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VULNERABILIDADE DE ESPÉCIES ÀS MUDANÇAS CLIMÁTICAS E PRIORIDADES PARA CONSERVAÇÃO NA AMAZÔNIA

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VULNERABILIDADE DE ESPÉCIES ÀS MUDANÇAS CLIMÁTICAS E PRIORIDADES PARA CONSERVAÇÃO NA AMAZÔNIA

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pelo apoio e dedicação.

Ao meu Tio Camilo,

que fez da vida uma verdadeira cantoria.

"O mundo não será destruído por aqueles que fazem o mal,

mas por aqueles que os olham e não fazem nada."

(Albert Einstein)

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Resumo

As mudanças climáticas de causa antrópica são consideradas uma das principais ameaças a biodiversidade no século XXI. Contudo, nem todas espécies/populações serão igualmente afeadas pelas mudanças no clima. Portanto, identificar onde e quais espécies são mais vulneráveis às mudanças climáticas é fundamental para guiar ações de conservação. Assim, procurei i) avaliar a exposição de mamíferos da Amazônia às mudanças climáticas e se as Unidades de Conservação desse bioma são eficientes em mitigar os efeitos das mudanças climáticas sobre as espécies "criticamente expostas"; ii) desenvolver um esquema de priorização para conservação de mamíferos que eficientemente identifica áreas prioritárias dentro das áreas de distribuição atual e futura das espécies nas quais esforços de conservação devem ser direcionados de modo a mitigar os efeitos da mudanças climáticas sobre a biodiversidade. De modo geral, os resultados indicam que grande parte dos mamíferos poderão ser altamente expostos às mudanças climáticas e que as atuais Unidades de Conservação provavelmente não serão eficientes para evitar os impactos das mudanças climáticas nas espécies "criticamente expostas". Sendo assim, esperamos que nosso plano espacial para conservação possa ajudar planejadores e tomadores de decisão a guiar esforços de conservação de modo a mitigar impactos e evitar a perda da biodiversidade na Amazônia.

Palavras-chave: mudanças climáticas, vunerabilidade, exposição, priorização espacial para conservação, Amazônia.

Abstract

Human-induced climate change are acknowledged as one of the major treats to biodiversity over the 21 st century. However, species/populations are not equally affected by climate change. Therefore, identify where and which species are more vulnerable to climate change is paramount for guide conservation efforts. Hence, I sought to i) evaluate mamall exposure to climate change and assess the effectiveness of Amazon network of Protected Areas (PAs) in buffer the impacts of climate change on “critically-exposed” species; ii) develop a spatial conservation scheme for mammals in the Brazilian Amazon that efficiently identifies highly-exposed areas within species current and future distributions in which conservation efforts should be targeted in order to mitigate the impacts of climate change on the biodiversity found in the Brazilian Amazon. In general, the results indicated that mammals might face high exposure to climate change and Protected Areas will probably not be efficient enough to avert impacts of climate change on “critically-exposed” species. In this vein, we hope that our spatial conservation plan may help planners and stakeholders to guide conservation efforts aiming at mitigate impacts and avert biodiversity loss due to climate change.

Key Words: Climate change, vulnerability, exposure, spatial conservation planning, Amazon

Introdução Geral

Mudanças no clima sempre ocorreram durante toda história do planeta. Contudo, grandes alterações no clima em um período temporal tão pequeno não possuem precedentes históricos. Durante o máximo termal dos períodos Paleoceno-Eoceno (a cerca de 55,8 milhões de anos) a temperatura da Terra aumentou cerca de 5 a 6 ºC em um período de aproximadamente 10.000 anos, uma taxa de aquecimento cem vezes mais lenta do que a prevista para as próximas décadas [1]. Segundo o Painel Intergovernamental sobre Mudanças Climáticas (IPCC), até o final deste século a temperatura média do planeta deverá aumentar cerca de 2,6 a 4,8 ºC a mais do que a temperatura média atual, caso as emissões de gases do efeito estufa não sejam consideravelmente reduzidas [2].

As mudanças climáticas são uma das maiores ameaças a biodiversidade no século XXI [3,4]. A exposição a novas condições climáticas é um complicador a mais para a sobrevivência das espécies e pode levar a possíveis alterações na área de distribuição geográfica das espécies [5], em seus eventos fenológicos [6], nas interações por elas realizadas (por ex., encontro com novos competidores ou perda de um polinizador; [7]), na composição de comunidades [8]; podendo haver inclusive extinções [9]

Entretanto, extinções de espécies raramente ocorreram de forma aleatória ao longo da história [10]. Os Charles (Lyell e Darwin), por exemplo, já haviam notado que o tamanho da área de distribuição geográfica é uma característica que confere às espécies maior risco de extinção [10]. Segundo IPCC (2014) [11], o termo vulnerabilidade pode ser definido como “propensão ou predisposição a ser negativamente afetado”. A vulnerabilidade de um sistema (espécies, populações, habitat ou ecossistemas) pode ser avaliada em função de fatores intrínsecos - sensibilidade e a capacidade adaptativa; e extrínsecos - exposição a um fator de risco [12–14].

A sensibilidade é determinada por um conjunto de características que confere a um organismo maior resistência e resiliência a ser negativamente afetado por um fator de risco, tal como as mudanças no clima. Limites de tolerância fisiológica e plasticidade fenotípica são exemplos de características relacionadas a sensibilidade que possibilitam a permanência de um organismo no seu hábitat local, mesmo quando exposto a alterações climáticas [12,15]. A capacidade adaptativa, por sua vez, está relacionada a capacidade de um organismo se adaptar a novas condições climáticas – por meio de alterações evolutivas ou plásticas – e/ou seu potencial de dispersar em direção a outros locais climaticamente favoráveis [6,13]. Espécies com por exemplo, grande tamanho corporal, longo tempo de geração, populações pequenas e/ou com baixa diversidade genética são mais susceptíveis a serem afetadas pelas mudanças climáticas [14].

O terceiro componente da vulnerabilidade, exposição, diz respeito à mudança no clima de determinado local ou região na qual um organismo se encontra [13]. Uma vez que o clima é um sistema complexo, a exposição pode ser quantificada em função de diferentes aspectos da mudança do clima, os quais podem ser agrupados em duas categorias. Mudanças climáticas "locais", relacionadas a magnitude de mudança na média ou nos extremos de uma variável climática (por exemplo, temperatura) e que ocorrem em um determinado local; e mudanças climáticas "regionais", relacionadas à taxa (ou velocidade) na qual o clima se desloca ao longo de uma região [16].

A Amazônia, a maior floresta tropical do planeta, é também um dos ecossistemas mais vulneráveis às mudanças climáticas. Ela cobre cerca de 61% do território brasileiro e é um dos biomas mais biodiversos do mundo abrigando, por exemplo, 399 espécies de mamíferos - a maior riqueza de mamíferos entre todos biomas do Brasil [17]. Espécies presentes nesse bioma são altamente sensíveis às mudanças no clima, pois mesmo um pequeno aumento na temperatura pode exceder o limite termal máximo tolerável por essas espécies [18,19]. Além disso, estudos indicam que um grande número de espécies não será capaz de se dispersar a uma velocidade suficiente para acompanhar a taxa de mudança no clima [20]. Esta combinação de alta sensibilidade e a baixa capacidade de dispersão faz com que espécies dependam, principalmente, de adaptações genéticas e/ou plásticas para sobreviver às mudanças climáticas [6].

Além dos fatores intrínsecos, uma série de fatores extrínsecos (ou fatores de risco) ameaçam a sobrevivência de espécies na Amazônia. Os principais fatores "locais" de risco envolvem o aumento na intensidade e na frequência de climas extremos (como grandes eventos de secas; [21]), o surgimento de novas condições climáticas e o desaparecimento das condições climáticas atuais [22]. Por outro lado, o principal fator "regional" de risco é a velocidade na qual o clima se desloca ao longo de uma região [16,23]. Cada dos fatores contém diferentes desafios e oportunidades a biodiversidade [16]. Mudanças climáticas locais podem causar alterações na morfologia, fisiologia e/ou no comportamento de organismos que, por sua vez, podem causar reduções no tamanho de uma população [16]. Em contrapartida, alterações regionais no clima estão relacionadas com a redução (ou expansão em alguns casos) da área de distribuição geográfica de uma espécie [24].

Contudo, apesar das fortes evidências que a Amazônia será exposta a grandes alterações climáticas, uma espécie não será igualmente exposta em todos locais da sua área de distribuição geográfica. Ao longo da área de distribuição de uma espécie certas populações serão mais expostas às mudanças no clima do que outras. Além disso, diferentes populações poderão ser expostas a diferentes fatores de risco. Por exemplo, enquanto algumas populações poderão experimentar temperaturas extremas, outras poderão enfrentar reduções no regime de chuva. Portanto, a exposição às mudanças climáticas é geograficamente estruturada dentro da área de distribuição geográfica de uma espécie. Sendo assim, identificar onde e a qual fator de risco uma espécie será exposta é o primeiro e fundamental passo no processo de avaliação e mitigação da vulnerabilidade de espécies às mudanças climáticas. A razão pela qual esforços de conservação devem ser direcionados à locais mais expostos dentro da área de distribuição geográfica de uma espécie tem um pressuposto simples: os impactos biológicos serão maiores onde a taxa e a magnitude de mudança climática forem maiores [25].

As Unidades de Conservação (UCs) exercem um papel crucial na adaptação e mitigação dos efeitos das mudanças sobre as espécies. Unidades de Conservação oferecem uma maior gama de oportunidades ecológicas como, por exemplo, microclimas e habitats heterogêneos que favorecem e facilitam à adaptação de espécie às mudanças climáticas através de alterações plásticas (morfológicas, fisiológicas e comportamentais) ou genéticas [13], e diminuem a exposição a outras ameaças (por ex., desmatamento). Em todo o globo, um dos maiores sistemas de UCs existentes encontra-se na Amazônia, cobrindo cerca de 22% da extensão do bioma. O número de UCs no bioma aumentou de forma considerável a partir dos anos 2002 com a criação do programa do governo Federal “Áreas Protegidas da Amazônia” (ARPA). Contudo, apesar de ter sido um grande avanço na rede de reservas da região, nenhuma das UC criada teve como intuito proteger e/ou favorecer espécies mais vulneráveis às mudanças climáticas. Sendo assim, surge a seguinte questão: as UCs da Amazônia serão eficientes para proteger a biodiversidade e mitigar os efeitos das mudanças climáticas sobre as espécies mais vulneráveis no futuro?

Além de ser uma grande ameaça à sobrevivência das espécies, às mudanças climáticas representam grande desafio para conservação da biodiversidade por basicamente três motivos. Primeiro, conforme o clima local se torna inadequado a sobrevivência de uma espécie ela deverá se dispersar para áreas que passarão a ser climaticamente adequadas causando, assim, alterações na área de distribuição geográfica de uma espécie. Segundo, as principais estratégias sugeridas (contudo escassamente implementadas) de conservação da biodiversidade frente às mudanças climáticas são baseadas principalmente na proteção de espécies em áreas climaticamente estáveis (conhecidas como "refúgios" climáticos; [25]). Terceiro, como uma consequência do segundo motivo espécies/populações mais expostas e, por isso, com maior risco de serem afetadas pelas mudanças no clima não são protegidas e, consequentemente, comprometidas a serem localmente extintas.

Portanto, dada a complexidade e urgência do assunto, precisamos de ferramentas que guiem a tomada de decisão. Nesse contexto, o planejamento sistemático para conservação surge como uma ferramenta quantitativa de otimização para seleção de áreas prioritárias nas quais esforços de conservação devem ser direcionados [26]. Tal ferramenta, combinada com outras que buscam prever a alterações na distribuição geográfica das espécies em resposta às mudanças no clima (Modelos de Nicho Ecológico) são essenciais para guiar esforços de conservação para áreas mais expostas e, portanto, onde espécies provavelmente serão mais afetadas pelas mudanças no clima.

Objetivos

O objetivo geral dessa dissertação, composta por dois capítulos, foi avaliar a vulnerabilidade de espécies de espécies às mudanças climáticas e definir prioridades para conservação na Amazônia brasileira. No primeiro capítulo, identificamos onde, dentro da sua área de distribuição geográfica, cada espécie de mamífero deverá ser “criticamente exposta” à diferentes fatores de risco (variáveis climáticas). Além disso, avaliamos a eficiência da atual rede de unidades de conservação da Amazônia de mitigar os impactos das mudanças climáticas sobre espécies, através da comparação da riqueza de espécies “criticamente expostas” encontrada em cada UC contra os valores esperados de riqueza gerados por um modelo nulo que aleatoriza cada UC dentro da Amazônia atentando para manter o tamanho, a forma e a orientação de cada UC.

No segundo capítulo, desenvolvemos um esquema de priorização para conservação que eficientemente identifica áreas prioritárias para conservação considerando em todo processo de priorização diferentes medidas de exposição climática, a área de distribuição geográfica atual e futura de uma espécie e locais que podem ser importantes para facilitar à dispersão entre estas duas áreas de distribuição. Além disso, o esquema de priorização também atenta para incertezas provenientes das medidas das exposição climática e dos modelos de distribuição de espécies, tornando o processo de priorização mais robusto à incertezas.

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Capítulo I

Ribeiro, B.R.; De Marco Jr, P.; Sales, L.P.; Loyola, R. **Assessing mammal exposure to climate change in the Brazilian Amazon**

Artigo submetido ao periódico *Biological conservation*.

Assessing mammal exposure to climate change in the Brazilian Amazon

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Abstract

Human-induced climate change is considered a conspicuous threat to biodiversity in the 21 st century. Species' response to climate change depends on their exposition to climate anomalies, their physiological sensitivity, and their ability to adapt to new changes. Therefore, identifying the most exposed localities to climate change across species' geographic range is a first-order assessment to determine species vulnerabilities. However, exposure to climate change is uneven within species' range, so that some populations may be more at risk than others. Here, we aimed at quantifying mammal local exposure to climate change across species' ranges. We identified areas in the Brazilian Amazon where mammals are critically exposed using different climatic variables predicted by 17 climate hindcasts. We also built a null model to assess the effectiveness of the Amazon Protected Areas in buffer effects of climate change on mammals. We found that almost all species will be exposed in some degree to non-analogue climatic conditions, in at least part of their range. However, endemic species will have a large proportion of their ranges exposed to climate change. Exposure patterns also varied with different climatic variables and seem to be geographically structured. Northern Amazon species are more likely to experience temperature anomalies while eastern species will be more affected by rainfall abnormality. We also observed an increase in the number of critically-exposed species from 2050 to 2070. Overall, our results indicate that mammals might face high exposure to climate change and Protected Areas will probably not be efficient enough to avert those impacts.

Key words: conservation biogeography, global changes, physiological tolerance, protected areas, species vulnerability.

1. Introduction

Human-induced climate change increases species extinction risk and is considered a prominent threat to biodiversity during and beyond the 21 st century (Pereira et al., 2010; Dawson et al., 2011; Bellard et al., 2012). Novel (non-analogue) climate conditions are expected in almost a third (12-39 %) of the global surface. Likewise, 10-48 % of Earth's extent is projected to experience disappearing of current climate conditions (Williams et al., 2007). As climate changes, many species might be exposed to climatic conditions likely to exceed their physiological tolerance. That exposure will probably result in physiological stress (Huey et al., 2012), reduction in fitness (Kearney et al., 2009; Bozinovic et al., 2011; Oswald et al., 2011) or even extinction (Sinervo et al., 2010), especially if species are unable to track other suitable environmental conditions or undergo some kind of in situ adaptation (Davis and Shaw, 2001; Bradshaw and Holzapfel, 2006; Chevin et al., 2010; Hoffmann and Sgrò, 2011).

Tropical species are particularly at risk from climate change (Colwell et al., 2008; Deutsch et al., 2008; Khaliq et al., 2014). Despite the smaller amount of climate change expected to the tropics when compared to temperate regions, tropical species are currently living closer to their thermal safety margin (Deutsch et al., 2008; Tewksbury et al., 2008; Huey et al., 2009; Dillon et al., 2010; Huey et al., 2012; Khaliq et al., 2014;). Thus, even small climate changes might have deleterious consequences on species long-term survival because high conservatism of upper thermal limits prevent species to develop adaptations to increased temperature that will probably exceed their physiological tolerance (Araújo et al., 2013; Sunday et al., 2014).

Further, tropical species are more likely to have to cope with climate change in situ, since shallower temperature gradients within tropical lowlands prevents species to disperse and track their suitable climatic conditions (Colwell et al., 2008). The combination of higher sensitivity, narrower climatic niches and geographic distributions, increase of non-analogous climate conditions, and higher species richness, set the tune for tropical species being more vulnerable to climate change (McCain, 2009; Williams et al., 2007; Dillon et al., 2010; Khaliq et al., 2014).

However, species are not equally exposed to climate change. Along all localities of a species distribution, some populations will be more at risk than others because exposure to climate change is geographically structured within species range. Projected changes on temperature and precipitation are unevenly distributed around the globe (see Garcia et al., 2014). Therefore, some populations might be able to cope with increase in local temperature or reduction in rainfall, meanwhile others populations might suffer climate stress. Different physiological, demographic and ecological characteristics across a species range will probably result in geographically distinct exposure to climate change.

If exposure to climate change varies geographically within species' ranges, estimating how much and where populations are most at risk is paramount to understand the effects of climate change on species. Is any part of a species' range safe? Protected areas (PAs) play a central role in averting negative consequences of climate change (Lovejoy, 2006). PAs are supposed to guarantee the maintenance of different microclimate conditions in heterogeneous habitats that are essential for species to avoid extreme climatic conditions (Sunday et al., 2014). Additionally, PAs buffer species against other human-induced threats such as habitat loss and fragmentation.

The Brazilian Amazon is a perfect study case to address these questions for basically two reasons. First, it is the largest intact tropical rainforest in the world covering around 5 million km^2, which corresponds to 61 % of the Brazilian territory. Second, the Amazon has one of the most vast species composition on Earth containing one out every five plant (40000 vascular plants), bird (1300) and mammal (399) species (Veríssimo et al., 2011) and the highest richness of mammals among all Brazilians biomes; from 701 Brazilian mammals, 399 occur the in Amazon (Paglia et al., 2012). Finally, conservation status of the Brazilian Amazon is particularly interesting. Although it has been transformed in a mosaic of altered environments due to population growth and economic activities (Nepstad et al., 2008), it also holds the largest network of protected areas existing in Brazil.

Here, we quantified mammal local exposure to climate change across species' range and identify which areas in the Brazilian Amazon have the highest concentrations of species with critical exposure to different climatic variables. We also assessed the effectiveness of Amazon network of Protected Areas (PAs) in buffer the impacts of climate change on species by comparing the number of critically-exposed species found in each PA against expected values of species richness estimated by a null model that randomly allocated PAs within the Amazon while keeping their size, shape and orientation (see Lemes et al., 2013; Ferro et al., 2014).

2. Methods

2.1 Species' data

Data on species distribution was obtained from range maps for terrestrial mammals on the International Union for Conservation of Nature website (IUCN version 2015-2; http://www.iucnredlist.org/technical-documents/spatial-data). We followed Paglia et al. (2012)

to account for taxonomic differences and to check for species occurrences in the Amazon. A total of 376 mammals species inhabiting the Brazilian Amazon were analyzed in this work. We overlapped each range map into an equal-area grid of 0.5° x 0.5° latitude/longitude (around 55 km at equator line) containing 12,807 and 1,767 cells covering the full extent of species' range and the extent of the Brazilian Amazon, respectively. We assumed that a species was present in a cell if any portion of its distribution map overlapped the respective cell.

2.2 Climatic data

We selected four bioclimatic variables to quantify mammal exposure to climate change: mean annual temperature, temperature seasonality, maximum temperature of warmest month, and precipitation seasonality. We chose these variables because they encompass multiple climate dimensions representing general trends, variation (seasonality) and extremes (maximum) climatic relevant aspects that affect, direct or indirectly, species distribution and survival (see Supplementary Material Table S1 for further details about climatic variable selection and collinearity among variables).

We obtained bioclimatic variables relative to current (1950-2000) and future (2050 and 2070) periods from the WorldClim database (http://www.worldclim.org/download). Current variables were generated from interpolation of observed data from weather stations (version 1.4; Hijmans et al., 2005). We used future climate projections derived from 17 downscaled Atmosphere-Ocean General Circulation Models from CMIP5 (AOGCMs; ACCESS1-0, BCC-CSM1-1, CCSM4, CNRM-CM5, GFDL-CM3, GISS-E2-R, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, INMCM4, IPSL-CM5A-LR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR, MRI-CGCM3, NorESM1-M) for high-emission greenhouse gases scenario (Representative

Concentration Pathways, RCPs 8.5; IPCC 2013) to quantify species local exposure to climate change.

Current and future bioclimatic variables were obtained at the resolution of 10 arc-minutes (~ 0.16º) and rescaled to our grid resolution using mean of values within 0.5 º cell. Calculations were performed in R version 3.1.2 mainly using the *LetsR* and *Raster* packages (Vilela and Villalobos, 2015, Hijmans, 2015).

2.3 Estimates of species local exposure to climate change

To identify the most exposed cells to climate change across species geographic range, we followed three steps. First, we used the current climate conditions (1950-2000) within the entire species' range to identify the amplitude (maximum and minimum limits) of each climatic variable to which species are currently exposed within its range. This procedure is useful to identify areas within species' ranges where future climate conditions will probably exceed current climatic variability.

Second, for each grid cell and each variable we calculated the standard deviation of projections derived from the 17 AOGCMs. The mean of each cell-based projection minus their corresponding standard deviation was considered the value of each climatic variable in the future (2050 and 2070). In doing so, we incorporated the variation from different future climate projections by assuming the value that a particular climatic variable may achieve in future as the mean minus one standard deviation. Therefore, our approach is extreme for we selected the highest emission scenario but conservative for assuming the lower values of climate variables.

Third, we identified cells within species' range in which future climate conditions may exceed the current climate conditions experienced by the species; we denominated these species as "critically-exposed". Endemic species were also analyzed separately, to assess their exposure in relation to other groups. Finally, we mapped areas with highest concentration of critically-exposed species to each climatic variable separately and thereafter, we combine these maps to build a "combined" exposure map.

2.4 Data on protected areas

In this study, the network of the Brazilian Amazon PAs was therefore composed by 101 federal PAs covering approximately 60 million ha corresponding to 14.5% of the biome (Figure 6). We obtained Federal Protected Areas (PAs) spatial data from the Chico Mendes Institute for Biodiversity Conservation (ICMBio, February 2015; http://www.icmbio.gov.br/portal/servicos/geoprocessamento). We overlapped the polygons of PAs to our grid and considered a grid cell as "protected" if at least 20 % of its area was overlapped by any PAs. We followed this procedure to maintain the real proportion of the Brazilian Amazon territory included in PAs. After trying different thresholds, we obtained that optimum value of 20% because the percentage of grid cells assigned as "protected" is relatively similar to the percentage of the Amazon PAs (18 and 14.5 %, respectively).

PAs are broadly classified into two main groups relative to the degree of allowed human intervention: PAs of Sustainable Use, which aims to combine conservation of ecosystems and habitats with economics activities and guaranteeing the permanence of traditional populations; and PAs of Full Protection, where only scientific research, tourism, and environmental education activities are permitted, while the permanence of traditional population is still allowed (Veríssimo et al., 2011).

2.5 Effectiveness of Protected Areas – Null model

We assessed the effectiveness of PAs by comparing the number of critically-exposed species inside each PA against the estimated number of species predicted by a null model. That null model randomly allocated PAs within the Amazon while keeping its size, shape and orientation (see Lemes et al., 2013; Ferro et al., 2014). We used the equation below to compare the observed species richness in each PA (OR) against the species richness (RR) obtained by 1000 (n) randomization runs. A given PA was considered effective when OR ≥ RR at least 95% of runs, or $p \leq 0.05$ (Table 2).

$$\mathrm{p} = \sum_{i=1}^{n} \frac{(OR \geq RRi) + 1}{n + 1} \quad (1)$$

3. Results

All species were exposed to novel climate conditions in at least one cell within their ranges, although different climatic variables revealed contrasting patterns of exposure. Overall, we found that the majority of critically-exposed species to temperature anomalies (interannual average, variability and extremes) were concentrated in northern Amazon. Yet critically-exposed species to rainfall anomalies were predominately concentrated in the eastern portion of the biome. Additionally, given that climatic conditions will continue to change from 2050 to 2070, our results showed that the number of species and the proportion of species' range exposed to climate change also tend to increase (Fig. 1 and 2; Table 1).

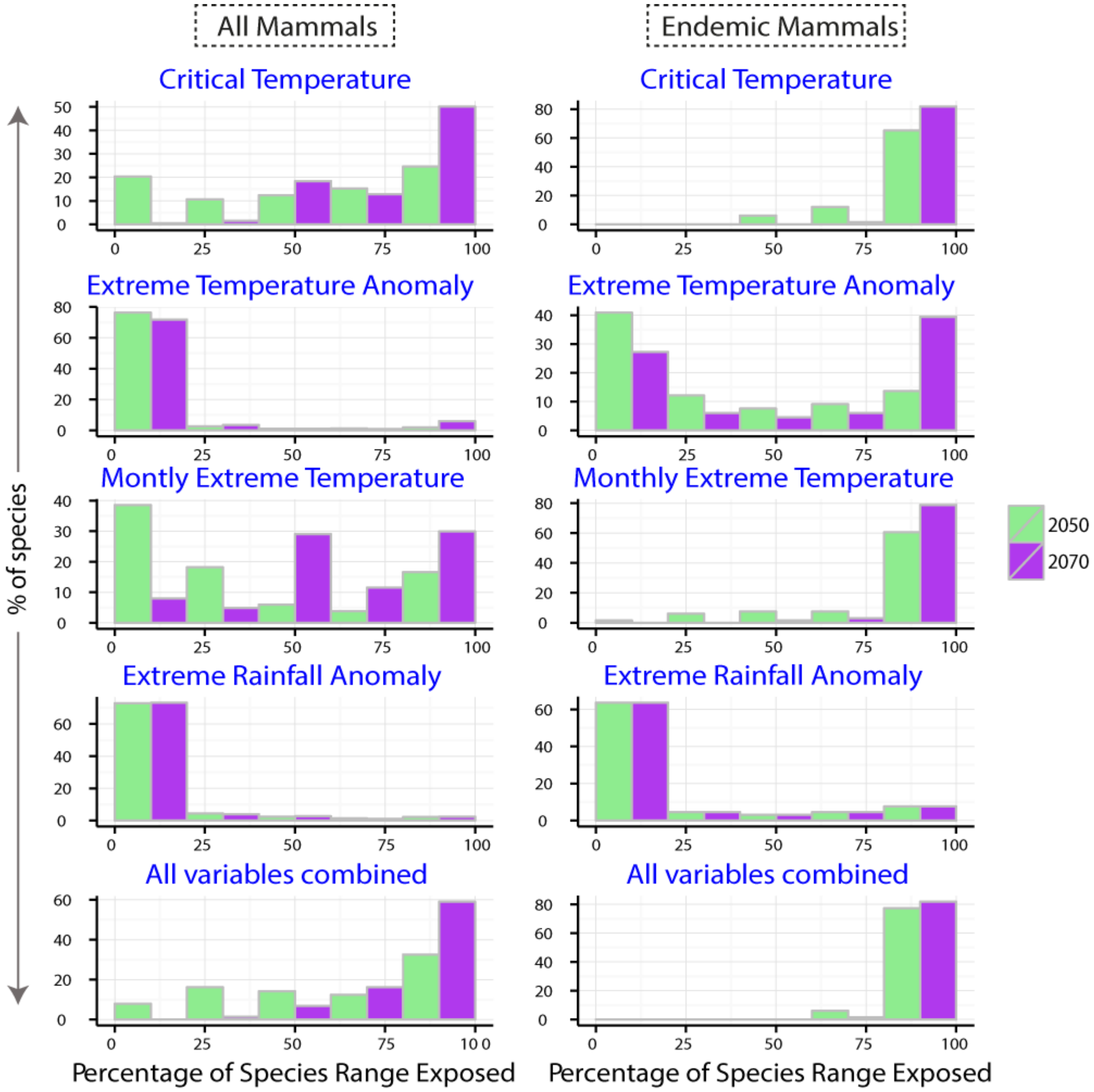

Figure 1. Percentage of Amazon mammal range exposed to four future climatic variables taken separately and together quantified using an average of 17 General Circulation Models for a high-emission greenhouse scenario (RCP 8.5).

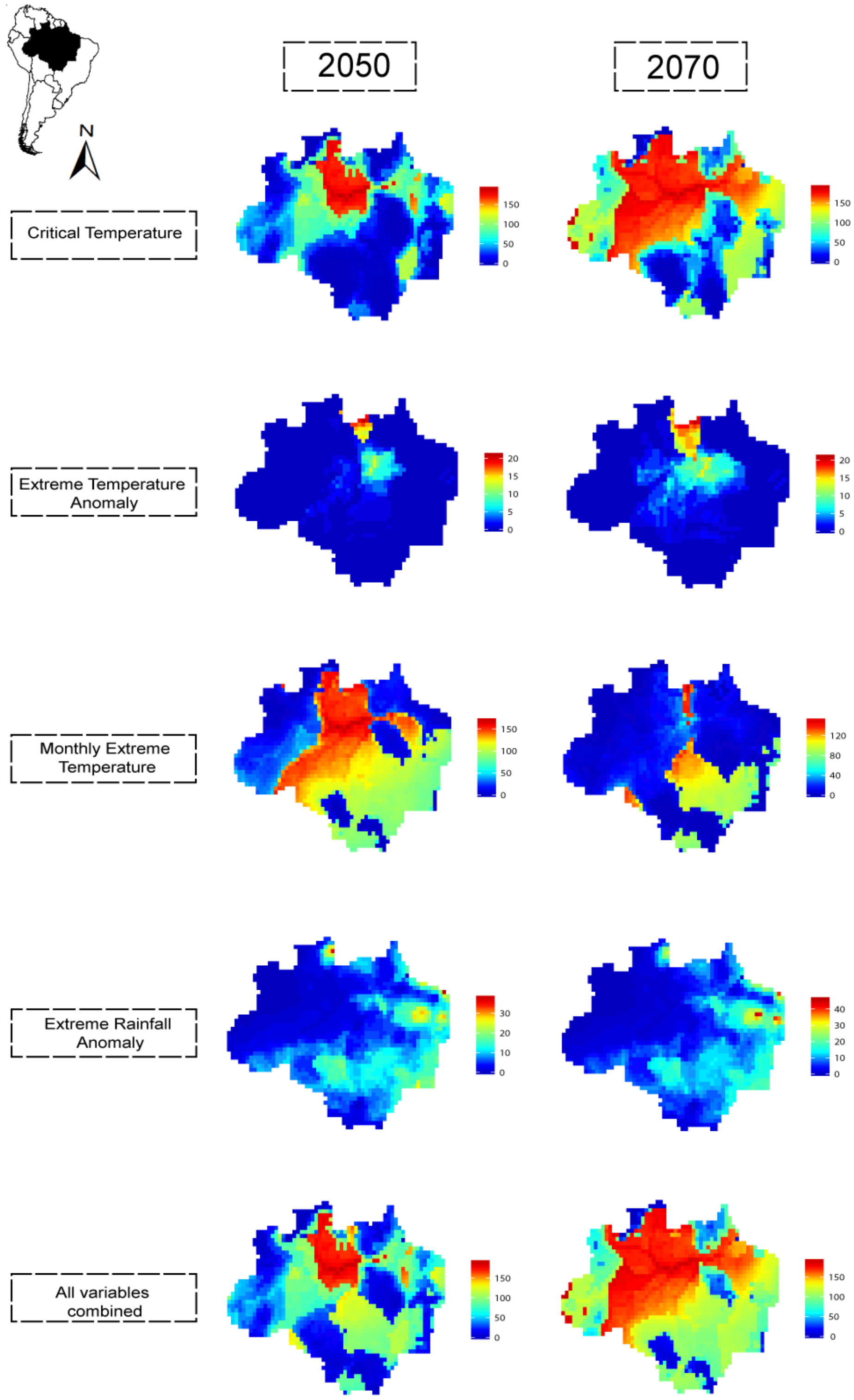

Figure 2. Areas in the Brazilian Amazon with greatest concentrations of species with critical exposure to four climatic variables separately and taken together. Species were considered exposed in any locality of its range when future climate exceeds the current climate variability of its range. Colors close to red indicate localities with higher number of species.

Table 1. Current and future climate conditions (average and standard deviation) in Brazilian Amazon quantified using an average of 17 General Circulation Models for a high-emission greenhouse scenario (RCP 8.5). The percentage of mammals exposed at least one portion of their range to different climatic variables separately and taken together are showed.

	Critical Temperature (°C)	**Extreme Temperature Anomaly (CV)**	**Monthly Extreme Temperature (°C)**	**Extreme Rainfall Anomaly (mm)**	**All variables combined**
Present (1950-2000)	25.76 ± 1.02	57.58 ± 30.07	32.84 ± 1.19	58.41 ± 17.66	-
Future (2050)	28.60 ± 0.97	90.57 ± 26.66	36.63 ± 1.32	64.57 ± 18.01	-
Future (2070)	29.90 ± 0.98	106.19 ± 26.49	38.34 ± 1.44	66.73 ± 18.19	-
Percentage of species exposed (2050)	98	17	88	27	19
Percentage of species exposed (2070)	100	19	97	28	19
Median Percentage of range exposed (2050)	57	0.00	20	0	64
Median Percentage of range exposed (2070)	89	0.00	59	0	93

We found that almost all mammals (98-100% of species) might experience local changes on average temperature beyond current variability, in a large extent of their range (57-66%). Yet 88-97% of species might be exposed to monthly extreme temperature anomalies although in a narrower proportion of their range (20-59%; Fig. 1 and Table 1). All endemic mammals analyzed in this study (55 species) will be exposed to temperature anomalies (average and extreme) in almost all cells of their ranges (Fig. 1). On the other hand, few species will be exposed to precipitation anomalies, or exposed to all climatic variables when taken together (Fig. 1). However, climate variability within species' range (maximum and minimum values) was higher for precipitation compared to temperature, which might have affected differential exposure (Fig. S1 in Supplementary Material).

The majority of critically-exposed species were barely represented by PAs (Fig. 3 and Table S2 in Supplementary Material). Although Amazon federal PAs cover 14.5 % of the Amazon (Fig.

S3; Verissimo et al 2011), only 32% of PAs are likely to harbor more species than expected by our null model (Fig. 4). Further, the number of PAs considered effective decreased from 32 to 25 from 2050 to 2070, respectively (Table S2 in Supplementary Material). Finally, we found no differences between the effectiveness of Full Protection versus Sustainable Use PAs regarding PA effectiveness (Fig. 3).

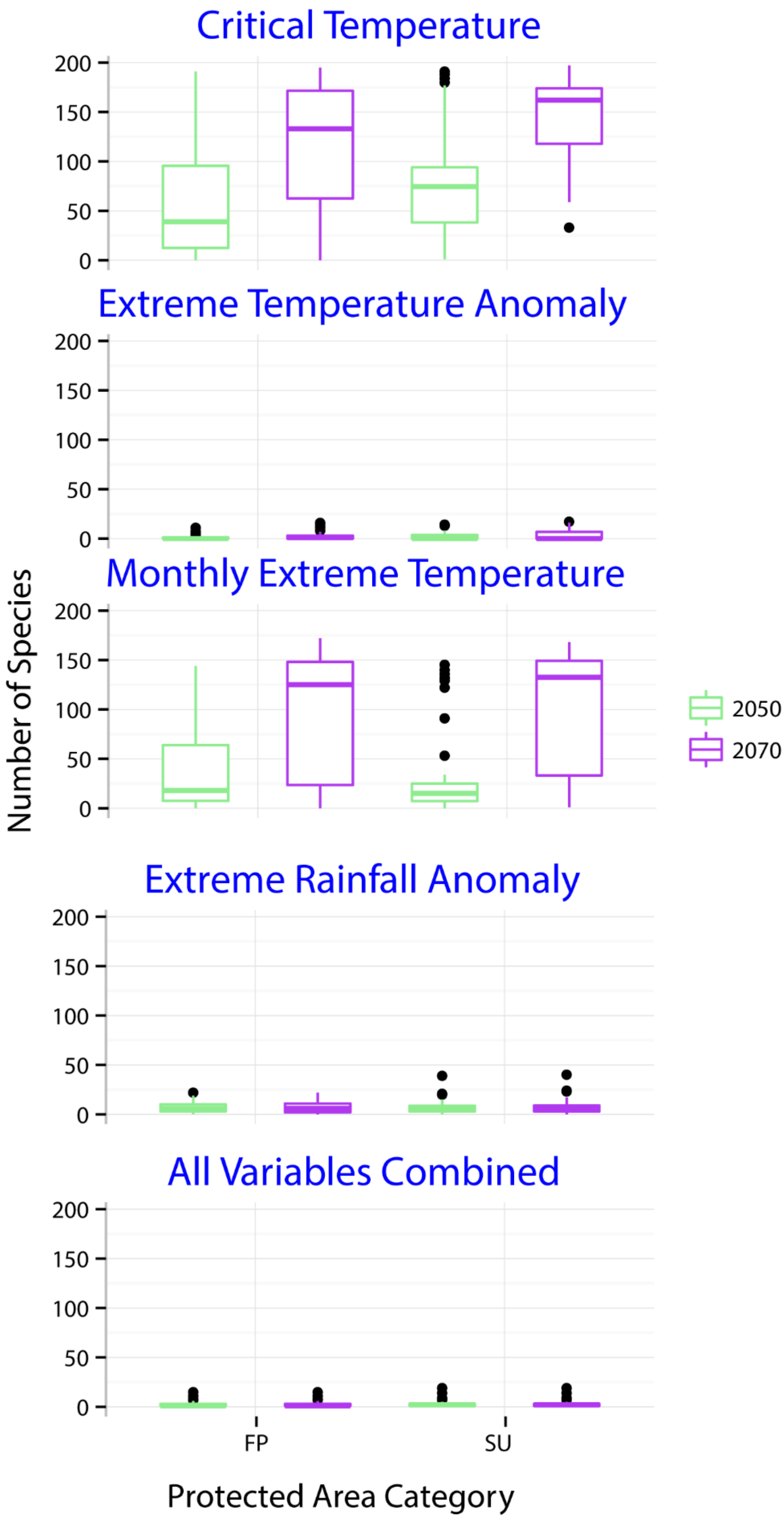

Figure 3. Number of critically-exposed mammal to climate change within Amazon Protected Areas (FP, Full Protection and SU, Sustainable Use).

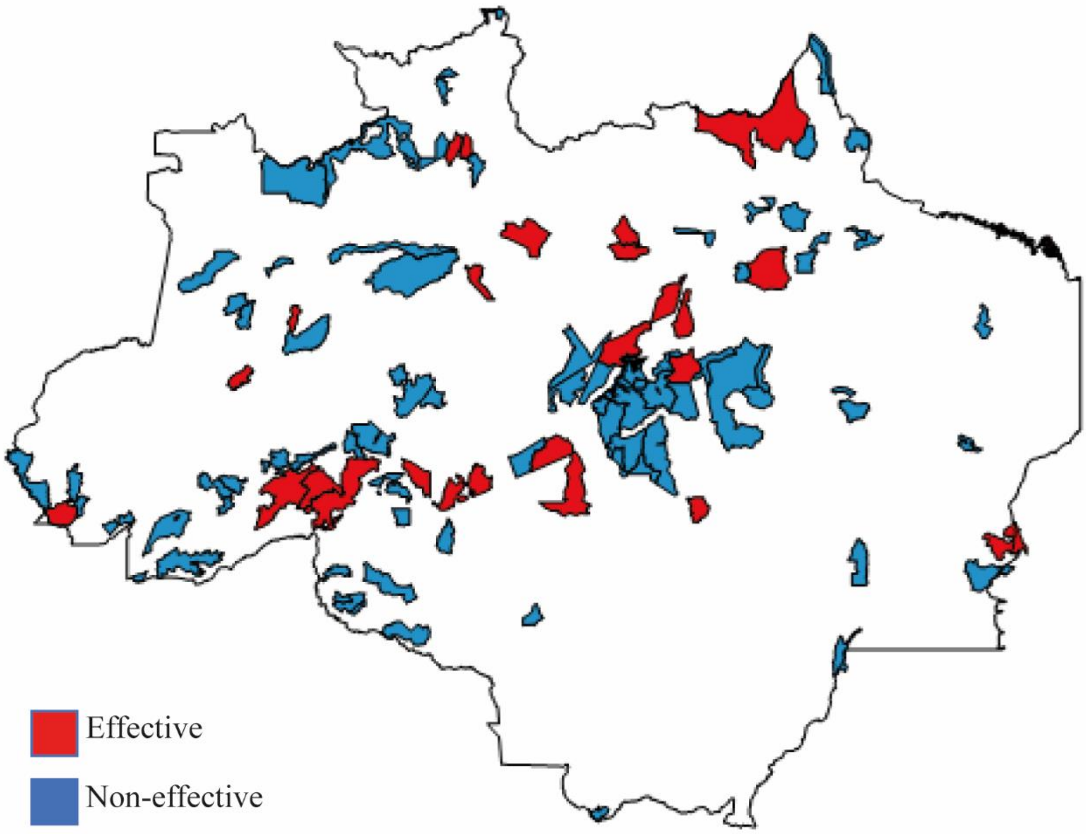

Figure 4. Spatial distribution of effective and non-effective protected areas (PAs) to mitigate effects of future climate change in the Brazilian Amazon. Effective PAs are those supposed to buffer species against effects of climate change as assessed by a null model that allocated each PA within the Amazon keeping its size, shape and orientation.

4. Discussion

In this paper, we quantified mammal local exposure to climate change and identified areas in the Brazilian Amazon with highest concentrations of critically-exposed species. Further, we highlighted that these species are barely represented by the Amazon network of Protected Areas. Although most Amazon mammal species were classified as ‘exposed’, exposure was not equal along the species’ range, implying that some populations will be more at risk than others. On average, 60 % of the Amazon mammals will be exposed in more than 75 % of their ranges. That percentage is even higher for endemic mammals because 80% of the analyzed endemics are predicted to be exposed in more than 75% of their range. The ability to identify populations at higher risk is paramount to implement proactive on-the-ground conservation actions, aiming to increase population resilience against negative effects of climate change (Ameca y Juárez et al., 2013; Garcia et al., 2014).

However, exposure itself does not mean vulnerability. Although our results highlight a general pattern of local climate exposure in the Amazon, the overall picture of species vulnerability depends ultimately on their sensibility and adaptability to new climate conditions (Williams et al., 2008; Foden et al., 2013; Pacifici et al., 2015). Studies have pointed out that some species’ ecological and physiological traits are more related to vulnerability in endotherms (Ameca y Juárez et al., 2012; Foden et al., 2013). For example, larger, exclusively diurnal or nocturne mammals are more sensitive to climate change than smaller mammals and those with flexible activities periods (Huey et al., 2012; Mccain and King, 2014). Despite these findings, all else being equal, populations in places undergoing larger climatic changes are more likely to be negatively affected (Garcia et al., 2014). Physiology, behavior and morphology of individuals are expected to be adversely affected by reductions in climatic suitability, ultimately interfering on population dynamics (Garcia et al., 2014; Cruz-McDonnell and Wolf, 2015) Therefore, although exposure represents only one component of species vulnerability, it constitutes a first-order assessment to identify where species are more potentially vulnerable to climate change. Subsequently, this information can be used to complement species extinction risk assessments (Garcia et al., 2014).

We found that most mammals inhabiting the Brazilian Amazon are in some degree exposed to climate change. Indeed, species living in tropical regions are particularly vulnerable to climate change (Deutsch et al., 2008; Khaliq et al., 2014). Tropical species tend to live closer to their maximum critical temperature (maximum temperatures that a species can withstand without additional energy expenditure to keep body temperature constant; Sunday et al., 2014). Thus, even the slighter amount of climate change projected for the tropics might exceed species physiological tolerance. It follows that the additional amount of energy expenditure necessary to maintain homeostasis reduces energy available for other functions, such as reproduction. That decreased available energy may also lead to fitness reduction, loss of genetic variation at population level and possibly local extinction (Buckley et al., 2012; Sinervo et al., 2010).

On the other hand, some mammals currently experience temperatures that exceed their maximum thermal tolerance limit in at least part of the year (Khaliq et al., 2014). This implies that they rely on their behavior plasticity to avoid overheating. Mammals may have developed different strategies to avoid extremes temperatures, such as create burrows and dens (Boyles et al., 2011). As temperature increases, more and more species will rely on behavior thermoregulation and on availability of different microclimate conditions providing cool habitat necessary to species avoid extreme exposure. Those characteristics will be especially relevant in the tropics because of the high likelihood of undergoing local climate changes that exceed current climate variability (Garcia et al., 2014; Sunday et al., 2014).

We found that only 25 % of the PAs harbored more critically-exposed species than expected by our null model. Protected Areas are the keystone of current conservation strategies and play a vital role in buffering species against extreme exposure to climate change. Beyond safeguarding habitat and different microclimate conditions, PAs also buffer species against other human-induced stress, such as habitat fragmentation. In addition, our findings strengthen the need to assess the PAs effectiveness using dynamic approaches, since climate is predicted to continuously change from 2050 to 2070. Those expected changes impose new challenges for establishment of PAs or adaptation of current PAs network.

We highlighted areas in the Brazilian Amazon with the highest abundance of species critically-exposed to different climatic variables. In addition, we showed that the current network of PAs has small effectiveness to protect these species. However, our study has its own caveats. First, our coarse temporal and spatial resolution climate variables do not encompass microclimate variation present in heterogeneous habitat could potentially allow species to endure the effects of extreme climate change exposure (Sunday et al., 2014). Nevertheless, coarser resolution is useful for minimizing effects of biotic factors on species distributions (Hortal et al., 2010). Second, we inferred species climate preferences from their geographic ranges and assumed that species were critically exposed when future climate conditions exceed current variability within species range. In doing so, we do not intend to infer climate physiological tolerances. Conversely, we intended to identify where in the species' range species will be exposed to different climate variables.

In summary, in this work we highlight a general pattern of areas in which species with the potential to be critically-exposed to effects of climate change are concentrated. Such an examination provides the first step to a more comprehensive assessment of species vulnerability, and might guide conservation decisions on where to take place on-the-ground actions aiming at minimizing negative effects of climate change on species.

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Supplementary Material

Table S1. Factorial Analysis showing the collinearity among 19 bioclimatic variables. Values in bold indicate variables used to quantify mammal exposure to climate change in the Brazilian Amazon. The minus sign (-) indicates very small values.

Climatic Variables	**Loadings**				
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Annual Mean Temperature	0.72	0.251	**0.641**	-	-
Mean Diurnal Range	-0.166	-0.358	-0.312	0.825	-
Isothermality	0.871	0.346	0.2	-	-
Temperature Seasonality	**-0.939**	-0.29	-0.166	-	-
Max Temperature of Warmest Month	0.229	**0.946**	0.195	-	-
Min Temperature of Coldest Month	0.836	0.277	0.454	-0.113	-
Temperature Annual Range	-0.911	-0.305	-0.149	0.217	-
Mean Temperature of Wettest Quarter	0.3	0.215	0.74	-0.13	-
Mean Temperature of Driest Quarter	0.813	0.216	0.421	-	-
Mean Temperature of Warmest Quarter	0.346	0.146	0.922	-	-
Mean Temperature of Coldest Quarter	0.832	0.271	0.48	-	-
Annual Precipitation	0.361	0.796	0.188	**0.409**	-0.137
Precipitation of Wettest Month	0.426	0.856	0.228	-0.139	-
Precipitation of Driest Month	0.32	0.934		-	-
Precipitation Seasonality	0.325	**-0.699**	0.112	-	-
Precipitation of Wettest Quarter	0.419	0.863	0.218	0.103	-0.134
Precipitation of Driest Quarter	0.115	0.36	0.919	-	-
Precipitation of Warmest Quarter	0.203	0.534	0.15	0.435	-
Precipitation of Coldest Quarter	0.253	0.632	0.392	-0.171	-
Loadings of each factor	6.054	3.792	3.582	2.845	0.92
Proportion of variance explained	0.319	0.2	0.189	0.15	0.048
Cumulative proportion of variance explained	0.319	0.518	0.707	0.856	0.905

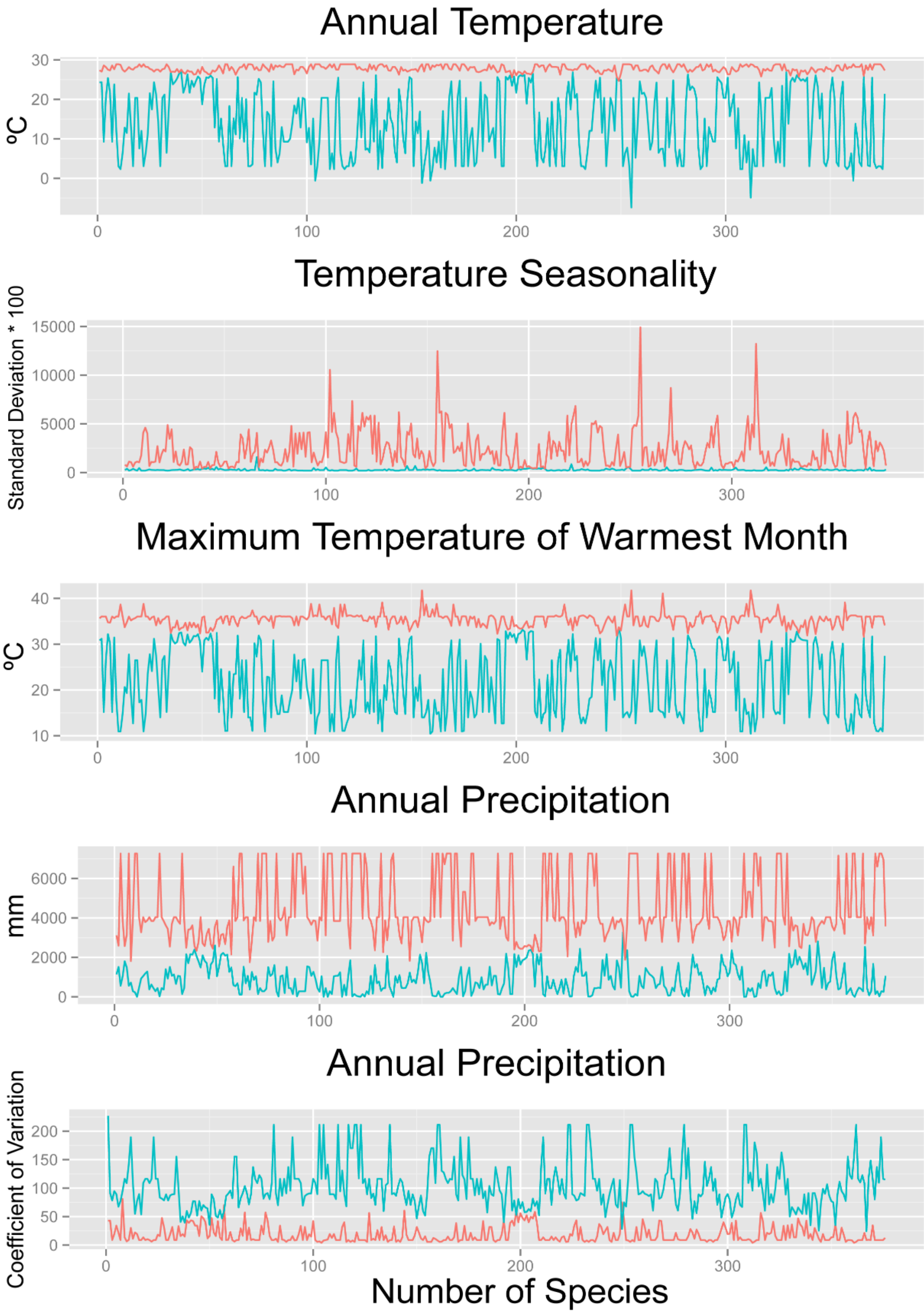

Figure S1. Climatic variability (maximum and minimum) present within all extent of 376 Amazon mammal species' range (range not exclusively within Amazon extent). Maximum and minimum values for each climatic variable within species' range are shown in red and green, respectively.

Table S2. Effectiveness of the Brazilian Amazon Protected Areas (PAs) in representing critically-exposed mammal assessed by comparing species richness of each PA against richness estimated by a null model. PAs are divided into two categories: Sustainable Use (SU) and Full Protection (FP). See methods for further details.

Protected Area	**Category**	**Critical Temperature**		**Extreme Temperature Anomaly**		**Monthly Extreme Temperature**		**Extreme Rainfall Anomaly**		**All variables combined**		**Non-random Exposure ?**	
		2050	**2070**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**
Área De Proteção Ambiental Meandros Do Rio Araguaia	SU	112*	112	0	0	91	94	15	15	112	112	Yes	No
Estação Ecológica Da Terra Do Meio	FP	9	80	7	11	11	141	10	13	27	146	No	No
Parque Nacional De Anavilhanas	FP	191*	191*	1	3	20	172*	2	2	191*	191*	Yes	Yes
Estação Ecológica De Cunã	FP	78	164	0	2	21	145	7	6	22	164	No	No
Estação Ecológica De Iquê	FP	0	1	0	1	0	9	17	17	0	19	No	No
Estação Ecológica De Jutaí-Solimões	FP	29	93	0	0	2	11	0	0	38	93	No	No
Estação Ecológica De Maracá	FP	84	178	0	0	8	149	5	5	178*	178	Yes	No
Estação Ecológica Niquía	FP	178*	178	0	1	21	157*	3	2	178*	178*	Yes	Yes
Estação Ecológica Do Jari	FP	36	100	0	0	11	19	5	7	39	101	No	No
Estação Ecológica Rio Acre	FP	8	54	0	0	4	35	6	6	64	56	No	No
Estação Ecológica Juami-Japurá	FP	13	86	0	0	0	2	0	0	31	86	No	No
Estacao Ecológica Serra Geral Do Tocantins	FP	2	46	0	0	57	88	17	17	21	92	No	No
Floresta Nacional De Altamira	SU	30	86	4	6	11	133	7	7	26	136	No	No
Floresta Nacional De Anauá	SU	171	171	0	1	20	151	1	1	171	171	No	No
Floresta Nacional De Balata-Tufari	SU	92	178	0	0	25	159	7	6	39	178	No	No
Floresta Nacional De Carajás	SU	3	59	0	3	3	9	7	13	15	66	No	No
Floresta Nacional De Caxiuana	SU	95	163	0	0	14	135	5	8	34	163	No	No
Floresta Nacional De Humaitá	SU	78	164	2*	4*	24	145	9	9	23	164	Yes	Yes
Floresta Nacional De Itaituba I	SU	94	160	7*	9	131*	142	1	2	160	160	Yes	No
Floresta Nacional De Itaituba II	SU	168	168	8*	10	132*	150	2	2	168	168	Yes	No
Floresta Nacional De Jacundá	SU	78	164	2	4	22	145	9	9	23	164	No	No

Floresta Nacional De Mulata	SU	43	173	3	3	13	25	6	8	32	173	No	No
Floresta Nacional De Pau-Rosa	SU	180	180	4	12	34	161	3	3	180	180	No	No
Floresta Nacional De Roraima	SU	82	175	0	0	8	146	5	5	93	175	No	No
Floresta Nacional De Santa Rosa Do Purus	SU	42	118	0	0	9	36	9	6	189*	118	Yes	No
Floresta Nacional De Saracá-Taquera	SU	177*	177	6*	17*	136*	159*	6	6	177	177	Yes	Yes
Floresta Nacional De Tefé	SU	116	186	0	0	11	46	1	1	84	186	No	No
Floresta Nacional Do Amapá	SU	38	100	0	0	1	18	4	4	52	100	No	No
Floresta Nacional Do Amazonas	SU	184	189	0	0	6	144	2	2	191	189	No	No
Floresta Nacional Do Jamari	SU	29	151	1	2	15	132	7	7	15	151	No	No
Floresta Nacional Do Jatuarana	SU	71	157	1	4	24	139	8	8	26	157	No	No
Floresta Nacional Do Purus	SU	33	107	0	0	10	41	5	4	25	107	No	No
Floresta Nacional Do Tapajós	SU	94	183	14*	16*	24	163*	9	9	79	183*	Yes	Yes
Floresta Nacional Mapiá - Inauini	SU	34	107	0	0	10	42	5	4	27	107	No	No
Parque Nacional Da Amazônia	FP	180	180	11*	14*	140*	161	4	4	180	180	Yes	Yes
Parque Nacional Da Serra Do Divisor	FP	63	133	0	0	19	47	3	3	204*	133	Yes	No
Parque Nacional Da Serra Do Pardo	FP	4	29	2	4	2	14	6	8	12	33	No	No
Parque Nacional Das Nascentes Do Rio Parnaiba	FP	1	38	0	0	71	87	19	20	19	90	Yes	Yes
Parque Nacional De Pacaás Novos	FP	5	33	0	0	18	127	7	7	20	127	No	No
Parque Nacional Do Araguaia	FP	117	117	0	0	97	99	17	17	117	117	No	No
Parque Nacional Do Cabo Orange	FP	26	83	0	0	18	21	10	10	37	85	No	No
Parque Nacional Do Jaá	FP	180	180	0	3	11	149	1	1	180	180	No	No
Parque Nacional Do Monte Roraima	FP	0	0	0	0	0	0	5	5	0	5	No	No
Parque Nacional Do Pantanal Matogrossense	FP	37	104	0	0	83	86	2	2	12	104	No	No
Parque Nacional Do Pico Da Neblina	FP	122	195	0	0	4	25	0	0	198*	195	Yes	No
Parque Nacional Do Viruá	FP	177*	177	0	1	21	156*	3	2	177*	177*	Yes	Yes
Parque Nacional Montanhas Do Tumucumaque	FP	22	88	0	0	18	22	10	12	52	92	No	Yes

Parque Nacional Serra Da Cutia	FP	33	148	0	0	127*	129	7	6	25	148	Yes	No
Parque Nacional Serra Da Mocidade	FP	173	174	0	1	9	153	2	2	174	174	No	No
Reserva Biológica Do Abufari	FP	90	176	0	3	7	37	2	2	36	176	No	No
Reserva Biológica Do Guaporé	FP	12	61	0	0	104	125	7	7	21	125	No	No
Reserva Biológica Do Gurupi	FP	56	139	0	0	3	16	22*	22	138	139	Yes	No
Reserva Biológica Do Jaru	FP	7	64	1	3	16	125	15	15	13	126	No	No
Reserva Biológica Do Lago Piratuba	FP	74	163	0	0	14	15	12	12	32	163	No	No
Reserva Biológica Do Rio Trombetas	FP	171	171	3	16*	141*	153	4	6	171	171	Yes	Yes
Reserva Biológica Do Tapirapé	FP	16	61	0	3	3	10	9	13	19	68	No	No
Reserva Biológica Do Uatumã	FP	171	171	0	12*	20	151	1	2	171	171	Yes	Yes
Reserva Biológica Nascentes Da Serra Do Cachimbo	FP	1	13	1	2	110*	113	13	13	7	114	Yes	Yes
Reserva Extrativista Auatí-Paraná	SU	24	90	0	0	2	8	0	0	36	90	No	No
Reserva Extrativista Barreiro Das Antas	SU	67	150	0	0	129*	132	7	7	26	150	Yes	No
Reserva Extrativista Chico Mendes	SU	56	186	0	0	25	150	12	10	67	186	No	No
Reserva Extrativista Do Baixo Juruá	SU	54	181*	0	0	5	25	1	0	44	181*	No	Yes
Reserva Extrativista Do Cazumbá-Iracema	SU	16	91	0	0	7	31	9	9	49	93	No	No
Reserva Extrativista Do Médio Juruá	SU	54	188*	0	0	6	33	2	1	44	188	No	Yes
Reserva Extrativista Do Rio Do Cautário	SU	31	143	0	0	122*	125	7	7	24	143	Yes	No
Reserva Extrativista Do Rio Jutaí	SU	27	89	0	0	2	12	0	0	32	89	No	No
Reserva Extrativista Do Lago Do Capanã Grande	SU	85	171	0	3	18	152	3	2	35	171	No	No
Reserva Extrativista Mapuá	SU	81	151	0	0	6	12	1	3	53	151	No	No
Reserva Extrativista Marinha De Gurupi-Piriá	SU	26	71	0	0	0	4	20*	23	16	83	No	Yes
Reserva Extrativista Do Rio Ouro Preto	SU	70	153	0	0	132*	134	7	6	28	153	Yes	No
Reserva Extrativista Riozinho Da Liberdade	SU	40	118	0	0	6	26	2	2	96	118	No	No
Reserva Extrativista Riozinho Do Anfrísio	SU	37	162	8*	11*	11	143	5	7	41	162	Yes	Yes
Reserva Extrativista Tapajós-Arapiuns	SU	98	187	13*	13	27	167*	11	11	70	187	Yes	Yes

Reserva Extrativista Verde Para Sempre	SU	188*	189	8*	8	22	168*	21	24	187*	189*	Yes	Yes
Parque Nacional Do Rio Novo	FP	22	78	2	3	126*	127	7	7	25	129	Yes	No
Floresta Nacional Do Trairão	SU	70	155	6*	8	15	136	2	2	92	155	Yes	No
Floresta Nacional Do Jamanxim	SU	27	147	3	4	129	131	9	10	41	148	No	No
Parque Nacional Do Jamanxim	FP	85	153	5	7	123*	135	5	6	153	153	Yes	No
Área De Proteção Ambiental Do Tapajós	SU	97	164	6	9	145*	147	8	8	164	164	Yes	No
Floresta Nacional Do Crepori	SU	91	159	5*	7	140*	142	7	7	159	159	Yes	No
Floresta Nacional Do Amana	SU	102	168	2	9	53	150	3	3	168	168	No	No
Parque Nacional Da Chapada Das Mesas	FP	15	57	0	0	2	88	9	10	7	96	No	No
Reserva Extrativista Do Alto Tarauacá	SU	40	115	0	0	6	33	3	2	186*	115	Yes	No
Reserva Extrativista De Cururupu	SU	51	125	0	0	0	1	39*	40	0	125	Yes	Yes
Reserva Extrativista Rio Iriri	SU	31	92	7*	10	7	137	6	6	24	141	Yes	No
Parque Nacional Do Juruena	FP	77	163	5*	7*	144*	147	13	10	53	164	Yes	Yes
Reserva Extrativista Terra Grande - Pracuúba	SU	85	155	0	0	8	111	4	5	77	155	No	No
Reserva Extrativista Rio Unini	SU	191	192	0	3	18	161	1	1	192	192	No	No
Parque Nacional Dos Campos Amazônicos	FP	39	160	3*	6*	25	142	11	10	24	160	Yes	Yes
Reserva Extrativista Arapixi	SU	39	111	0	0	14	46	6	6	32	111	No	No
Reserva Extrativista Gurupá-Melgaço	SU	94	164	0	0	10	128	2	4	31	164	No	No
Reserva Extrativista Do Alto Juruá	SU	57	197*	0	0	19	45	3	3	197*	197*	Yes	Yes
Reserva Extrativista Do Rio Cajari	SU	104	174	0	0	16	34	5	8	85	174	No	No
Reserva Extrativista Do Médio Purus	SU	89	174	0	0	17	155	5	4	32	174	No	No
Floresta Nacional Do Iquiri	SU	89	175	0	0	27	156*	10	9	32	175*	No	Yes
Parque Nacional Nascentes Do Lago Jari	FP	86	172	0	2	12	153	1	1	33	172	No	No
Reserva Extrativista Ituxi	SU	84	169	0	1	22	150*	10	10	27	169*	No	Yes
Parque Nacional Mapinguari	FP	92	180	0	3	33	160*	10	10	34	180	No	Yes
Reserva Extrativista Rio Xingu	SU	1	33	4	7	4	12	8	11	15	39	No	No
Reserva Extrativista Renascer	SU	80	167	7*	7	9	17	15	17	25	167	Yes	No

Estação Ecológica Alto Maués	FP	99	165	2	8	27	147	3	3	165	165	No	No
Total												38	25

Capítulo II

Ribeiro, B.R; Sales, L.P; Loyola, R. **Matching biodiversity conservation priorities to climate change vulnerability in the Brazilian Amazon**

Artigo formatado nas normas do periódico *Global Change Biology*.

Matching biodiversity conservation priorities to climate change vulnerability in the Brazilian Amazon

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Abstract

Human-induce climate change is already acknowledged as major treat to biodiversity during and beyond the 21 st century. Under a climate change perspective, conservation strategies have focused on identifying climatically stables areas that will serve as "climate refugia" to species implying that highly impacted species/populations inhabiting highly exposed areas are set aside and probably committed to extinction. Here, by combining species distribution models to simples climate change metrics we developed a spatial conservation scheme for mammals in the Brazilian Amazon that efficiently identifies highly-exposed areas within species current and future distributions. Further, our prioritization includes important areas that increase connection between current and future distributions and also takes into account uncertainties associated to alternative climate models. We found that most priorities areas concentrated on northwest, northeast and south of the Amazon and that some of the high-priority areas are located in the Amazon "Arch of Deforestation" - a high fragmented zone of the Amazon and a frontier for agribusiness. We also found that, on average, 25-24 % of the modeled current and future mammal distribution is already represented in the established PAs network, respectively. We also observed that 26% priority areas resulting from our analysis is already covered by Indigenous Lands, corresponding to an addition of 6% of mammal current and future distributions. We hope that our spatial conservation plan may help planners and stakeholders to guide conservation efforts aiming at mitigate impacts and avert biodiversity loss due to climate change in the Brazilian Amazon.

Keywords: species vulnerability, spatial conservation planning, global changes, Amazon

Introduction

Human-induced climate change is already taking place being acknowledged as a major treat to biodiversity over the coming century (Thomas *et al.*, 2004; Pereira *et al.*, 2010; IPCC, 2014a). Predicted impacts of climate change on species comprise changes on population abundance (Parmesan, 2006; Cruz-McDonnell & Wolf, 2015), distribution shifts mainly towards higher latitudes and elevated regions (Parmesan *et al.*, 2003), changes on species interactions and community composition (Walther, 2010), and even extinctions, when species are unable to keep pace with their suitable climate or to locally adapt to new climatic conditions (Sinervo *et al.*, 2010).

Climate change is not only a major threat to biodiversity, it is also a big challenge to the way we are used to plan for the conservation of biodiversity. Effective conservation actions require a clear identification of species and ecosystems most at risk under climate change without ignoring their present-day conservation value (Kujala *et al.*, 2013).

Under the climate change perspective, conservation studies have focused on identifying climatically stables areas that will serve as "climate refugia" to species and habitats (i.e., Killeen & Solórzano, 2008; Carroll *et al.*, 2010; Ashcroft *et al.*, 2012; Loyola *et al.*, 2012, 2013; Terribile *et al.*, 2012; Watson *et al.*, 2013; Schmitz *et al.*, 2015). Such approach is based on the assumption that species are more likely to persist for long-term in climatically less impacted areas. However, that approach implies choosing areas that would be less impacted at the expense of those that will suffer more with climate change. Therefore, populations and species inhabiting possibly highly impacted regions are left unprotected and maybe pushed to extinction.

This trade-off between low *vs* highly-impacted areas may be possibly a unreliable choice in some cases. Tropical species, for example, are expected to face high rates of climate change on a large portion of their distribution, risking their long-term survival (Williams *et al.*, 2007; Tewksbury *et al.*, 2008; Loarie *et al.*, 2009). In face of climate change, species must either disperse, adapt or perish (IPCC, 2014b). Beyond high rates of climate change expected in the tropics, tropical species also experience current climate conditions close to their physiological tolerance limits (Deutsch *et al.*, 2008; Sunday *et al.*, 2014). Exceeding those climatic thresholds may lead to fitness reduction (Deutsch *et al.*, 2008; Huey *et al.*, 2012; Kingsolver *et al.*, 2013; Khaliq *et al.*, 2014). Meanwhile, fast rates of climate change in the tropics may outpace species ability to disperse to new favorable climatic areas, in order to keep pace with climate. In addition, their ability to locally adapt to new climate conditions may be diminished by other pressures such habitat deforestation (Malhi *et al.*, 2008).

Ecological Niche Models (ENMs) are one of the most important tools for conservation planning with respect to climate change (Elith and Leatwick 2011). These 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 (Peterson et al. 2011). Predicting current and future distribution can be crucial to enhance conservation plans in face of dynamic climate change (Strange *et al.*, 2011). However, regardless of its importance, predicting species distributions will always carry uncertainties (Diniz-Filho *et al.*, 2009). The use of ENMs faces at least two challenges. First, uncertainties are intrinsically present in ENMs and arise from models, greenhouse gas emission scenarios, models of future climate projections, along other sources (Araújo & New, 2007). Second, analyzing and integrating projections for hundreds, even thousands of species, in order to discern which are the most at risk area/species under climate change, is always challenging (Diniz-Filho *et al.*, 2009; Elith & Leathwick, 2009; Ackerly *et al.*, 2010).

In addition to ENMs, simple climate change metrics can be used to identify areas most exposed or likely to be impacted to climate change. Since the climate is a complex system, the use of different climate change metrics depicts different information when applied to biodiversity conservation (Garcia *et al.*, 2014). Local climate anomalies, climate extremes and the velocity of climate change are three commonly used climate change metrics (Williams *et al.*, 2007; Loarie *et al.*, 2009; Beaumont *et al.*, 2010; Garcia *et al.*, 2014). Those former two metrics are mainly related with changes on average and extreme climates, with implications to local species persistence (Ameca y Juárez *et al.*, 2013; Garcia *et al.*, 2014). Yet climate change velocity is a measure of the rate of climate displacement across the landscape and provides an indicative at which pace species should move across the landscape to keep track of their suitable climate (Loarie *et al.*, 2009).

The Amazon is an ideal case study for assessing climate change effects on biodiversity. Increasing temperature and rainfall reductions along with other non-climate threats such fires and deforestation, set the tune to Amazon be considered one of the Earth's most impacted biomes under climate change. We might witness a set of expected future impacts on the Amazon, from extreme climatic events (i.e. droughts and floods; Brando *et al.*, 2014; Gloor *et al.*, 2015) to species extinctions, since tropical species are highly sensitivity to even small temperature increases and therefore have a limited ability to adapt to climate change (Deutsch *et al.*, 2008; Dillon *et al.*, 2010). Amazon rainforest biodiversity is among the greatest in the world yet new species continue to be discovered there at a higher rate than anywhere else (Pimm *et al.*, 2010; Jenkins *et al.*, 2013). Further, the Brazilian Amazon also holds one of the largest system of protected areas worldwide covering about 1,110,652 km^2 or 22.2 % of its extent (Veríssimo *et al.*, 2011).

Here, we couple current and future species distribution models with climate-change metrics in order to identify a network of priority areas for mammal conservation in the Brazilian Amazon. We developed a spatial conservation scheme that efficiently identifies highly-exposed areas within species current and future distributions. Further, our prioritization includes important areas that increase connection between current and future species distribution, while also considering the uncertainties associated to model projections.

Methods

Species distribution models

We obtained occurrences records for 256 mammal species inhabiting the Amazon. We only included species for which more than 10 independent records were available at the Global Biodiversity Information Facility (GBIF; www.gbif.org), SpeciesLink project (www.splink.cria.org.br); VertNet database (www.vertnet.org), and the Instituto Chico Mendes para Conservação da Biodiversidade (*Chico Mendes Institute for Biodiversity Conservation* – ICMBio; www.icmbio.gov.br). We superimposed species' records onto a grid of 0.083º x 0.083º of latitude/longitude covering the full extent of the Neotropics.

We obtained current bioclimatic variables (1950-2000) derived from monthly temperature and rainfall values from the WorldClim database (www.wordclim.org/current). Then we selected five (mean diurnal range, isothermality, max temperature of warmest month, precipitation of wettest month and precipitation of driest month) out of nineteen variables for modeling species distributions. We selected these variables using factorial analysis with Varimax rotation based on the correlation matrix among variables to avoid collinearity issues (Terrible et al. 2012). We obtained these same climatic variables from future climate models (2050) from the WorldClim database (www.worldclim.org/cmip5_10m) derived from three coupled Atmosphere-Ocean General Circulation Models (AOGCMs; GISS-E2-R, HadGEM2-ES, MIROC5) under a high-emission greenhouse gases scenario (Representative Concentration Pathway 8.5). These future climate models were generated by application of delta downscaling method on original data used by the IPCC's Fifth Assessment Report (AR5; IPCC, 2014a). Both current and future climate variables were resampled to our grid resolution.

We used the Maxent modeling method to build species distribution models. For each species model, we randomly split the presence and pseudo-absence data into two subsets for calibration (75%) e validation (25 % remaining), and repeated this procedure five times, generating five models for each species. We projected each model to current species distributions into the future using the three AOGCMs mentioned above and obtained fifteen projections per species (5 models x 3 AOGCMs; Fig. 1). To convert continuous predictions in binary ones we found a threshold with maximum sensitivity and specificity values in a relative operating characteristic curve (ROC). Finally, we used True Skill Statistic to measure each model performance (TSS, range from -1 to +1; where prediction values less than or equal to zero indicate a performance not better than random; Allouche et al. 2006).

We applied the ensemble-forecasting approach to produce more robust predictions by accounting for uncertainties arising from models (Araújo & New, 2007; Diniz-Filho *et al.*, 2009). The consensus maps for current period and for each future climatic model was done by weighting each model according to their performance measured by TSS values (Allouche *et al.*, 2006). All analysis were done using “biomod2” and “LetsR” packages in the R platform (Thuiller et al., 2009; R Core Team, 2015; Vilela & Villalobos, 2015).

Climate change metrics

No single metric can represent the multiple dimensions of climate change. Hence, we calculated the following climate change metrics, each one containing a complementary information and different implications for conservation (see Garcia *et al.*, 2014): i) Standardized local anomalies (Williams *et al.*, 2007); ii) Climate extremes (Beaumont *et al.*, 2010); iii) Velocity of climate change (Hamann *et al.*, 2015).

All climate change metrics were calculated based on current monthly average temperature (years 1950-2000) and the 17 AOGCMs for the year 2050 (ACCESS1-0, BCC-CSM1-1, CCSM4, CNRM-CM5, GFDL-CM3, GISS-E2-R, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, INMCM4, IPSL-CM5A-LR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR, MRI-CGCM3, NorESM1-M) under a high green gas emission scenario (Representative Concentration Pathway 8.5) used by IPCC’s Fifth Assessment Report. Both current and future temperatures were gathered from the WorldClim database at the resolution of 0.083 º x 0.083 º latitude/longitude (around 9 km at equator line; www.worldclim.org/download).

We focused our calculations of climate change metrics on temperature mainly due to the widely uncertainty arising from future rainfall projections in tropical regions (IPCC, 2013). In order to reduce uncertainty arising from contrasting AOGCMs, we generated ensemble and uncertainty maps for each climate-change metric by calculating the mean and standard deviation from the 17 AOGCMs, respectively.

Local climate change anomalies were calculated using the Standardized Euclidian distance (SED) between current and future temperature conditions weighted by standard deviation of current inter-annual variability (Williams *et al.*, 2007). Standardizing the inter-annual variability allows weighing climate trends that are larger compared to inter-annual variability. High SED scores indicate larger local temperature anomalies.

We assessed the extent to which areas in the Amazon will experience extreme mean annual temperatures compared to current climate conditions. We followed Beaumont *et al.*, (2010) and assumed that a future temperature value projected for a certain locality (a single raster cell) may be considered “extreme” when its exceeded 2 standard deviations (SD) of current variability. To compute climate extremes we calculated the Standardized Manhattan Distance (M) as follow:

$$M = ((21^{st}C\ \mu - 20^{th}C\ \mu) / \sigma\ (20^{th}\ C)$$

Where $21^{st}C\ \mu$ and $20^{th}C\ \mu$ are annual mean temperature for future and current, respectively, and σ is the monthly standard deviation of current period (Beaumont *et al.*, 2010).

We are aware that there are more sophisticated methods to identify climate extremes (i.e. Extreme Value Theory; Katz *et al.*, 2005; IPCC *et al.*, 2012 pp. 116 for a deeper discussion on this topic). Indeed, these methods are more useful when daily temperature data are available.

However, temperatures exceeding 2SD of current ($M > 2$) represents a good approximation for identifying extreme climate events and fits the purpose of the present work, for we are dealing with larger timescales.

Climate change velocity represents the rate (km/year) at which a climate condition is expected to shift along the landscape. Consequently, the velocity index also indicates the speed at which an organism must to move to keep pace with changes in climate (Loarie *et al.*, 2009; IPCC, 2014b). We computed a “forward” climate change velocity, using a distance-based method that represents the shortest distance between a cell in the current and a cell where analogous climate conditions will be found in the future (Hamann *et al.*, 2015). The “analog-based” method searches for cells with future climate conditions analogous of a focal cell using as background the entire region of study. This method, therefore, overcomes some limitations of methods that seek for climate analogous in the 3x3 neighboring cells, for example (Loarie *et al.*, 2009; Carroll *et al.*, 2015).

An important decision when deriving “analog-based” velocity is choosing the threshold that defines what constitute a climate analogous (i.e. width of a climate bin). Given enough precision in measurements, no two cells will have the same values. Smaller thresholds indicate that only values very similar (narrow bins) to those of a focal cell will be chosen.

However, when high precision is request (a very small threshold value), large and small distances start to occur by chance and the resulting map becomes noisy (Carroll *et al.*, 2015). In addition, the number of disappearing or no-analogue climates rapidly increases (see Fig. S1A). Conversely, as the bins widens (larger thresholds) information is lost once the distance to a climate analogous decrease and velocity in some areas becomes zero. We found that a value of ± 0.5 ºC would be a good threshold because it represents a balance between the distance to a climate analogue and the precision (proportion of no analogue climates), making velocity index more robust (see Fig. S1B).

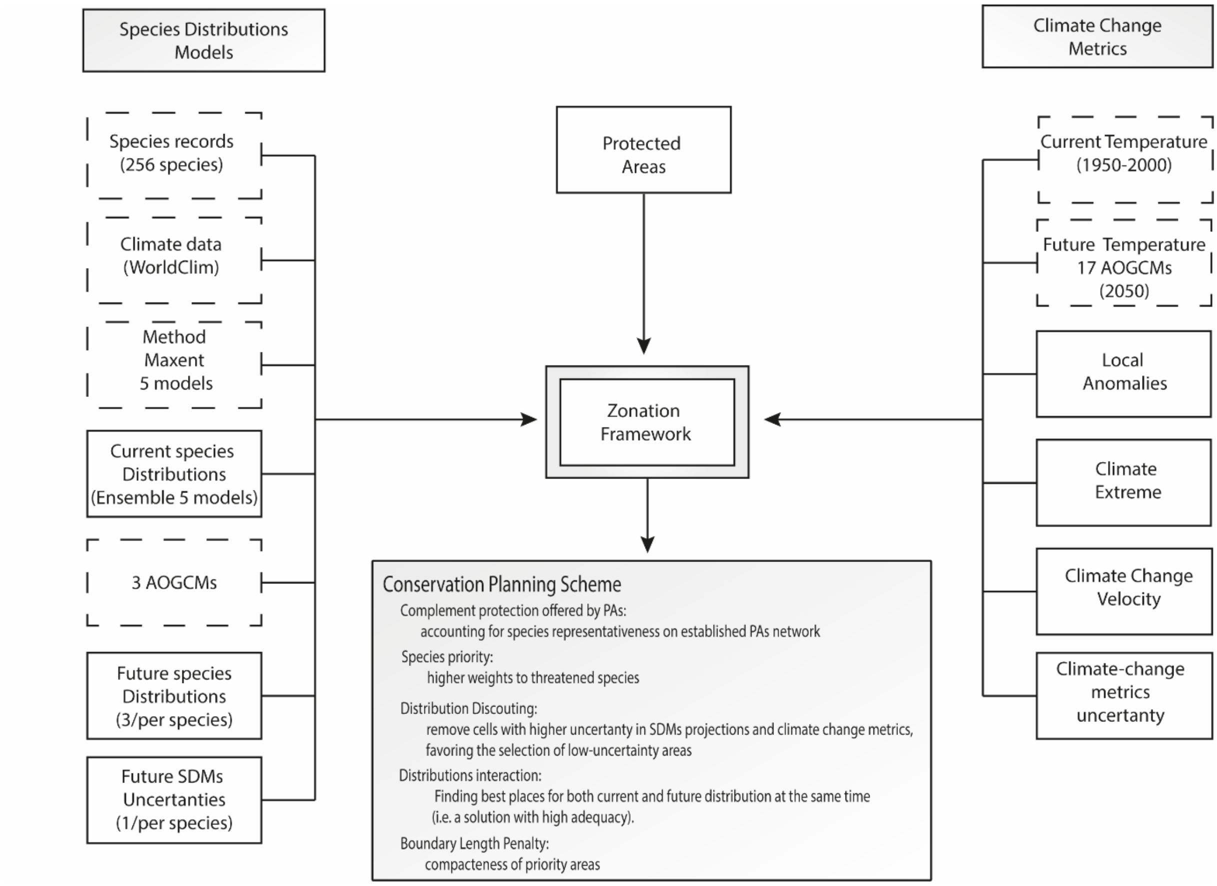

Figure 1. A schematic representation of the methods used in the spatial conservation plan to define high exposed areas within mammal distributions in the Brazilian Amazon. We fitted five ENMs and used these models to predict species future distributions based on three climate models (AOGGMs). We calculated three climate change metrics containing complementary information on climate change. We also quantified uncertainties arising from AOGCMs associated with both future species distribution and climate-change metrics. Finally, we used current and future distribution maps, climate-change maps, uncertainty maps, and current network of protected areas as input to generate the spatial conservation plan. The boxes with dashed line were used as primary data for the study. While boxes with continuous line were used as input in the Zonation software. See text for details.

Spatial prioritization analysis

We used the Zonation algorithm and software (Moilanen *et al.*, 2005) to implement a spatial prioritization procedure to guide conservation efforts in face of climate change. Zonation delivers complementarity-based and nested hierarchical rank of priority sites along the entire studied region (Moilanen *et al.*, 2005). The Zonation method can be divided in two parts. First, its meta-algorithm produces a priority ranking, which is generated by iteratively removing grid cells (i.e. sites) with the least marginal loss, in other words, those cells with smallest conservation contribution relative to the total conservation value of the region. Second, the cell removal procedure defines marginal loss. There are four conceptually different models to define marginal loss in Zonation (Moilanen *et al.*, 2014). Here, we used the core-area cell removal rule, which emphasize the selection of areas of high-quality habitats for the rarest and/or highly weighted features (in our case species and climate change metrics layers). Therefore, even generally poor-feature cells received high conservation value, if those features have small distribution or high weights (Moilanen *et al.*, 2014).

We used the following primary data as input in the spatial prioritization analysis: i) ensemble-based continuous suitability maps of the present and future species' distributions (256 layers for each time period); ii) climate change metrics representing local anomalies, climate extremes and the velocity of climate change (3 layers); iii) species-specific future distribution uncertainty layers arising from models generated with three alternative AOGCMs (256 layers) and; iv) uncertainty layers related to each climate change metric arising from calculation based on seventeen AOGCMs (3 layers). In order to adapt species distribution layers for application in the spatial prioritization analysis we rescaled these layers to the resolution of 0.083º x 0.083º of latitude/longitude (the original resolution of the climate-change metrics layers). That downscaling procedure is supposed to produce prioritization at the regional scale, which is relevant to a landscape planning.

To define priorities for conservation we established different weights for species and climate change metrics. We assigned weights for species according to their conservation status defined by the Brazilian list of threatened species, which in turn is based on IUCN threat categories: non-threatened = 1, vulnerable = 1.25, endangered = 1.5, critically endangered = 2. Following these weights, vulnerable species were considered as 25 % more important than non-threatened species in the prioritization process; endangered species 50 % and critically endangered as being twice more important than non-threatened species (because weights are multiplicative). In addition, since we aimed at acting on areas at higher risk of being impacted by climate change, for each climate-change metric we assigned a weight resulting of the sum of all species' weights divided by three (resulting in a weight of 267.5 for each metric). The specific weights of each feature is an arbitrary choice, although transformation of IUCN treat categories to an ordinal scale has already been used in other spatial planning analysis (Loyola *et al.*, 2008; Lemes & Loyola, 2013).

We also included Federal and State Protected Areas (PAs) already established in the Amazon in the spatial conservation analysis. Polygons of PA limits were gathered from online databases available at the websites of the Instituto Chico Mendes para Conservação da Biodiversidade (the *Chico Mendes Institute for Biodiversity Conservation;* www.icmbio.gov.br) and the Ministério do Meio Ambiente (the *Brazilian Ministry of the* Environment; www.mma.gov.br). According to these data, *ca.* 23% of the Brazilian Amazon extent is currently covered by PAs. Considering PAs in our analysis means that our spatial conservation scheme was built upon a complementarity-based approach indicating priority areas in which conservation actions should take place to complement the species' protection level already achieved in the region. Finally, Amazon Indigenous Lands are protected by the Brazilian legislation and cover about 22% of the Amazon territory. Therefore, to evaluate the overlapping pattern of priority areas resulting from our analysis, we superimposed our priority map to the Amazon Indigenous Lands. In doing so, we can evaluated the additional percentage of species distribution represented in Indigenous Lands that complement the representation level already achieved in PAs.

We sought to identify more robust spatial solutions by including uncertainties from alternative AOGCMs in our spatial analysis. We used the info-gap models in Zonation that penalizes areas where predictions of species distributions and changes in the climate are more contrasting due to higher uncertainties arising from three AOGCMs. These high-uncertainty areas are then removed of the analysis by a procedure of "distribution discounting". This procedure depends on an alfa parameter called "horizon of uncertainty" in info-gap information theory that is unknown and has no correct value (Moilanen & Wintle, 2006). Therefore, there is a trade-off on the choice of alfa values. High alfa value diminishes error surface, but increasing values could discounting all species distribution, resulting in a total loss of biological information. On the other hand, low alfa values could be insufficient to account for uncertainties, resulting a high-uncertainty solution. Here, we chose to use an alfa value of 0.1 that diminished error surface while avoiding the loss of biological information.

We also used the Zonation distribution interactions component to produce more resilient solutions to climate change that account for species-specific connectivity requirements. This component sought to identify areas important to maintain the connectivity between the current and future species distributions. Thus, overlapping areas between distributions receive high conservation values. Further, connectivity is supposed to be highest on the edges of spatially segregated distributions (Rayfield *et al.*, 2009; Carroll *et al.*, 2010). In order to account for connectivity, both distributions are firstly transformed on a connectivity layer by using a negative exponential function which converts the distribution maps into a connectivity layer via a species-specific dispersal kernel parameter (beta, Moilanen *et al.*, 2014 for details). This parameter depicts species dispersal capacity and could be estimated using species home-range, (i.e., Faleiro *et al.*, 2013). However, the scarcity of biological data for the majority of mammals of the Amazon prevented us from estimating their dispersal capacity. Here, we assumed conservative estimate of species potential dispersal of 9 kilometers over the entire 50 years (2000-2050). In addition to distribution interactions, we used the boundary length penalty (BLP) in Zonation which produces a more compact set of priority areas. These two connectivity components of Zonation aggregate priority areas and reduce their numbers, which may be an advantage for implantation and management of conservation actions (Moilanen *et al.*, 2014).

Results

Overall, species distribution models had high TSS values (TSS ± SD = 0.65 ± 0.16) indicating good models fit, and for most species (60%) these values were higher than 0.7. Combined model projections indicated high species richness in the north of the Amazon, and low species richness in the south portions of the biome, both for current time and for year 2050 (Fig. 2, A-B). Projections for year 2050 showed that species richness pattern will remain approximately constant - although some highly-elevated regions mainly in the south would gain species -, whereas all models forecasted a reduction in species richness along almost all regions of the Amazon (Fig. 2B). In total, 49% species are predicted to lose an average of 26% of their climatically suitable areas. Variation among predicted future species distributions arising from alternative AOGCMs was low, and mainly concentrated on the Amazon river basin. (Fig. S1A).

Climate change metrics depicted complementary information about climate-related exposure. Local anomalies and climate extreme were more correlated each other than with were with velocity (Fig. 2, C-E). The northwest and the northeast are the portions of the Amazon expected to experience the highest local anomalies and climate extremes that may exceed more than 5 σ of the current temperature variability (Fig. 2, C-D). As expected, since climate velocity is a metric that accounts for the heterogeneity of the landscape, high-elevation regions in the Amazon will likely experience high rates of temperature shift (Fig. 2E). This means that species inhabiting these areas should disperse at a rate up to 0.5 km yr^{-1} (around 50 m per decade) until to 2050 to keep pace with their suitable temperature.

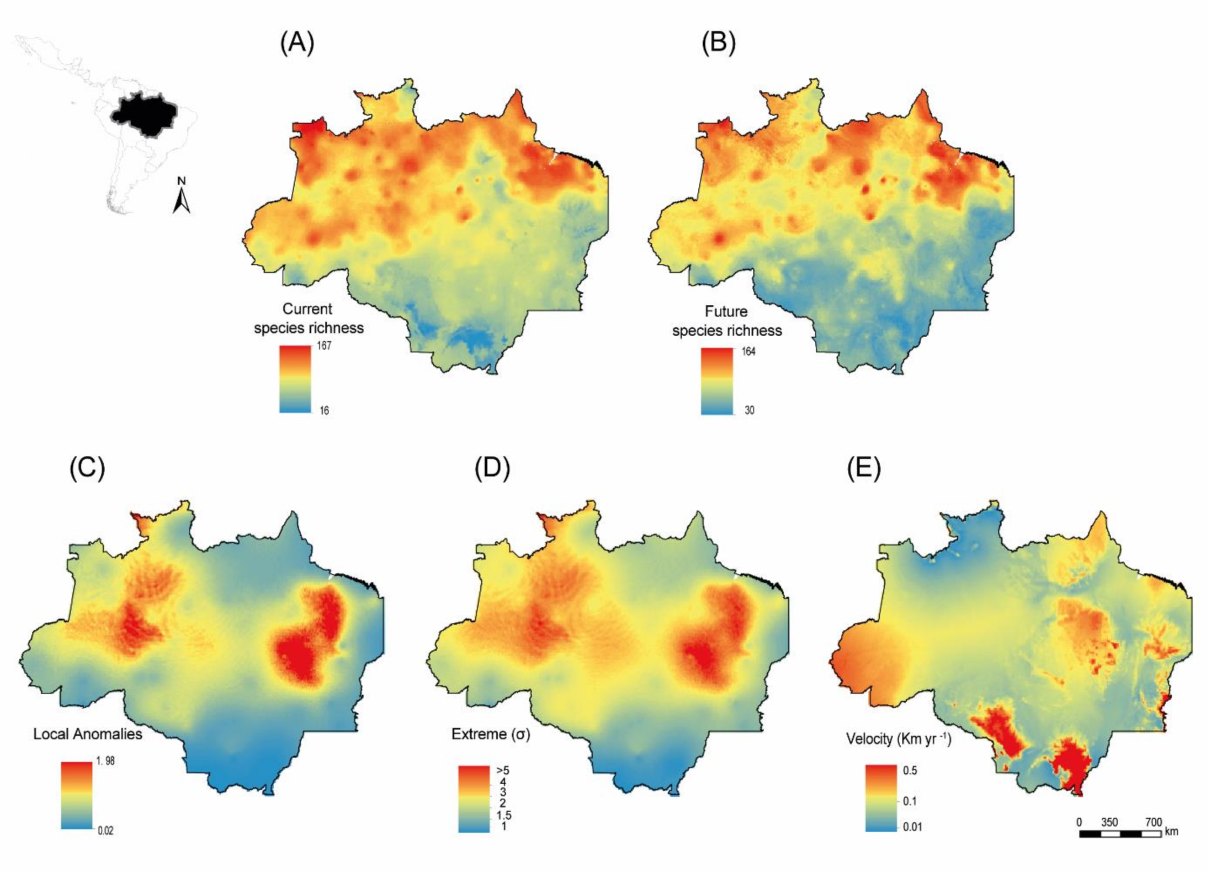

Figure 2. Pattern of species richness for mammals in Brazilian Amazon and projected climate change according to three climate change metrics used in the study. (A-B) Patterns of mammal species richness projected for current (A) and future (year 2050, B) forecasted by species distributions models. (C-E) Maps of projected changes in mean annual temperature between the current and future (year 2050) ensemble of climate models according to three climate-change metrics: standard local anomalies (C), climate extreme (D) and climate change velocity (E). See text for details.

The resulting map of the spatial prioritization showed a hierarchical nested rank of priority areas for guiding conservation efforts (Fig. 3). It is hierarchical because it prioritizes the most important cells containing the highest conservation value which are nested, i.e. the top 5% of priority areas were nested in the top 10%, which in turn is nested in top 25% of priorities. As we used a complementarity-based approach, most priorities areas were situated on the neighborhood of the established PAs and mainly concentrated on northwest, northeast and south of the Amazon (Fig. 3). In addition, some of the high-priority areas are located in the Amazon "Arch of Deforestation" - a high fragmented zone of the Amazon and a frontier for agribusiness (Pacheco, 2009). That overlay probably implies great conservation challenges and possibly conflicts with socio-economics activities in these regions.

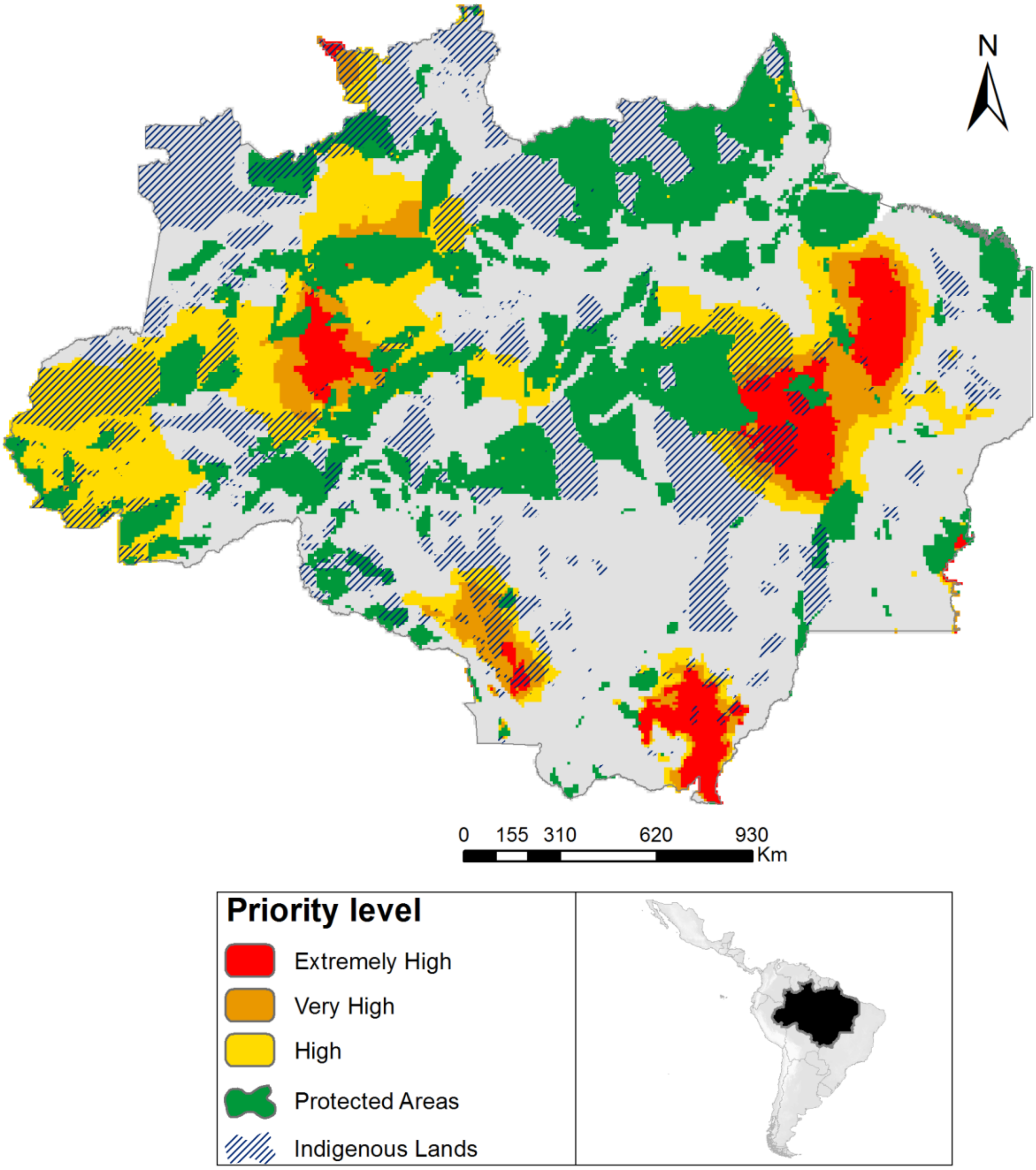

Figure 3 Spatial distribution of priority areas to mitigate the impacts of climate change on mammal distribution of the Brazilian Amazon. Areas are classified according to the degree of priority for guiding conservation efforts to mitigate impacts of climate change on species. The top Extremely High (5%) priority areas are nested in the top Very High (10%), which in turn is nested in top High (25%) priority areas.

We found that, on average, 25-24 % of the modeled current and future mammal distribution is already represented in the established PAs network, respectively. These values represent a high-level of species representation in PAs. These representation levels were well fitted between species according to their IUCN treat category (Fig. 4) and between mammal orders (Fig. 4), although two species (Chiropera: *Nyctinomops macrotis;* Perissodactyla*: Tapirus terrestris*) had a quite lower representation level in PAs (see Table S1). Further, we also evaluated the percentage of the set of priority areas overlapping the Amazon's Indigenous Lands. We overlapped our priority map to the Amazon's Indigenous Lands and found that 26% of priority areas are covered by Indigenous Lands and these overlapped areas corresponding to an additional of 6-7% of mammals current and future species range representation, respectively. Therefore, a total of 31% of current and future species distributions is represented by PAs and Indigenous Lands.

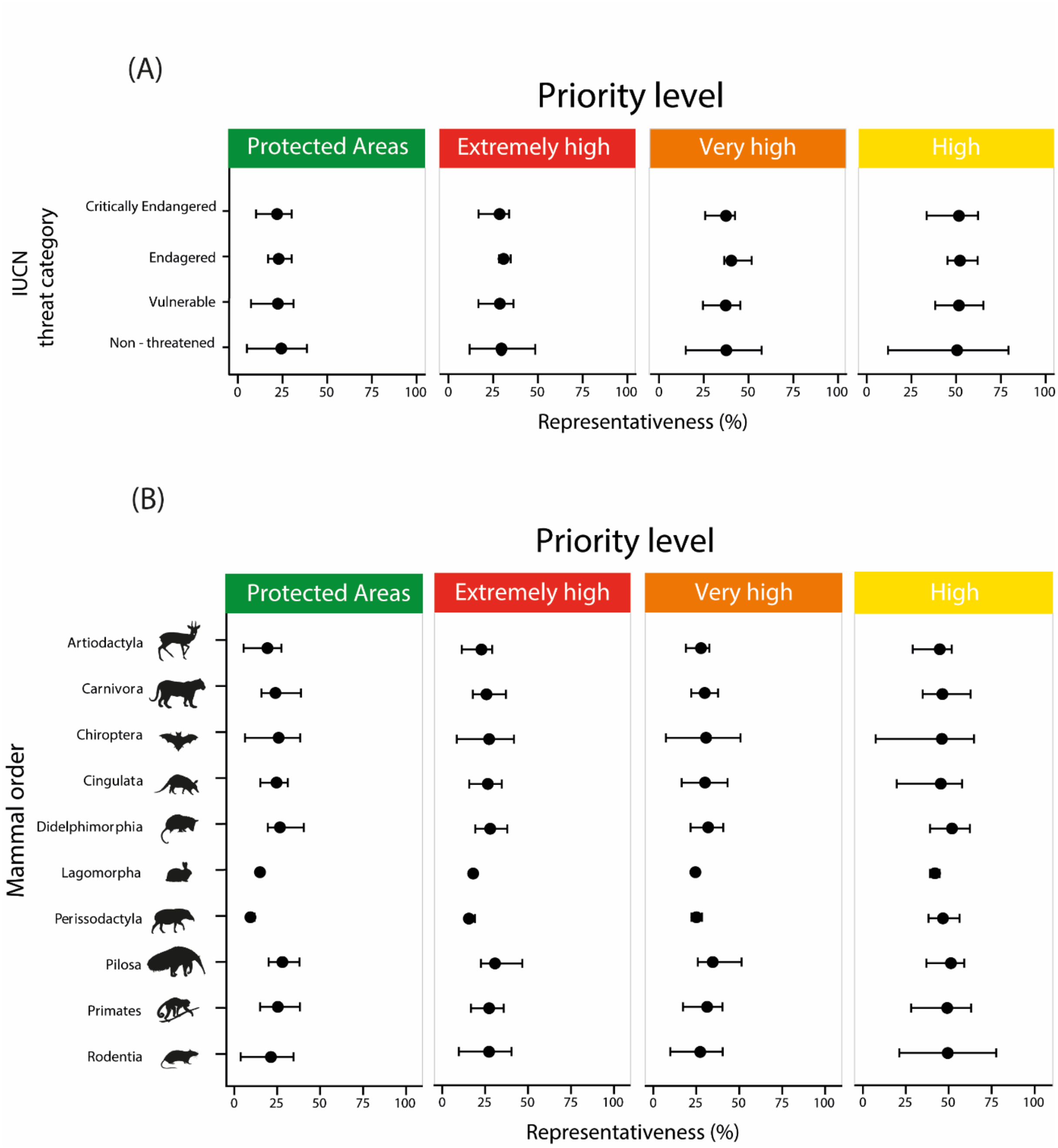

Figure 4 Percentage of current and future (year 2050) species distributions represented in priority areas for mitigating the impact of climate change on mammal in the Brazilian Amazon. Representation level are showed according to species' IUCN threat category (A); and taxonomic order (B) in each set of priority areas where conservation efforts should be targeted in order to mitigate the impacts of climate change as well as in current established protected areas.

Discussion

Successful adaptation of natural systems to climate change will depend on the ability to identify areas at higher risk. Here, by combining species distribution models for a large number of species and simple metrics of climate change, we were able to identify highly-exposed areas towards which conservation efforts should be targeted in order to mitigate the impacts of climate change on the biodiversity found in the Brazilian Amazon.

The Amazon network of PAs has been established by reasons other than climate change (e.g. to avoid deforestation, Veríssimo *et al.*, 2011); yet we found that, on average, a quarter of current and future mammal distributions are already represented in this network. That imply that the large number of PAs, covering around 23% of the Brazilian Amazon, might compensate the fact that several low-effective areas for biodiversity conservation are part of the network. While one should not overcome poor quality with greater quantity when it comes to biodiversity protection (Pressey *et al.*, 2015), it seems that this situation establishes the current *status quo* of the Amazon network of PAs in Brazil (at least for mammals).

Different metrics of climate change hold complementary information about the challenges and opportunities for species (Garcia *et al.*, 2014). Species exposed to local temperature anomalies exceeding current inter-annual variability are more likely to experience population declines (IPCC, 2014b). Conversely, climate extremes are highly pervasive and, depending on their intensity and frequency, they can drastically reduce population size (i.e. “population die-offs”; Ameca y Juárez *et al.*, 2012). Further, species occupying extensive flat areas or confined to isolated habitats as mountain tops might be unable to move fast enough and over longer distances to match changes in climate, resulting on range contractions (Garcia *et al.*, 2014).

Given that these three metrics represent different dimension of climate change taking them in combination may be a reasonable choice about to where and which adaptation actions will be more appropriated and consequently more effective.

From an applied perspective, which conservation actions might be more effective to ameliorate the impacts of climate change on biodiversity in projected high-exposed areas? The answer to this question depends on a set of factors including, for instance, species vulnerability and regional level of landscape fragmentation. Conservation planning is fundamentally an iterative process. A spatial conservation plan is paramount to develop a dynamic conservation strategy under climate change. This strategy, however, constitutes only one important source of information that should be weighted and complemented with other non-climatic threats and socio-economic concerns in order to develop a more comprehensive conservation planning (Knight *et al.*, 2006).

All particularities of tropical regions might make conventional conservations actions (such as establishing protected areas or setting aside climate refugia in low-impacted areas) non-effective in face of a high climate change. One should ask: what would have happened if there had been no conservation actions in highly-impacted areas? Basically, there are two answers to that question: (1) we assume some loss and decide not to manage species perceived at most risk, or (2) we decide to enhance conservation actions through expanding the protected area network, increasing landscape resilience, mitigating other threats, implementing some kind of *ex-situ* conservation, or even more contentious strategies as species assisted translocation (see a review in Heller & Zavaleta, 2009). The second answer to the question is arguably the only option that can make a difference for conservation. Success of conservation actions depends on their ability to reduce impacts as well as to increase species capacity to adapt to climate change, even when risks cannot be completely eliminated (IPCC, 2014a).

Certainly, we do not advocate that all conservation strategies for protecting biodiversity under climate change should be directed to highly-exposed areas. Given that financial resources addressed to conservation are scarce, a trade-off between investing finite conservation funds on low *vs* highly-impacted areas exist and should be considered in conservation planning. Protecting species in likely low-impacted areas is fundamental to ensure species long-term persistence. However, when a level of species representation and habitat protection has been already achieved or when species are endemic to a highly-exposed area, conservation actions may take place on highly-impacted areas. Only in highly-exposed areas adaptations actions could make a difference to species and population in which, without any adaptation action would be committed to be locally extinct.

To sum up, we developed a spatial conservation plan that efficiently identifies highly-exposed areas within species current and future distribution and within areas important to facilitate species dispersal between these suitable areas within these distributions. Incorporating uncertainties arising from alternative climate projections in conservation planning strengthens our approach, which is therefore more robust to uncertainties. We highlighted that relatively high-level of species current and future distribution is already represented in PAs and that Amazon Indigenous Lands also has a crucial role in buffer the effects of climate change on species. We hope that our spatial conservation plan may help planners and stakeholders to guide conservation efforts aiming at mitigate impacts and avert biodiversity loss due to climate change in the Brazilian Amazon.

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Supplementary Material

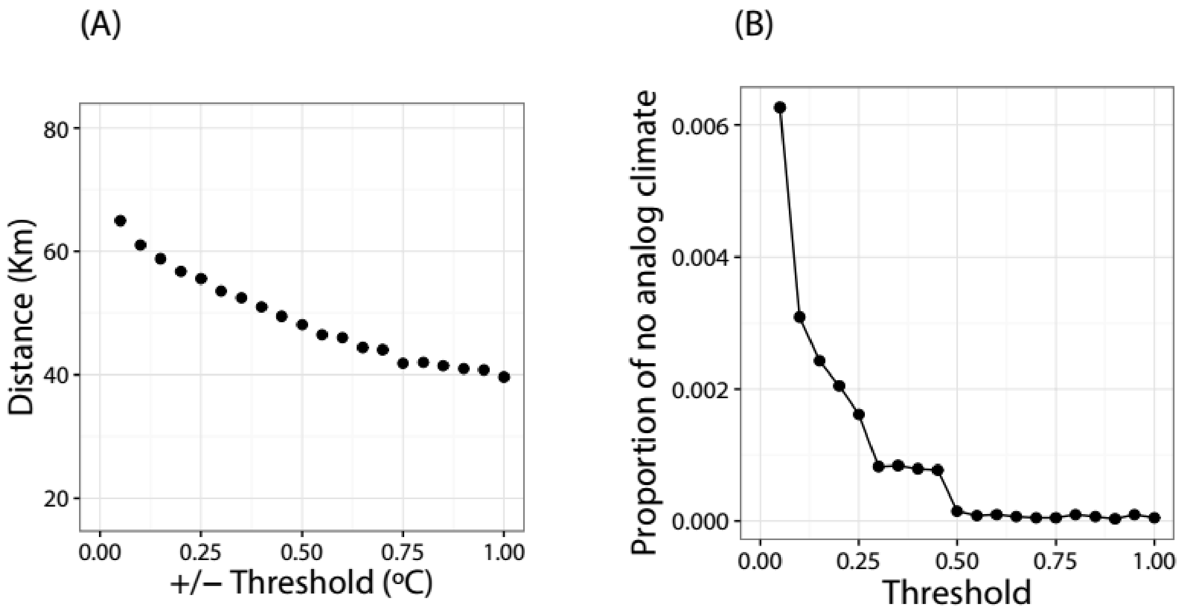

Figure S1. Sensitivity analysis of climate change velocity to the threshold values used to define a climate-analog. Sensitivity is defined in terms of distance to a cell with climatic analogous temperature conditions (A) and number of disappearing or no-analog climate (B).

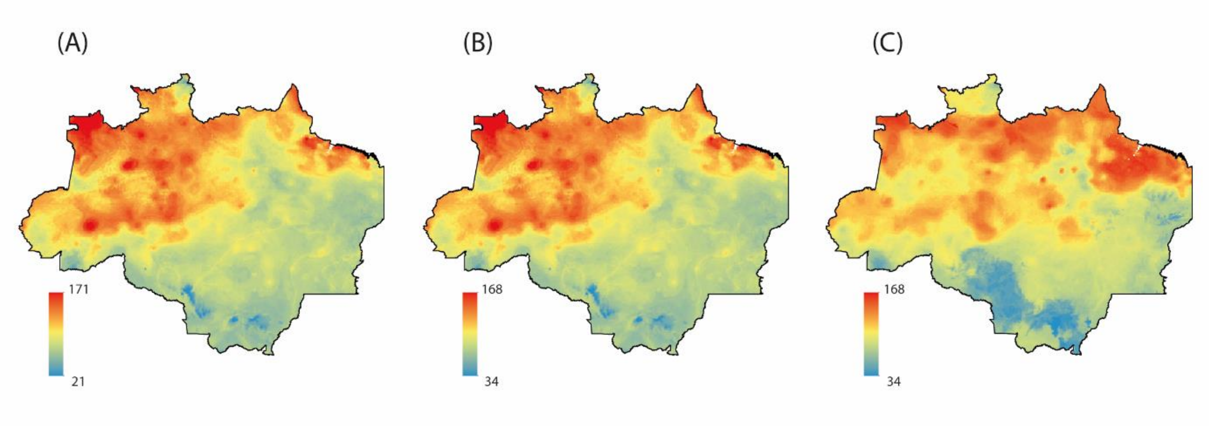

Figure S2. Spatial pattern of uncertainties arising from mammal future species distribution models generated from three Atmosphere-Ocean General Circulation Models (AOGCMs). (A) MIROC; (B) HadGEM2-ES and; (C) GISS-E2-R. Colors display climatic suitability values for 256 species in the future (2050) based on high-emission greenhouse gases scenario (Representative Concentration Pathway 8.5).

Table S1. Species-specific percentage of current and future (year 2050) species distributions represented in priority areas for mitigating the impact of climate change on mammal in the Brazilian Amazon.

		Representativeness (% species range)							
Species	**Mammal Order**	**Protected Areas (PAs)**		**PAs + 5 %**		**PAs + 10 %**		**PAs + 25 %**	
		Current	**Future**	**Current**	**Future**	**Current**	**Future**	**Current**	**Future**
Mazama americana	Artiodactyla	0.14	0.06	0.22	0.15	0.29	0.23	0.55	0.33
Mazama gouazoubira	Artiodactyla	0.24	0.23	0.29	0.27	0.33	0.32	0.50	0.50
Tayassu pecari	Artiodactyla	0.26	0.25	0.30	0.29	0.35	0.34	0.51	0.50
Atelocynus microtis	Carnivora	0.25	0.22	0.30	0.27	0.33	0.32	0.55	0.47
Bassaricyon alleni	Carnivora	0.25	0.24	0.30	0.28	0.36	0.33	0.54	0.48
Eira barbara	Carnivora	0.23	0.23	0.28	0.28	0.33	0.33	0.49	0.49
Galictis vittata	Carnivora	0.23	0.24	0.26	0.28	0.29	0.33	0.47	0.60
Histiotus velatus	Carnivora	0.34	0.37	0.37	0.39	0.40	0.41	0.46	0.51
Leopardus pardalis	Carnivora	0.25	0.24	0.30	0.29	0.36	0.34	0.51	0.50
Leopardus tigrinus	Carnivora	0.22	0.19	0.29	0.23	0.38	0.27	0.65	0.45
Leopardus wiedii	Carnivora	0.22	0.22	0.28	0.27	0.33	0.31	0.46	0.41
Lontra longicaudis	Carnivora	0.21	0.21	0.26	0.24	0.32	0.29	0.51	0.43
Nasua nasua	Carnivora	0.26	0.26	0.30	0.30	0.35	0.35	0.54	0.53
Panthera onca	Carnivora	0.17	0.17	0.23	0.21	0.29	0.26	0.40	0.49
Potos flavus	Carnivora	0.24	0.22	0.29	0.27	0.35	0.30	0.50	0.39
Pteronotus personatus	Carnivora	0.21	0.23	0.26	0.28	0.31	0.33	0.40	0.45
Pteronura brasiliensis	Carnivora	0.27	0.24	0.31	0.29	0.35	0.34	0.52	0.49
Herpailurus yagouaroundi	Carnivora	0.25	0.22	0.30	0.27	0.35	0.32	0.57	0.47
Speothos venaticus	Carnivora	0.21	0.21	0.26	0.26	0.31	0.32	0.47	0.50
Ametrida centurio	Chiroptera	0.34	0.28	0.36	0.32	0.38	0.36	0.51	0.53
Anoura caudifer	Chiroptera	0.20	0.24	0.24	0.25	0.29	0.27	0.56	0.49
Anoura geoffroyi	Chiroptera	0.17	0.13	0.26	0.19	0.36	0.29	0.53	0.39
Artibeus anderseni	Chiroptera	0.24	0.28	0.28	0.35	0.30	0.39	0.37	0.53
Artibeus cinereus	Chiroptera	0.27	0.27	0.31	0.32	0.36	0.35	0.53	0.48
Artibeus concolor	Chiroptera	0.36	0.24	0.38	0.28	0.41	0.33	0.52	0.49
Artibeus glaucus	Chiroptera	0.31	0.28	0.33	0.32	0.37	0.37	0.52	0.56
Artibeus gnomus	Chiroptera	0.29	0.23	0.32	0.28	0.37	0.32	0.52	0.47
Artibeus lituratus	Chiroptera	0.26	0.31	0.30	0.39	0.37	0.47	0.59	0.58

Artibeus obscurus	Chiroptera	0.32	0.25	0.33	0.29	0.37	0.33	0.52	0.46
Artibeus planirostris	Chiroptera	0.30	0.26	0.32	0.29	0.36	0.33	0.50	0.47
Carollia brevicauda	Chiroptera	0.28	0.24	0.31	0.29	0.33	0.33	0.44	0.41
Carollia perspicillata	Chiroptera	0.23	0.22	0.29	0.27	0.35	0.32	0.55	0.41
Centronycteris maximiliani	Chiroptera	0.29	0.30	0.33	0.33	0.38	0.37	0.55	0.55
Chiroderma trinitatum	Chiroptera	0.27	0.27	0.31	0.31	0.36	0.37	0.55	0.53
Chiroderma villosum	Chiroptera	0.23	0.24	0.27	0.29	0.32	0.34	0.45	0.49
Choeroniscus godmani	Chiroptera	0.34	0.34	0.36	0.37	0.38	0.42	0.47	0.56
Choeroniscus minor	Chiroptera	0.29	0.29	0.31	0.32	0.35	0.36	0.55	0.52
Chrotopterus auritus	Chiroptera	0.27	0.26	0.30	0.30	0.35	0.34	0.51	0.51
Cormura brevirostris	Chiroptera	0.28	0.24	0.34	0.28	0.39	0.32	0.54	0.49
Cynomops abrasus	Chiroptera	0.25	0.25	0.30	0.30	0.35	0.35	0.52	0.53
Cynomops paranus	Chiroptera	0.29	0.29	0.33	0.33	0.39	0.38	0.55	0.55
Cynomops planirostris	Chiroptera	0.28	0.30	0.34	0.35	0.38	0.40	0.49	0.55
Desmodus rotundus	Chiroptera	0.23	0.20	0.28	0.25	0.33	0.29	0.47	0.38
Diaemus youngi	Chiroptera	0.29	0.25	0.32	0.29	0.35	0.33	0.46	0.49
Diclidurus albus	Chiroptera	0.21	0.24	0.22	0.28	0.24	0.33	0.31	0.50
Diphylla ecaudata	Chiroptera	0.25	0.26	0.30	0.31	0.34	0.35	0.45	0.46
Eptesicus andinus	Chiroptera	0.25	0.26	0.31	0.31	0.37	0.36	0.55	0.50
Eptesicus brasiliensis	Chiroptera	0.27	0.28	0.32	0.32	0.38	0.37	0.56	0.55
Eptesicus chiriquinus	Chiroptera	0.33	0.29	0.35	0.31	0.39	0.35	0.56	0.57
Eptesicus diminutus	Chiroptera	0.13	0.17	0.14	0.20	0.14	0.23	0.15	0.30
Eptesicus furinalis	Chiroptera	0.25	0.24	0.30	0.28	0.35	0.32	0.45	0.43
Eumops auripendulus	Chiroptera	0.25	0.24	0.30	0.29	0.35	0.35	0.54	0.54
Eumops bonariensis	Chiroptera	0.30	0.26	0.39	0.30	0.46	0.34	0.59	0.48
Eumops dabbenei	Chiroptera	0.24	0.24	0.28	0.28	0.32	0.33	0.46	0.47
Eumops glaucinus	Chiroptera	0.21	0.23	0.24	0.27	0.26	0.32	0.34	0.44
Eumops hansae	Chiroptera	0.24	0.25	0.28	0.30	0.32	0.35	0.37	0.45
Eumops perotis	Chiroptera	0.22	0.23	0.26	0.28	0.29	0.33	0.38	0.44
Eumops trumbulli	Chiroptera	0.27	0.26	0.32	0.31	0.37	0.36	0.55	0.53
Euryoryzomys nitidus	Chiroptera	0.13	0.16	0.18	0.24	0.24	0.32	0.37	0.51
Furipterus horrens	Chiroptera	0.21	0.23	0.25	0.28	0.30	0.32	0.40	0.44
Glossophaga commissarisi	Chiroptera	0.17	0.19	0.23	0.26	0.28	0.31	0.35	0.40
Glossophaga longirostris	Chiroptera	0.20	0.25	0.22	0.28	0.25	0.32	0.39	0.48
Glossophaga soricina	Chiroptera	0.25	0.24	0.29	0.29	0.35	0.34	0.54	0.51
Glyphonycteris daviesi	Chiroptera	0.29	0.33	0.33	0.36	0.38	0.40	0.56	0.55
Glyphonycteris sylvestris	Chiroptera	0.23	0.23	0.28	0.28	0.32	0.33	0.46	0.47
Holochilus sciureus	Chiroptera	0.24	0.23	0.29	0.27	0.34	0.32	0.61	0.61

Lasiurus ega	Chiroptera	0.21	0.23	0.24	0.28	0.27	0.33	0.39	0.47
Lionycteris spurrelli	Chiroptera	0.29	0.24	0.33	0.28	0.37	0.32	0.57	0.44
Lonchophylla mordax	Chiroptera	0.24	0.34	0.26	0.43	0.31	0.53	0.49	0.65
Lonchophylla thomasi	Chiroptera	0.28	0.28	0.33	0.32	0.38	0.38	0.58	0.60
Lonchorhina aurita	Chiroptera	0.25	0.25	0.29	0.30	0.34	0.35	0.50	0.51
Lophostoma brasiliense	Chiroptera	0.26	0.27	0.29	0.31	0.32	0.36	0.47	0.56
Lophostoma carrikeri	Chiroptera	0.28	0.28	0.33	0.32	0.38	0.37	0.55	0.54
Lophostoma silvicolum	Chiroptera	0.28	0.27	0.32	0.31	0.37	0.37	0.53	0.54
Macrophyllum macrophyllum	Chiroptera	0.29	0.25	0.33	0.30	0.38	0.34	0.52	0.47
Mesophylla macconnelli	Chiroptera	0.27	0.27	0.31	0.29	0.35	0.34	0.56	0.57
Micronycteris hirsuta	Chiroptera	0.30	0.25	0.31	0.30	0.33	0.35	0.59	0.52
Micronycteris megalotis	Chiroptera	0.24	0.23	0.29	0.28	0.35	0.33	0.50	0.47
Micronycteris microtis	Chiroptera	0.24	0.24	0.27	0.29	0.33	0.33	0.49	0.46
Micronycteris minuta	Chiroptera	0.28	0.27	0.32	0.30	0.37	0.35	0.54	0.58
Micronycteris schmidtorum	Chiroptera	0.22	0.23	0.27	0.28	0.33	0.33	0.52	0.42
Mimon bennettii	Chiroptera	0.22	0.24	0.25	0.29	0.28	0.34	0.33	0.48
Mimon crenulatum	Chiroptera	0.31	0.25	0.33	0.29	0.36	0.33	0.54	0.49
Molossops temminckii	Chiroptera	0.27	0.26	0.29	0.30	0.32	0.35	0.44	0.55
Molossus coibensis	Chiroptera	0.21	0.20	0.26	0.27	0.32	0.34	0.49	0.48
Molossus currentium	Chiroptera	0.24	0.24	0.30	0.29	0.36	0.36	0.55	0.56
Molossus molossus	Chiroptera	0.27	0.28	0.28	0.30	0.30	0.34	0.48	0.56
Molossus rufus	Chiroptera	0.26	0.26	0.28	0.30	0.30	0.34	0.36	0.45
Myotis albescens	Chiroptera	0.25	0.25	0.28	0.29	0.32	0.33	0.45	0.50
Myotis nigricans	Chiroptera	0.24	0.25	0.29	0.30	0.34	0.35	0.49	0.50
Myotis riparius	Chiroptera	0.27	0.27	0.31	0.31	0.37	0.36	0.55	0.56
Myotis simus	Chiroptera	0.26	0.23	0.29	0.28	0.34	0.33	0.55	0.49
Noctilio albiventris	Chiroptera	0.27	0.26	0.30	0.29	0.34	0.34	0.51	0.55
Noctilio leporinus	Chiroptera	0.23	0.23	0.27	0.28	0.31	0.33	0.44	0.46
Nyctinomops laticaudatus	Chiroptera	0.26	0.24	0.31	0.29	0.35	0.33	0.47	0.43
Nyctinomops macrotis	Chiroptera	0.08	0.21	0.20	0.26	0.32	0.31	0.44	0.40
Peropteryx kappleri	Chiroptera	0.35	0.25	0.35	0.29	0.36	0.33	0.43	0.45
Peropteryx macrotis	Chiroptera	0.28	0.24	0.30	0.28	0.32	0.32	0.35	0.48
Peropteryx trinitatis	Chiroptera	0.28	0.25	0.32	0.29	0.36	0.33	0.47	0.48
Phylloderma stenops	Chiroptera	0.33	0.24	0.37	0.28	0.41	0.33	0.51	0.43
Phyllostomus discolor	Chiroptera	0.26	0.25	0.31	0.30	0.36	0.35	0.49	0.47
Phyllostomus elongatus	Chiroptera	0.29	0.27	0.32	0.30	0.36	0.35	0.54	0.54
Phyllostomus hastatus	Chiroptera	0.27	0.26	0.31	0.31	0.36	0.35	0.54	0.51

Phyllostomus latifolius	Chiroptera	0.27	0.28	0.33	0.33	0.38	0.38	0.49	0.50
Platyrrhinus aurarius	Chiroptera	0.26	0.24	0.30	0.26	0.35	0.31	0.59	0.59
Platyrrhinus brachycephalus	Chiroptera	0.22	0.23	0.26	0.29	0.32	0.34	0.63	0.50
Platyrrhinus infuscus	Chiroptera	0.22	0.17	0.23	0.20	0.25	0.25	0.57	0.59
Platyrrhinus lineatus	Chiroptera	0.20	0.24	0.21	0.28	0.22	0.31	0.43	0.51
Promops centralis	Chiroptera	0.23	0.26	0.26	0.29	0.30	0.33	0.42	0.48
Promops nasutus	Chiroptera	0.19	0.22	0.21	0.27	0.23	0.32	0.34	0.43
Pteronotus gymnonotus	Chiroptera	0.26	0.27	0.33	0.34	0.40	0.41	0.52	0.51
Rhogeessa io	Chiroptera	0.25	0.23	0.32	0.32	0.39	0.41	0.58	0.54
Rhynchonycteris naso	Chiroptera	0.30	0.26	0.33	0.30	0.37	0.35	0.54	0.50
Saccopteryx bilineata	Chiroptera	0.27	0.27	0.30	0.30	0.34	0.34	0.48	0.50
Saccopteryx canescens	Chiroptera	0.29	0.24	0.30	0.28	0.33	0.33	0.38	0.48
Saccopteryx leptura	Chiroptera	0.27	0.23	0.30	0.28	0.35	0.32	0.49	0.44
Sphaeronycteris toxophyllum	Chiroptera	0.23	0.23	0.31	0.27	0.39	0.32	0.51	0.46
Sturnira lilium	Chiroptera	0.25	0.24	0.30	0.28	0.35	0.33	0.52	0.44
Sturnira magna	Chiroptera	0.21	0.21	0.25	0.25	0.30	0.29	0.49	0.43
Sturnira tildae	Chiroptera	0.29	0.31	0.33	0.33	0.37	0.37	0.54	0.53
Thyroptera discifera	Chiroptera	0.27	0.27	0.31	0.31	0.36	0.36	0.50	0.51
Thyroptera tricolor	Chiroptera	0.26	0.23	0.26	0.27	0.26	0.29	0.33	0.41
Tonatia bidens	Chiroptera	0.31	0.26	0.36	0.28	0.42	0.33	0.62	0.62
Tonatia saurophila	Chiroptera	0.28	0.35	0.32	0.37	0.37	0.40	0.47	0.53
Trachops cirrhosus	Chiroptera	0.29	0.27	0.32	0.31	0.37	0.36	0.54	0.50
Trinycteris nicefori	Chiroptera	0.29	0.28	0.33	0.31	0.38	0.36	0.54	0.54
Cabassous unicinctus	Cingulata	0.29	0.27	0.32	0.30	0.35	0.35	0.49	0.51
Dasypus kappleri	Cingulata	0.27	0.26	0.31	0.29	0.37	0.34	0.59	0.59
Euphractus sexcinctus	Cingulata	0.17	0.22	0.20	0.37	0.22	0.46	0.25	0.59
Caluromys lanatus	Didelphimorphia	0.26	0.26	0.31	0.30	0.36	0.35	0.58	0.60
Caluromys philander	Didelphimorphia	0.32	0.26	0.37	0.31	0.43	0.36	0.65	0.50
Caluromysiops irrupta	Didelphimorphia	0.26	0.24	0.29	0.26	0.34	0.30	0.57	0.56
Chironectes minimus	Didelphimorphia	0.26	0.25	0.30	0.29	0.35	0.34	0.53	0.53
Didelphis imperfecta	Didelphimorphia	0.26	0.22	0.32	0.28	0.38	0.36	0.62	0.61
Didelphis marsupialis	Didelphimorphia	0.24	0.26	0.29	0.31	0.34	0.35	0.49	0.51
Marmosa murina	Didelphimorphia	0.26	0.27	0.30	0.31	0.35	0.36	0.51	0.53
Marmosops neblina	Didelphimorphia	0.23	0.23	0.29	0.28	0.36	0.35	0.56	0.55
Marmosops noctivagus	Didelphimorphia	0.23	0.20	0.25	0.23	0.29	0.28	0.62	0.63
Marmosops parvidens	Didelphimorphia	0.29	0.32	0.33	0.36	0.38	0.44	0.60	0.60
Marmosops pinheiroi	Didelphimorphia	0.40	0.33	0.40	0.35	0.40	0.38	0.46	0.52

Metachirus nudicaudatus	Didelphimorphia	0.26	0.24	0.31	0.28	0.37	0.33	0.58	0.45
Marmosa demerarae	Didelphimorphia	0.27	0.24	0.30	0.28	0.35	0.33	0.55	0.51
Marmosa regina	Didelphimorphia	0.25	0.23	0.27	0.25	0.31	0.29	0.62	0.62
Monodelphis brevicaudata	Didelphimorphia	0.29	0.26	0.32	0.30	0.35	0.34	0.55	0.51
Monodelphis glirina	Didelphimorphia	0.25	0.25	0.29	0.29	0.34	0.34	0.50	0.50
Philander andersoni	Didelphimorphia	0.27	0.28	0.31	0.33	0.37	0.37	0.53	0.50
Philander opossum	Didelphimorphia	0.29	0.23	0.32	0.28	0.36	0.32	0.49	0.43
Sylvilagus brasiliensis	Lagomorpha	0.17	0.15	0.22	0.21	0.29	0.27	0.48	0.43
Tapirus terrestris	Perissodactyla	0.12	0.09	0.22	0.17	0.32	0.28	0.59	0.42
Bradypus tridactylus	Pilosa	0.25	0.24	0.30	0.29	0.35	0.34	0.52	0.51
Bradypus variegatus	Pilosa	0.29	0.31	0.33	0.35	0.37	0.40	0.57	0.55
Choloepus didactylus	Pilosa	0.27	0.28	0.31	0.32	0.36	0.37	0.58	0.58
Choloepus hoffmanni	Pilosa	0.29	0.31	0.34	0.35	0.38	0.40	0.57	0.54
Cyclopes didactylus	Pilosa	0.33	0.35	0.41	0.44	0.46	0.50	0.54	0.59
Myrmecophaga tridactyla	Pilosa	0.20	0.22	0.25	0.27	0.30	0.32	0.41	0.48
Tamandua tetradactyla	Pilosa	0.25	0.24	0.30	0.28	0.35	0.33	0.56	0.55
Alouatta belzebul	Primates	0.29	0.32	0.34	0.36	0.40	0.41	0.53	0.53
Alouatta discolor	Primates	0.27	0.23	0.33	0.28	0.38	0.33	0.58	0.48
Alouatta macconnelli	Primates	0.27	0.26	0.33	0.31	0.39	0.38	0.61	0.59
Alouatta puruensis	Primates	0.20	0.22	0.25	0.27	0.30	0.32	0.45	0.50
Alouatta ululata	Primates	0.18	0.19	0.28	0.30	0.36	0.38	0.47	0.46
Aotus azarae	Primates	0.22	0.24	0.25	0.28	0.28	0.33	0.33	0.47
Aotus nigriceps	Primates	0.23	0.23	0.28	0.28	0.34	0.34	0.50	0.50
Aotus trivirgatus	Primates	0.20	0.23	0.22	0.28	0.25	0.32	0.33	0.47
Aotus vociferans	Primates	0.27	0.24	0.31	0.27	0.35	0.31	0.57	0.56
Ateles belzebuth	Primates	0.24	0.25	0.30	0.31	0.37	0.37	0.60	0.59
Ateles chamek	Primates	0.23	0.17	0.29	0.22	0.37	0.31	0.56	0.60
Ateles marginatus	Primates	0.30	0.25	0.33	0.29	0.36	0.34	0.55	0.50
Ateles paniscus	Primates	0.31	0.31	0.35	0.33	0.39	0.37	0.58	0.57
Cacajao calvus	Primates	0.24	0.24	0.29	0.25	0.37	0.28	0.63	0.47
Cacajao hosomi	Primates	0.27	0.27	0.30	0.30	0.35	0.33	0.55	0.53
Callicebus brunneus	Primates	0.26	0.27	0.33	0.32	0.38	0.37	0.51	0.55
Callicebus cupreus	Primates	0.26	0.22	0.29	0.24	0.32	0.28	0.54	0.54
Callicebus lucifer	Primates	0.24	0.25	0.28	0.28	0.33	0.32	0.53	0.47
Callicebus moloch	Primates	0.26	0.26	0.30	0.30	0.34	0.35	0.53	0.56
Callicebus torquatus	Primates	0.25	0.23	0.30	0.28	0.36	0.33	0.53	0.48
Callimico goeldii	Primates	0.30	0.28	0.34	0.31	0.39	0.36	0.61	0.59
Cebuella pygmaea	Primates	0.26	0.27	0.30	0.29	0.37	0.33	0.64	0.54

Cebus albifrons	Primates	0.25	0.24	0.29	0.28	0.35	0.32	0.58	0.55
Cebus kaapori	Primates	0.20	0.21	0.29	0.27	0.36	0.33	0.49	0.42
Cebus olivaceus	Primates	0.20	0.23	0.27	0.28	0.33	0.32	0.41	0.47
Chiropotes albinasus	Primates	0.29	0.23	0.34	0.28	0.39	0.33	0.52	0.45
Chiropotes satanas	Primates	0.23	0.23	0.30	0.29	0.38	0.34	0.49	0.43
Chiropotes utahickae	Primates	0.24	0.26	0.30	0.31	0.36	0.35	0.50	0.44
Lagothrix lagotricha	Primates	0.26	0.24	0.31	0.29	0.36	0.33	0.60	0.45
Lagothrix poeppigii	Primates	0.26	0.20	0.26	0.20	0.29	0.21	0.61	0.64
Lampronycteris brachyotis	Primates	0.37	0.33	0.37	0.35	0.39	0.38	0.47	0.50
Mico melanurus	Primates	0.15	0.20	0.21	0.26	0.25	0.32	0.33	0.42
Mico rondoni	Primates	0.27	0.32	0.31	0.36	0.34	0.39	0.47	0.66
Saguinus bicolor	Primates	0.31	0.28	0.34	0.30	0.38	0.35	0.60	0.62
Saguinus fuscicollis	Primates	0.28	0.26	0.29	0.28	0.32	0.32	0.61	0.62
Saguinus imperator	Primates	0.22	0.22	0.27	0.27	0.32	0.32	0.47	0.47
Saguinus labiatus	Primates	0.23	0.23	0.28	0.28	0.33	0.33	0.47	0.47
Saguinus martinsi	Primates	0.24	0.24	0.28	0.29	0.33	0.34	0.44	0.47
Saguinus midas	Primates	0.30	0.23	0.34	0.28	0.38	0.32	0.55	0.49
Saguinus niger	Primates	0.26	0.26	0.32	0.34	0.38	0.40	0.55	0.52
Saguinus nigricollis	Primates	0.23	0.23	0.25	0.24	0.30	0.27	0.50	0.45
Saimiri boliviensis	Primates	0.30	0.26	0.36	0.29	0.41	0.33	0.58	0.54
Saimiri sciureus	Primates	0.29	0.28	0.35	0.32	0.41	0.36	0.58	0.57
Saimiri ustus	Primates	0.26	0.25	0.31	0.30	0.37	0.36	0.54	0.56
Coendou prehensilis	Rodentia	0.22	0.22	0.26	0.26	0.32	0.31	0.58	0.44
Cuniculus paca	Rodentia	0.15	0.09	0.21	0.16	0.27	0.26	0.51	0.38
Dactylomys boliviensis	Rodentia	0.20	0.18	0.26	0.25	0.33	0.31	0.51	0.48
Dactylomys dactylinus	Rodentia	0.26	0.24	0.28	0.25	0.32	0.27	0.54	0.50
Dasyprocta fuliginosa	Rodentia	0.28	0.27	0.32	0.30	0.36	0.35	0.48	0.55
Dasyprocta leporina	Rodentia	0.34	0.26	0.36	0.30	0.40	0.34	0.55	0.50
Dinomys branickii	Rodentia	0.23	0.28	0.32	0.34	0.40	0.40	0.58	0.54
Euryoryzomys macconnelli	Rodentia	0.27	0.24	0.30	0.29	0.34	0.34	0.46	0.49
Galea spixii	Rodentia	0.19	0.18	0.26	0.25	0.31	0.31	0.43	0.42
Hydrochoerus hydrochaeris	Rodentia	0.27	0.29	0.32	0.33	0.37	0.37	0.48	0.55
Hylaeamys megacephalus	Rodentia	0.28	0.27	0.31	0.30	0.36	0.34	0.55	0.61
Hylaeamys perenensis	Rodentia	0.27	0.23	0.32	0.27	0.38	0.33	0.64	0.56
Hylaeamys yunganus	Rodentia	0.26	0.23	0.30	0.27	0.35	0.32	0.68	0.59
Isothrix bistriata	Rodentia	0.25	0.23	0.31	0.29	0.37	0.36	0.57	0.62
Lagothrix cana	Rodentia	0.20	0.23	0.29	0.35	0.36	0.48	0.50	0.62
Makalata didelphoides	Rodentia	0.27	0.24	0.31	0.29	0.37	0.34	0.50	0.47

Makalata macrura	Rodentia	0.23	0.18	0.29	0.24	0.35	0.30	0.58	0.56
Mesomys hispidus	Rodentia	0.24	0.19	0.30	0.23	0.36	0.27	0.61	0.61
Microsciurus flaviventer	Rodentia	0.21	0.20	0.24	0.26	0.29	0.31	0.46	0.45
Myoprocta acouchy	Rodentia	0.27	0.24	0.32	0.25	0.38	0.28	0.64	0.52
Myoprocta pratti	Rodentia	0.24	0.25	0.28	0.29	0.33	0.34	0.53	0.53
Neacomys guianae	Rodentia	0.29	0.29	0.33	0.32	0.37	0.36	0.49	0.53
Neacomys paracou	Rodentia	0.30	0.30	0.34	0.34	0.39	0.39	0.59	0.58
Neacomys spinosus	Rodentia	0.18	0.18	0.23	0.21	0.29	0.28	0.68	0.80
Necromys lasiurus	Rodentia	0.15	0.21	0.17	0.26	0.18	0.30	0.26	0.41
Necromys urichi	Rodentia	0.30	0.32	0.35	0.40	0.39	0.47	0.67	0.58
Nectomys apicalis	Rodentia	0.26	0.27	0.32	0.34	0.39	0.39	0.54	0.51
Nectomys rattus	Rodentia	0.30	0.30	0.32	0.32	0.36	0.36	0.53	0.55
Oecomys auyantepui	Rodentia	0.33	0.31	0.35	0.33	0.38	0.37	0.57	0.60
Oecomys bicolor	Rodentia	0.25	0.28	0.31	0.32	0.35	0.36	0.46	0.48
Oecomys concolor	Rodentia	0.24	0.22	0.28	0.28	0.33	0.33	0.46	0.43
Oecomys paricola	Rodentia	0.26	0.25	0.31	0.30	0.36	0.35	0.50	0.49
Oecomys rex	Rodentia	0.32	0.33	0.36	0.37	0.42	0.42	0.55	0.56
Oecomys roberti	Rodentia	0.28	0.24	0.32	0.28	0.38	0.33	0.60	0.58
Oecomys rutilus	Rodentia	0.34	0.37	0.38	0.41	0.43	0.45	0.54	0.56
Oecomys superans	Rodentia	0.30	0.30	0.33	0.33	0.37	0.36	0.57	0.55
Oecomys trinitatis	Rodentia	0.27	0.24	0.30	0.28	0.35	0.33	0.56	0.48
Oligoryzomys fulvescens	Rodentia	0.25	0.30	0.31	0.41	0.35	0.47	0.41	0.54
Oligoryzomys microtis	Rodentia	0.21	0.21	0.28	0.26	0.34	0.31	0.53	0.42
Oxymycterus inca	Rodentia	0.23	0.24	0.28	0.27	0.34	0.31	0.55	0.53
Priodontes maximus	Rodentia	0.23	0.23	0.28	0.28	0.33	0.33	0.48	0.50
Procyon cancrivorus	Rodentia	0.15	0.07	0.25	0.13	0.32	0.23	0.73	0.30
Proechimys brevicauda	Rodentia	0.23	0.22	0.26	0.23	0.30	0.26	0.60	0.62
Proechimys cuvieri	Rodentia	0.33	0.28	0.35	0.31	0.38	0.35	0.53	0.58
Proechimys goeldii	Rodentia	0.23	0.23	0.29	0.29	0.36	0.36	0.52	0.50
Proechimys guyannensis	Rodentia	0.28	0.23	0.32	0.27	0.35	0.32	0.44	0.47
Proechimys quadruplicatus	Rodentia	0.24	0.19	0.27	0.20	0.33	0.23	0.57	0.48
Proechimys roberti	Rodentia	0.22	0.23	0.27	0.28	0.32	0.33	0.44	0.46
Proechimys simonsi	Rodentia	0.30	0.24	0.33	0.26	0.36	0.31	0.60	0.60
Proechimys steerei	Rodentia	0.22	0.21	0.29	0.26	0.34	0.31	0.54	0.50
Rhinophylla fischerae	Rodentia	0.26	0.21	0.27	0.22	0.31	0.24	0.49	0.48
Rhinophylla pumilio	Rodentia	0.29	0.21	0.31	0.22	0.35	0.24	0.59	0.33
Rhipidomys leucodactylus	Rodentia	0.22	0.17	0.24	0.22	0.29	0.26	0.51	0.39
Rhipidomys macconnelli	Rodentia	0.25	0.22	0.27	0.23	0.32	0.26	0.55	0.45

Rhipidomys nitela	Rodentia	0.24	0.24	0.27	0.28	0.32	0.32	0.45	0.47
Sigmodon alstoni	Rodentia	0.23	0.23	0.29	0.28	0.35	0.33	0.45	0.47

Conclusões

A presente dissertação fundamentou-se principalmente na avaliação da vulnerabilidade de espécies às mudanças climáticas e na identificação de prioridades para conservação de mamíferos na Amazônia brasileira. Dessa forma, o capítulo I "*Assessing mammals exposure to climate change"* mostra que a exposição às mudanças climáticas é geograficamente estrutura dentro da área de distribuição de uma espécie. Além disso, os resultados deste capítulo revelaram que i) quase todas espécies de mamíferos serão expostas em algum grau à novas condições climáticas em pelo menos parte da sua área de distribuição geográfica; ii) que os mamíferos endêmicos serão expostos em uma grande parte da suas área de distribuição e que; iii) as unidades de conservação da Amazônia são pouco efetivas para mitigar os impactos das mudanças climáticas sobre as espécies "criticamente-expostas". Sabendo disso, o capítulo II *"Matching biodiversity conservation priorities to climate change vulnerability in the Brazilian Amazon*" revelou que é possível combinar modelos de distribuição de espécie e simples medidas de mudanças climáticas em um esquema mais robusto de priorização para conservação, que eficientemente identifica áreas altamente expostas às mudanças climáticas e que leva em consideração as incertezas provenientes de diferentes projeções climáticas. Além disso, os resultados deste capítulo revelaram que cerca de um quarto da área de distribuição atual e fututura de mamíferos é representada nas Unidades de Conservação e que as Terras Indígenas deste bioma podem ter um papel fundamental em mitigar os efeitos das mudanças climáticas sobre mamíferos da Amazônia.