*., 2013., Queirolo *et al*., 2018.
Leopardus geoffroyi	Forest, Wetland, Field	Almeida *et al*., 2013a; Almeida *et al*., 2018a.
Leopardus wiedii	Forest, Wetland	Oliveira *et al*., 2013b; Tortato *et al*., 2018.
Puma yagouaroundi	Forest, Savanna, Mangrove, Wetland	Almeida et al., 2013b; Almeida et al., 2018b.
Panthera onca	Forest, Savanna, Wetland	Morato *et al*., 2013; Morato *et al*., 2018.

Table S2. AUC values of the models of each species.

Specie	AUC
Atelocynus microtis	0.907
Speothos venaticus	0.993
Chrysocyon brachyurus	0.989
Lycalopex vetulus	0.965
Leopardus guttulus	0.971
Leopardus tigrinus	0.971
Leopardus colocolo	0.994
Leopardus geoffroyi	0.986
Leopardus wiedii	0.996
Puma yagouaroundi	0.983
Panthera onca	0.988

Table S3. Percentage referring to the loss of suitable habitat for species for the year 2050 in scenarios SSP245 and SSP585.

Specie	SSP245	SSP585
Atelocynus microtis	58.3%	60%
Speothos venaticus	96%	98%

Chrysocyon brachyurus	64%	79.7%
Lycalopex vetulus	75.1%	68.3%
Leopardus guttulus	47.8%	50.6%
Leopardus tigrinus	91.5%	94.1 %
Leopardus colocolo	36%	48.7%
Leopardus geoffroyi	38.5%	64.7%
Leopardus wiedii	47%	54.3%
Puma yagouaroundi	81.6%	86%
Panthera onca	12.3%	13.8%

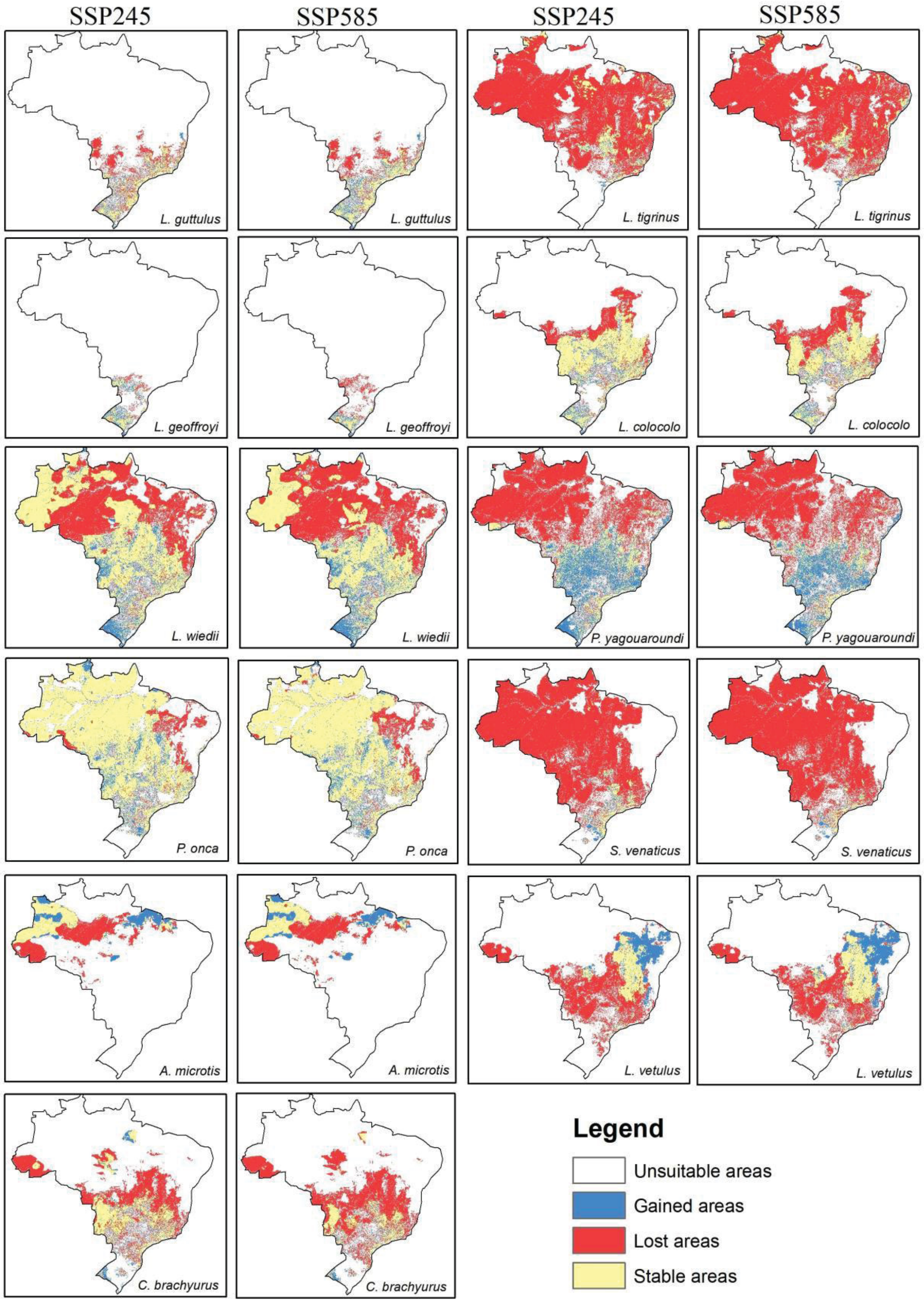

Figure S2. Spatial range change predictions based on combining climate area modeling with land use for the year 2050 in the SSP245 and SSP585 scenarios for each species.

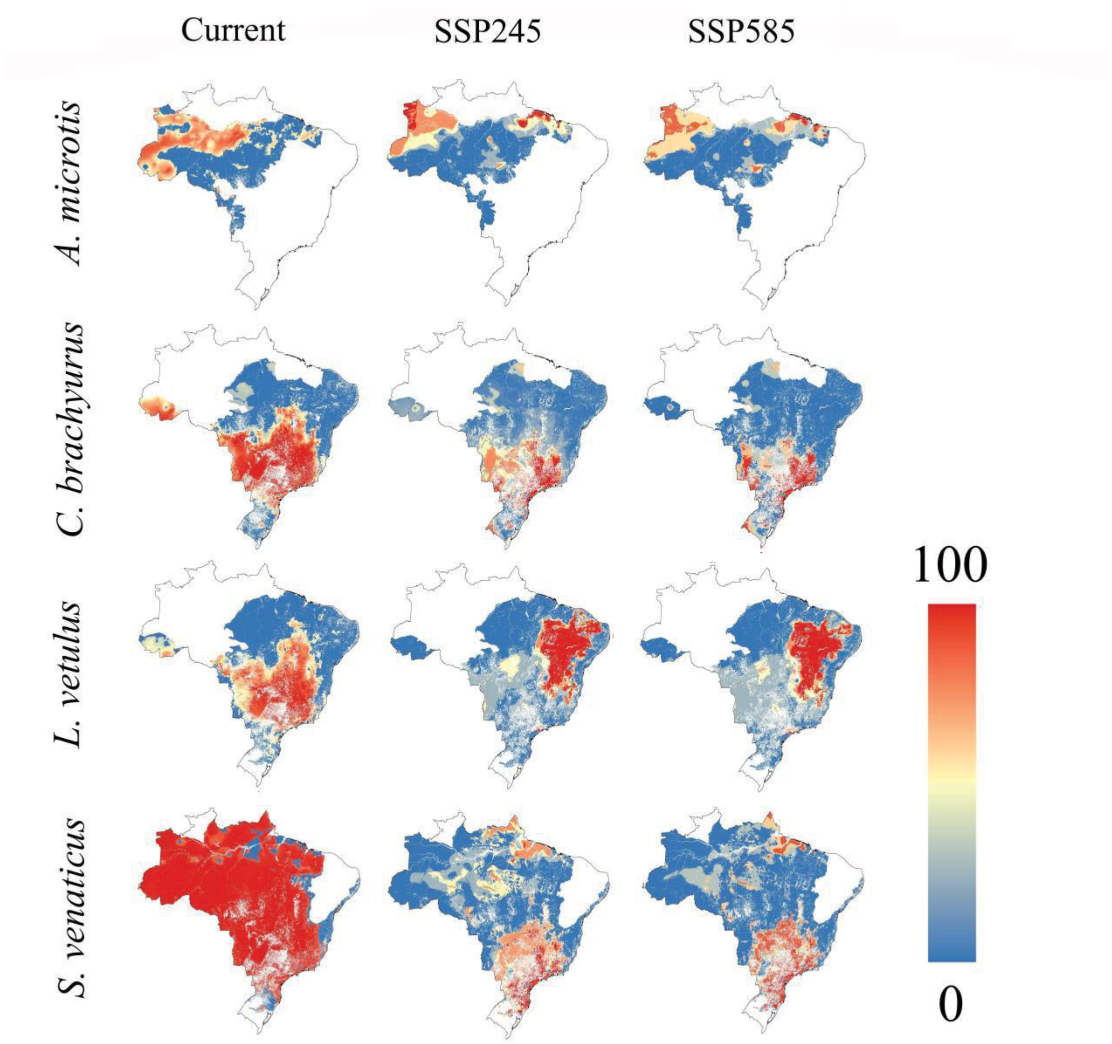

Figure S3. Suitability for the occurrence of species of the Canidae family. Suitability ranges from 0 to 1 and is greater in regions of values close to 1 and decreases to regions of values close to 0.

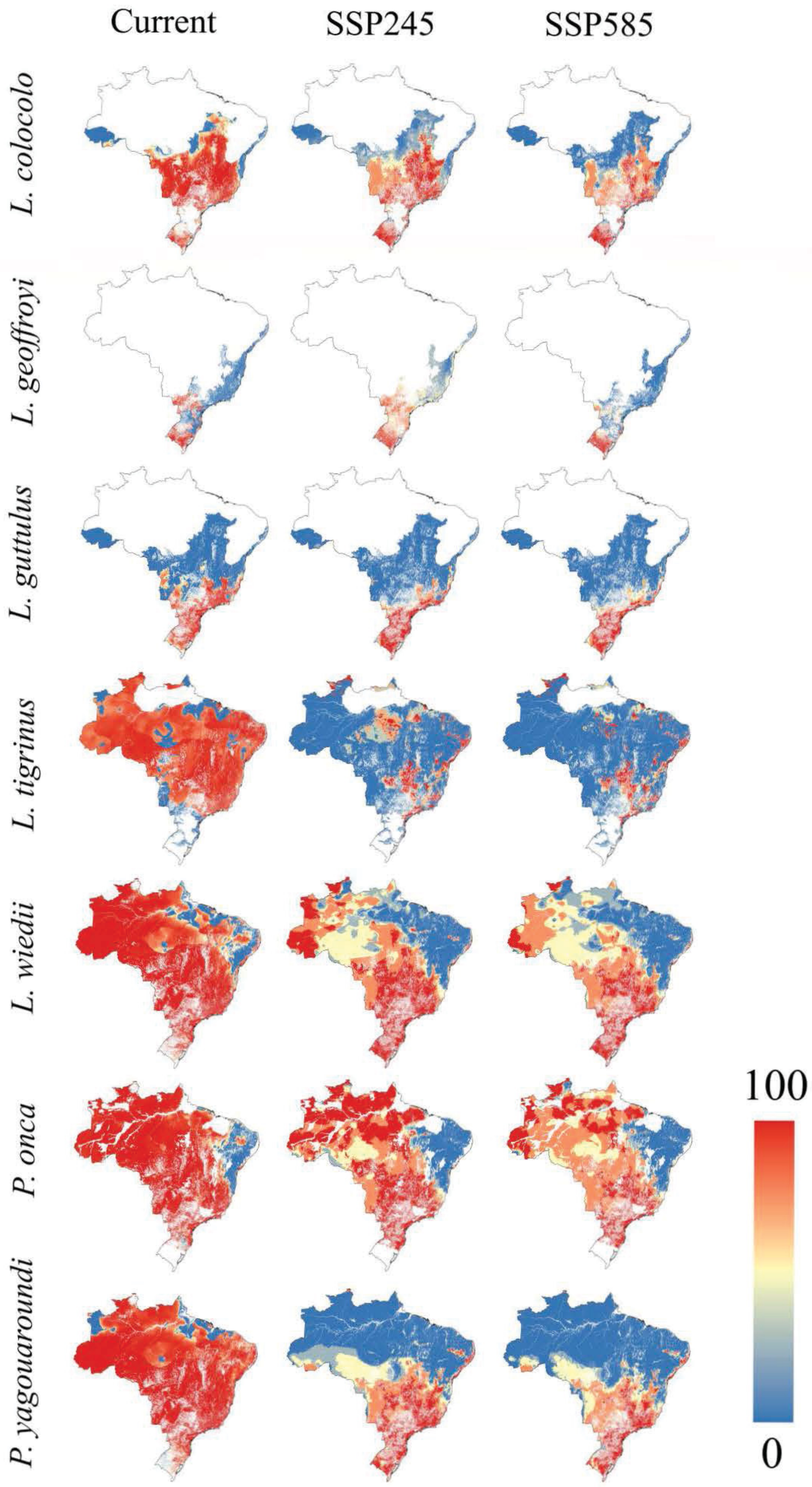
Current
SSP245
SSP585
L. colocolo
L. geoffroyi
L. guttulus
L. tigrinus
L. wiedii
P. onca
P. yagouaroundi
100
0

Figure S4. Suitability for the occurrence of species of the Felidae family. Suitability ranges from 0 to 1 and is greater in regions of values close to 1 and decreases to regions of values close to 0.

Table S4. Average percentage of protection of canine and felid species with protection of 17% and 30% of priority areas and within PAs in the current and future scenarios SSP245 and SSP585.

Family	Projection	17% Protection	30% Protection	PAs
Canidae	Current	16.3%	37.6%	10.0%
Felidae	Current	13.5%	43.8%	10.1%
Canidae	SSP245	12.1%	43.3%	3.7%
Felidae	SSP245	13.4%	30.9%	4.4%
Canidae	SSP585	15.2%	27.7%	3.3%
Felidae	SSP585	12.9%	38.8%	4.1%

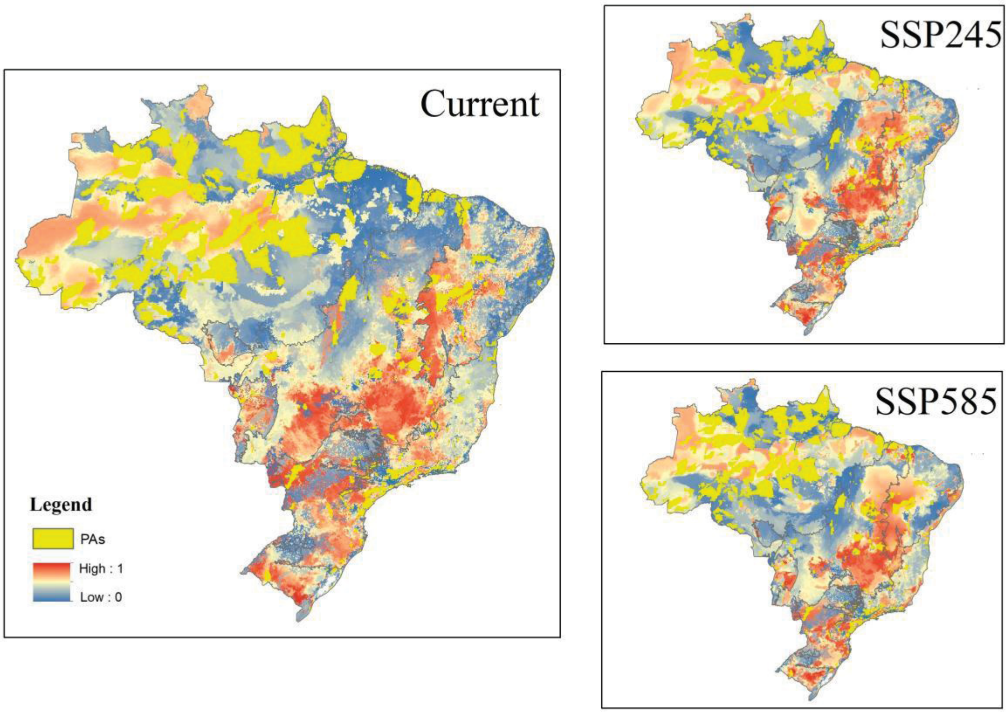

Figure S5. Priority areas for the conservation of threatened carnivore species in Brazil that best complement existing PAs. In red the areas with the highest priority for conservation, in blue the areas with the lowest priority, and in yellow the PAs Brazil.