UNIVERSIDADE FEDERAL DE ALAGOAS
INSTITUTO DE CIÊNCIAS BIOLÓGICAS E DA SAÚDE
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ANNA LUDMILLA DA COSTA PINTO NASCIMENTO

MUDANÇAS CLIMÁTICAS E PEQUENOS MAMÍFEROS NÃO-VOADORES NA CAATINGA: impactos na distribuição e estratégias de conservação

CLIMATE CHANGE AND SMALL NON-FLYING MAMMAL IN THE CAATINGA: impacts on distribution and conservation strategies

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Epígrafe
Epigraph

"Não posso respirar, não posso mais nadar
A terra está morrendo, não dá mais pra plantar
E se plantar não nasce, se nascer não dá
Até pinga da boa é difícil de encontrar

Não posso respirar, não posso mais nadar
A terra está morrendo, não dá mais pra plantar
E se plantar não nasce, se nascer não dá
Até pinga da boa é difícil de encontrar

Cadê a flor que estava aqui?
Poluição comeu
E o peixe que é do mar?
Poluição comeu
E o verde onde é que está?
Poluição comeu
Nem o Chico Mendes sobreviveu"

'Xote Ecológico', Luiz Gonzaga.

RESUMO

As mudanças climáticas vêm ameaçando a biodiversidade e o funcionamento dos ecossistemas. Elas são especialmente preocupantes em regiões áridas e semiáridas do mundo, como a Caatinga brasileira, pois têm causado redução da precipitação e aumento da temperatura nessas áreas as quais já enfrentam grande déficit hídrico. A Caatinga é um bioma exclusivamente brasileiro, além de ser a maior e mais biodiversa Floresta Tropical Seca Sazonal do mundo. Contudo, esta floresta seca possui inúmeras lacunas do conhecimento, sendo inclusive o bioma com menos informações sobre mamíferos. Portanto, esta tese foi iniciada pela elaboração de um compilado de registros de pequenos mamíferos não-voadores para o bioma, priorizando espécies com representantes tombados em coleções científicas e buscando garantir a acurácia das coordenadas geográficas. O dataset reúne um total de 3133 registros de 816 localidades, resultando numa riqueza de 47 espécies nativas (12 marsupiais e 35 roedores), além de três roedores exóticos (*Rattus rattus, Rattus norvegicus* e *Mus musculus*). Ttrês novas espécies são ainda citadas para o bioma e suas áreas de transição: os roedores *Calomys mattevii, Holochilus oxe* e *Nectomys squamipes*. Além da riqueza e composição, o dataset possui dados biométricos de muitos registros. Levantadas as espécies e seus pontos de ocorrência no bioma, buscou-se identificar áreas climaticamente adequadas para cada uma delas na Caatinga e onde estas áreas estariam considerando dois cenários de mudanças climáticas (SSP 245 e 585) e para os anos de 2050 e 2070. Para tal, utilizou-se a Modelagem de Nicho Ecológico (MNE) e obteve-se projeções para 24 espécies de roedores e marsupiais. Ao quantificar o quanto de área climaticamente adequada seria perdida ou ganha em cada um dos cenários e anos, verificou-se que, das espécies mais adaptadas à aridez, quatro roedores devem ganhar área climaticamente adequada, enquanto as demais espécies perderiam. As espécies pouco adaptadas à aridez, ou seja, mais comuns em áreas com influência da Mata Atlântica, seriam mais vulneráveis às mudanças climáticas, com uma grande redução de suas áreas climaticamente adequadas na Caatinga. Identificadas essas variações na adequabilidade climática para as espécies, foram então realizadas priorizações espaciais com o intuito de identificar áreas prioritárias para preservar espécies de pequenos mamíferos na Caatinga no presente e num futuro de mudanças climáticas, utilizando o software Zonation. As priorizações aqui apresentadas levam em consideração o futuro de mudanças climáticas e apresentam baixo risco de implementação, podendo ser consideradas como uma ação de conservação de “não-arrependimento”. Ao verificar que estas áreas prioritárias estão pouco suportadas pelo atual Sistema Nacional de Unidades de Conservação, definiu-se estratégias custo-eficientes para a expansão de áreas protegidas na Caatinga, em especial pela transformação de determinadas áreas de Uso Sustentável em Proteção Integral. Os resultados aqui apresentados, em especial a redução de áreas adequadas climaticamente para maioria das espécies de pequenos mamíferos na Caatinga, reforçam a necessidade de garantir a adoção de estratégias de conservação que lidem com as consequências inevitáveis das alterações climáticas neste bioma único.

Palavras-chave: Mudanças Climáticas, Semiárido, Marsupial, Roedor, dataset, adequabilidade climática, priorização espacial, Zonation.

ABSTRACT

Climate change is threatening biodiversity and the functioning of ecosystems. They are especially worrying in arid and semi-arid regions of the world, such as the Caatinga, as they have caused a reduction in precipitation and an increase in temperature in these areas, which already face a large water deficit. The Caatinga is an exclusively Brazilian biome and the largest and most biodiverse Seasonal Dry Tropical Forest in the world. However, this dry forest has numerous knowledge gaps, and it is the biome with the least information on mammals. Therefore, this thesis began by compiling a dataset of records of small non-flying mammals for the biome, prioritising species with vouchers held in scientific collections, and seeking to guarantee the accuracy of the geographical coordinates. The dataset gathered a total of 3133 records from 816 localities, resulting in a richness of 47 native species (12 marsupials and 35 rodents), as well as three exotic rodents (*Rattus rattus, Rattus norvegicus* and *Mus musculus*). Three new species are also reported for the biome and its transition areas: the rodents *Calomys mattevii, Holochilus oxe* and *Nectomys squamipes*. In addition to richness and composition, the dataset contains biometric data for many records. Having surveyed the species and their points of occurrence in the biome, we sought to identify climatically suitable areas for each of them in the Caatinga and where these areas would be considering two climate change scenarios (SSP 245 and 585) and for the years 2050 and 2070. Ecological Niche Modelling was used to obtain projections for 24 species of rodents and marsupials. By quantifying how much climatically suitable area would be lost or gained in each of the scenarios and years, it was found that among the arid adapted species, only four rodents should gain climatically suitable area, while the other species would lose. As for the no-arid adapted species, i.e. those that are more common in areas influenced by the Atlantic Forest, would be more vulnerable to climate change, with a large reduction in their climatically suitable areas in the Caatinga. Once these variations in climate suitability for species had been identified, spatial prioritisations were then carried out in order to identify priority areas for preserving small mammal species in the Caatinga in the present time and in the future of climate change, using Zonation software. The prioritisations presented here take into account the future of climate change and present a low risk of implementation, and can be considered as a "no regrets" conservation action. By verifying that these priority areas are poorly supported by the current National System of Conservation Units, cost-effective strategies were defined for expanding protected areas in the Caatinga, especially by transforming certain Sustainable Use areas into Integral Protection. The results presented here, especially the reduction in climatically suitable areas for the majority of small mammal species in the Caatinga, reinforce the need to ensure that conservation strategies are in place to deal with the unavoidable climate change consequences in this unique biome.

Key-word: Climate Change, Semi-arid, Marsupial, Rodent, dataset, climate suitability, spatial prioritisation, Zonation.

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SUMÁRIO / *SUMMARY*

1. APRESENTAÇÃO

Como as mudanças climáticas irão impactar a distribuição de pequenos mamíferos na Caatinga? Esta pergunta é a base norteadora desta tese que, de início, me levou a reunir informações básicas e necessárias, porém pouco conhecidas sobre quem são e onde estão os registros de pequenos mamíferos não-voadores na Caatinga. Focando na Modelagem de Nicho Ecológico e em cenários futuros de mudanças climáticas, trago uma nova visão para a conservação a médio e longo prazo para espécies de pequenos roedores e marsupiais na Caatinga e, por consequência, para fragmentos deste bioma único, contribuindo para a manutenção de seus importantes serviços ecossistêmicos.

Neste documento, apresento o referencial teórico e os objetivos do trabalho como um todo, seguidos por três capítulos em formato de artigo/manuscrito científico, resultantes destes quatro anos de pesquisa, e finalizo com as conclusões gerais.

O primeiro capítulo objetiva sanar lacunas básicas de conhecimento, através da elaboração de um banco de dados publicado no *data paper* "*Small mammals from the Caatinga: A dataset for the Brazilian semiarid biome*". Nele são divulgadas informações importantes, como a localização, riqueza, composição e dados biométricos dos pequenos mamíferos não-voadores registrados no bioma.

No segundo capítulo, identifico áreas climaticamente adequadas para espécies de pequenos mamíferos na Caatinga além de potenciais mudanças nesse espaço climático por consequência das mudanças climáticas. O artigo "*Where could they go? Potential distribution of small mammals in the Caatinga under climate change scenarios*", apresentado aqui, realça e direciona atenção para áreas que serão mais impactadas com o aumento da temperatura global na Caatinga.

O terceiro e último capítulo da tese é resultante do meu doutorado sanduíche na Universidade de Helsinki, na Finlândia. Nele, identificamos áreas prioritárias para conservação de 40 espécies de pequenos mamíferos na Caatinga, considerando as incertezas das mudanças climáticas. O manuscrito "*Planning for a future of changes:*

prioritizing areas for conservation of small mammals in the Caatinga" busca ainda auxiliar na definição de estratégias para a expansão das áreas protegidas no bioma.

Embora esta tese tem como primeiro plano questões urgentes em um bioma altamente impactado pelas Mudanças Climáticas e uso antrópico, ela busca ir além. Ao colocar em evidência a Caatinga e fornecer subsídios para sua conservação, também quis evidenciar o povo sertanejo, que sente diariamente o que é viver no semiárido, nos extremos e no esquecimento. Se a fauna sofre, o povo também sofre. Se o ecossistema vivencia ondas de calor e seca acima do normal, o povo também vivencia. Se o bioma é negligenciado e esquecido, seu povo também o é. Portanto, salve a Caatinga! Salve o povo sertanejo!

2. REVISÃO DA LITERATURA

2.1. Mudanças Climáticas no Antropoceno

Enquanto o planeta é dominado pela época dos humanos, o Antropoceno, os padrões ecológicos, físico-químicos e biogeográficos que conhecíamos vem mudando cada vez mais rapidamente (Ellis 2019). Com o aumento da temperatura média na Terra caminhando para 1.5ºC em comparação ao período pré-industrial (IPCC, 2021), as mudanças climáticas provocadas pelo homem se mostram globalmente significativas, com consequências também nas escalas regional e local (Moritz et al. 2008, Seddon et al. 2016, Ellis 2019) e ameaçando não apenas a manutenção da biodiversidade, mas também a própria sobrevivência dos seres humanos (IPCC 2021, Shivanna 2022). Essas são, inclusive, uma das razões para as alterações antropogênicas do clima na Terra serem consideradas não apenas um limite planetário – i.e., critérios globais de sustentabilidade ambiental que delimitam um espaço operacional ambientalmente seguro à vida no planeta -, mas um limite *core* (Steffen et al. 2015).

Dentre os impactos das mudanças climáticas, podemos citar o derretimento das calotas polares, aumento do nível dos mares, mudanças nos padrões de temperatura e precipitação, maior frequência e intensidade de eventos climáticos extremos, como secas e enchentes, além do processo de desertificação (Rafferty and Stuart L. Pimm 2020, Bera et al. 2023). Indo além, as consequências desses impactos incluem a queda da produção agrícola, surgimento e crescimento de epidemias e aumento das desigualdades sociais (IPCC 2021, Shivanna 2022, Bera et al. 2023). Na prática, os efeitos das mudanças climáticas na biodiversidade e bem-estar humano são incontáveis.

Na biodiversidade, especificamente falando, as mudanças climáticas agem de indivíduos a populações, de espécies a comunidades, de ecossistemas a biomas: seja com o aumento da temperatura corporal e estresse hídrico em períodos de calor anormais (Fuller et al. 2021); com a substituição de comunidades de vertebrados em áreas úmidas por espécies mais adaptadas à aridez (Sales et al. 2020); com regiões semiáridas tropicais se expandindo em direção à zona temperada (Rajaud and Noblet-Ducoudré 2017), entre outros exemplos. Em relação às espécies, estas podem responder mudando seu nicho climático ao longo de três eixos, que não são excludentes: tempo (ex., fenologia em plantas), espaço (ex., distribuição geográfica) e internamente (ex., fisiologia) (Root et al. 2003, Bellard et al. 2012, Fuller et al. 2021).

Espacialmente, ao tornarem partes das atuais áreas de distribuição das espécies climaticamente inadequadas, as mudanças climáticas forçam-nas a adaptarem-se às novas condições ou a migrarem para áreas onde as condições climáticas se mantêm, ou se tornam adequadas, para evitar a extinção (Parmesan 2006). Em outras palavras, ao avançar a um ritmo mais rápido do que qualquer outro evento climático conhecido na história (Loarie et al. 2009, Diffenbaugh and Field 2013), as alterações climáticas de origem antrópica impõem grandes desafios às espécies, as quais são forçadas a se deslocar de suas áreas de ocorrência originais para seguir o seu nicho climaticamente adequado. O impacto é ainda maior, portanto, quando as espécies têm fracas capacidades de dispersão e/ou pouca sobreposição entre os seus nichos climáticos atuais e futuros (Parmesan 2006).

2.2. A Caatinga

As mudanças climáticas são especialmente preocupantes em regiões áridas e semiáridas do mundo, a exemplo da maior Floresta Tropical Seca Sazonal do mundo: a Caatinga (Seddon et al. 2016, Silva et al. 2017). Com uma área de aproximadamente 912.529 km^2, o que corresponde a 10,7% do território brasileiro, este bioma ocupa a maior parte da região Nordeste do Brasil, estendendo-se do estado do Piauí ao Norte de Minas Gerais (Silva et al. 2017) (Figura R-1a). Localiza-se entre dois biomas classificados como *hotspot* de biodiversidade (Myers et al., 2000), o Cerrado a Oeste e a Mata Atlântica a Leste, e é atravessada pelo Rio São Francisco, o rio perene mais importante da região, onde estão localizados os principais projetos de energia e irrigação, além de ser uma importante barreira biogeográfica (Silva et al. 2017, Di-Nizo et al. 2022) (Figura R-1a).

A Caatinga possui uma característica estação seca longa, intensa e irregular, com precipitação que pode variar de menos de 40 mm/ano a cerca de 700 mm em um único mês (Andrade et al. 2017). A variação na duração da estação seca da Caatinga se dá tanto temporalmente, entre os anos, quanto espacialmente entre suas nove ecorregiões reconhecidas, favorecendo sua diversidade fitofisionômica (Velloso et al., 2002) (Figura R-1b). A vegetação dominante na Caatinga varia de matas abertas, com arbustos espaçados, a florestas altas e secas, além de diferentes composições vegetacionais intermediárias, e de alguns enclaves úmidos, representados principalmente pelo Complexo da Chapada Diamantina e por relictos de florestas úmidas, encontrados em regiões de altitude (até 1000 metros), conhecidos como Brejos de Altitude (Queiroz et al., 2017).

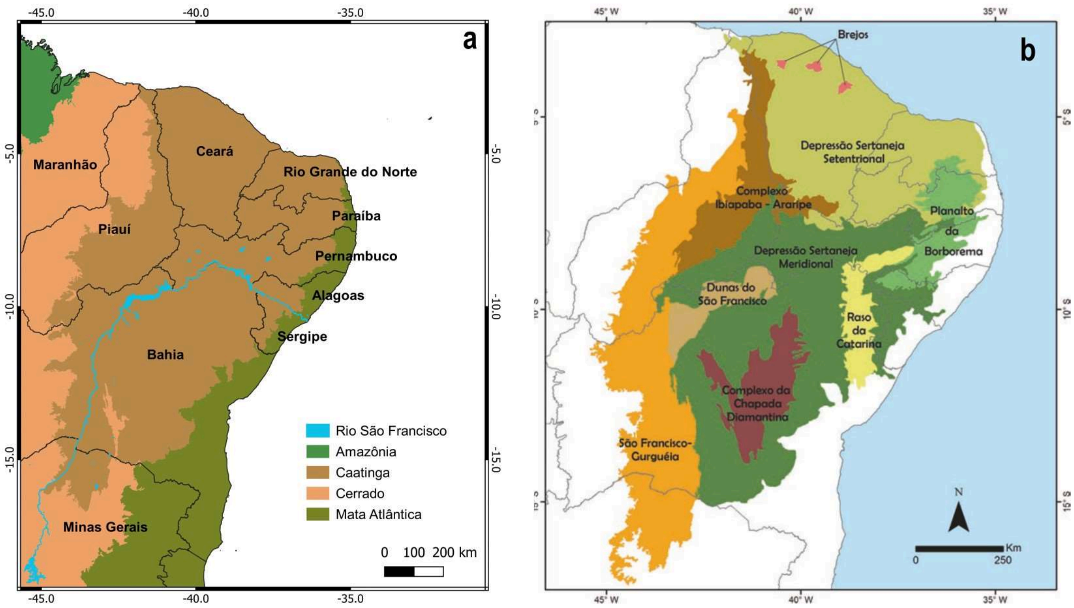

Figura R-1: Mapa político da Caatinga, seus biomas vizinhos e localização do Rio São Francisco (a); e ecorregiões do bioma (b). Figura R-1b modificada de Silva et al., 2017.

A diversidade fitofisionômica deste bioma exclusivamente brasileiro reflete-se na biota como um todo, de maneira que a Caatinga possui a maior biodiversidade entre as áreas semiáridas do mundo, com uma biota única e altos níveis de endemismo na região (Albuquerque et al. 2012). São cerca de 3.150 espécies de angiospermas, das quais 23% são endêmicas (Queiroz et al. 2017); 371 espécies de peixes, sendo 203 endêmicas (Lima et al. 2017); 177 espécies de lagartos e anfíbios, sendo 58 endêmicas (Garda et al. 2017, Mesquita et al. 2017); 548 aves

(Araujo and Silva 2017) e 182 espécies de mamíferos, das quais 10 são endêmicas (Carmignotto and Astúa 2017, Costa-Pinto et al. 2023).

Apesar de todas essas características únicas, atualmente, cerca de 9% da Caatinga está oficialmente protegida por Unidades de Conservação (MMA 2022), enquanto o bioma já perdeu metade de sua cobertura original e continua sendo impactado por perturbações antrópicas como desmatamento, extração de madeira, pastoreio e fogo (Antongiovanni et al. 2020). Somada a estas questões, as mudanças climáticas já vêm causando secas mais longas e frequentes na Caatinga, favorecendo o avanço do processo de desertificação (Seddon et al. 2016, IPCC 2021). Todos esses fatores têm consequências diretas e indiretas para a persistência e distribuição das espécies; mas as consequências das mudanças climáticas sobre a fauna, em especial dada a vulnerabilidade que certas espécies apresentam a este fenômeno (Albuquerque *et al*., 2012), ainda é uma grande lacuna. Em se tratando de mamíferos, por exemplo, essas lacunas incluem informações mais básicas, dado que a mastofauna do bioma Caatinga ainda é a menos estudada no Brasil (Carmignotto e Astúa 2017).

2.3. Os pequenos mamíferos não-voadores

No Brasil, são considerados pequenos mamíferos não-voadores todos os marsupiais (Ordem Didelphimorphia, Família Didelphidae) e roedores (Ordem Rodentia) com menos de 2 (dois) quilogramas. São animais que cumprem um papel fundamental em ecossistemas naturais, servindo como fonte de alimento para predadores e controlando populações de outros animais (Wright 2003), auxiliando na manutenção e recuperação do equilíbrio florestal (Robinson and Redford 1986), e desempenhando papel importante no recrutamento de espécies vegetais através da polinização, dispersão de sementes e até mesmo herbivoria (Chiarello 1999). Possuem diferentes espécies que movimentam-se por todos os estratos florestais e muitas são sensíveis aos distúrbios antrópicos, fornecendo indicativos de alterações nas paisagens e habitats (Pardini and Umetsu 2006).

São também úteis para entender as respostas às mudanças climáticas. Por apresentarem movimentos de dispersão limitados, em especial quando comparado a mamíferos de médio e grande porte ou até mesmo os voadores, os pequenos mamíferos serão menos capazes de alcançar refúgios climáticos adequados, gerando dificuldades para que as populações acompanhem as mudanças climáticas (Schloss et al. 2012, Hope et al. 2017). Por outro lado, são sensíveis à disponibilidade de recursos (Costa-Pinto et al. 2023a) e ao aquecimento do corpo, precisando mudar seu comportamento e buscar microclimas termicamente adequados em seus habitats (Fuller et al. 2021) também em resposta às mudanças ambientais e climáticas.

Estudos que busquem predizer e quantificar mudanças futuras na adequabilidade ambiental, incluindo mudanças nos limites de distribuição de espécies de pequenos mamíferos não são tão comuns (Beever et al., 2003; Mccain & King, 2014; Myers et al., 2009; Santoro et al., 2017; Szpunar et al., 2008), e apenas um inclui pequenos mamíferos em regiões áridas/semiáridas (Costa-Pinto et al. 2024).

2.4. Modelagem de Nicho e Priorização Espacial

A Modelagem de Nicho Ecológica (MNE) - também conhecida como Modelos de Distribuição de espécie (mas ver Sillero, 2011) ou Modelos de Adequabilidade de Habitat - é uma ferramenta estatísticas e de aprendizado de máquina (“*machine* learning”) que utiliza informações sobre a ocorrência conhecida de espécies e as condições ambientais existentes nesses locais para estimar a adequação ambiental de locais não estudados (Guisan and Zimmermann 2000, Elith and Leathwick 2009). Nos últimos anos, têm sido muito utilizada para explorar a forma como a adequabilidade dos locais é suscetível às mudanças globais antrópicas, estimando futuras alterações na adequabilidade ambiental ou distribuição das espécies e os seus impactos na biodiversidade (Araújo et al. 2011, Guisan et al. 2013, Kujala et al. 2015). Através de modelagem, por exemplo, reduções nas área de distribuição e perda de condições climáticas adequadas já foram preditas para espécies de marsupiais no Brasil (Loyola et al. 2012, Costa-Pinto et al. 2024). A MNE se tornou uma ferramenta difundida também para a conservação e o gerenciamento da natureza, em especial dentro do Planejamento Sistemático da Conservação (PSC) (Margules and Pressey 2000, Muscatello et al. 2021).

A conservação da biodiversidade requer decisões sobre como alocar recursos no espaço a fim de proteger, restaurar ou gerenciar áreas em uma paisagem (Muscatello et al. 2021). Neste sentido, o PSC orienta ações de conservação com boa relação custo-benefício por meio de um procedimento de várias etapas, em que as lacunas atuais na proteção de habitats e ecossistemas são primeiramente identificadas e, em seguida, são estabelecidas prioridades para proteção adicional (Margules and Pressey 2000). As análises de priorização espacial da conservação ajudam a identificar as áreas prioritárias onde a proteção resulta no maior benefício para o maior número de espécies e habitats (Moilanen et al. 2009). Softwares de priorização espacial como Marxan (Possingham et al. 2000) e Zonation (Moilanen et al. 2005, 2022) são comumente usados para realizar essas análises que, em suma, identificam áreas prioritárias para conservação da biodiversidade.

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3. OBJETIVOS

Entender os efeitos potenciais das mudanças climáticas na distribuição de pequenos mamíferos não-voadores na Caatinga, buscando desenvolver estratégias de conservação adaptativas a médio e longo prazo diante de cenários futuros de transformações climáticas.

3.1 Objetivos específicos

- Reunir informações de registros de espécies de pequenos mamíferos no bioma Caatinga, com foco na acurácia geográfica, confiança taxonômica e dados biométricos;
- Verificar áreas climaticamente adequadas para os pequenos mamíferos na Caatinga atualmente e prever quais seriam adequadas em cenários climáticos futuros;
- Quantificar a potencial extensão dessas mudanças de área climaticamente adequada em face das mudanças climáticas;
- Identificar áreas prioritárias para a preservação de pequenos mamíferos na Caatinga nos cenários atuais de clima e uso da terra, e em cenários de mudanças climáticas futuras;
- Verificar o quanto dessas áreas prioritárias estão atualmente em território de Área Protegida, identificando formas de melhorar essa proteção.

4. PRESENTATION

How will climate change affect the distribution of small mammals in the Caatinga? This question is the guideline of this thesis, which initially led me to gather basic and necessary, but little-known information about who and where are the records of small mammals (Rodentia and Didelphimorphia) in the Caatinga. Focusing on Ecological Niche Modelling and future climate change scenarios, I provide a new perspective to medium and long-term conservation for species of small rodents and marsupials in the Caatinga and, therefore, for fragments of this unique biome, contributing to the maintenance of its important ecosystem services.

In this document, I present the theoretical framework and the objectives of this research work as a whole, followed by three chapters in article/scientific manuscript format, resulting from these four years of research, and I finish with the general conclusions.

The first chapter aims to fill basic knowledge gaps by creating a database published in the data paper "Small mammals from the Caatinga: A dataset for the Brazilian semiarid biome". It contains important information such as the location, richness, composition and biometric data of the small mammals recorded in the biome.

In the second chapter, I identify climatically suitable areas for small mammal species in the Caatinga, as well as potential changes in this climatic space as a result of climate change. The paper "Where could they go? Potential distribution of small mammals in the Caatinga under climate change scenarios", presented here, highlights and directs attention to areas that will be most impacted by rising global temperatures in the Caatinga.

The third and final chapter of this thesis is the result of my sandwich doctorate (Internship PhD) at the Finnish Museum of Natural History, University of Helsinki, in Finland. Here, we identified priority areas for the conservation of 40 species of small mammals in the Caatinga, considering the uncertainties of climate change. The manuscript "Planning for a future of changes: prioritizing areas for conservation of small mammals in the Caatinga" also seeks to help define strategies for the expansion of protected areas in the biome.

Although this thesis focuses on urgent issues in a biome highly impacted by climate change and anthropogenic use, it seeks to go further. By highlighting the Caatinga and providing subsidies for its conservation, I also wanted to highlight the inhabitants of the region, the "sertanejo" people, who feel on a daily basis what it is like to live in the semiarid, in extremis and in oblivion. If the fauna suffers, so does the sertanejo. If the ecosystem experiences waves of heat and drought above normal, so do the sertanejo. If the biome is neglected and forgotten, so are its people. Save the Caatinga! Save the sertanejo people!

5. LITERATURE REVIEW

5.1. Climate Change in the Anthropocene

While the planet is dominated by the epoch of humans, the Anthropocene, the ecological, physico-chemical and biogeographical patterns we have known are changing ever more rapidly (Ellis 2019). With the average temperature on Earth rising by 1.5ºC compared to the pre-industrial period (IPCC, 2021), human-induced climate change is proving to be globally significant, with consequences at regional and local scales (Moritz et al. 2008, Seddon et al. 2016, Ellis 2019) and threatening not only the maintenance of biodiversity, but also the very survival of human beings (IPCC 2021, Shivanna 2022). This is even one of the reasons why anthropogenic climate change on Earth is considered not just a planetary boundary - i.e. global environmental sustainability criteria that delimit an environmentally safe operating space for life on the planet - but a core boundary (Steffen et al. 2015).

Among the impacts of climate change, we can quote the melting of the polar ice caps, rising sea levels, changes in temperature and precipitation patterns, greater frequency and intensity of extreme weather events such as droughts and floods, as well as the process of desertification (Rafferty and Stuart L. Pimm 2020, Bera et al. 2023). Furthermore, the consequences of these impacts include a drop in agricultural production, the emergence and growth of epidemics, and an increase in societal inequalities (IPCC 2021, Shivanna 2022, Bera et al. 2023). In practice, the effects of climate change on biodiversity and human well-being are countless.

In biodiversity, specifically speaking, climate change acts from individuals to populations, from species to communities, from ecosystems to biomes: whether with increased body temperature and water stress in periods of abnormal heat (Fuller et al. 2021); with the replacement of vertebrate communities in humid areas by species more adapted to aridity (Sales et al. 2020); with semi-arid tropical regions expanding towards the temperate zone (Rajaud and Noblet-Ducoudré 2017), among other examples. As for species, they can respond by changing their climatic niche along three axes, which are not mutually exclusive: time (e.g. phenology in plants), space (e.g. geographical distribution), and internally (e.g. physiology) (Root et al. 2003, Bellard et al. 2012, Fuller et al. 2021).

Spatially, by making parts of the current distribution areas of species climatically unsuitable, climate change forces them to adapt to the new conditions or migrate to areas where climatic conditions are maintained, or become suitable, to avoid extinction (Parmesan 2006). In other words, by advancing at a faster rate than any other known climatic event in history (Loarie et al. 2009, Diffenbaugh and Field 2013), climate change of anthropogenic origin imposes major challenges on species, which are forced to move from their original areas of occurrence to follow their climatically suitable niche. The impact is even greater, therefore, when species have poor dispersal capabilities and/or little overlap between their current and future climate niches (Parmesan 2006).

5.2. The Caatinga

Climate change is of particular concern in arid and semiarid regions of the world, such as the largest Seasonal Dry Tropical Forest in the world: the Caatinga (Seddon et al. 2016, Silva et al. 2017). With an area of approximately 912,529 km2, which corresponds to 10.7% of the Brazilian territory, this biome occupies most of the Northeast region of Brazil, stretching from the state of Piauí to the north of Minas Gerais (Silva et al. 2017) (Figure R-1a). It is located between two biomes classified as biodiversity hotspots (Myers et al., 2000), the Cerrado to the west and the Atlantic Forest to the east, and is crossed by the São Francisco River, the most important perennial river in the region, where the main energy and irrigation projects are located, as well as being an important biogeographical barrier (Silva et al. 2017, Di-Nizo et al. 2022) (Figure R-1a).

The Caatinga has a characteristic long, intense and irregular dry season, with rainfall that can vary from less than 40 mm/year to around 700 mm in a single month (Andrade et al. 2017). The variation in the length of the dry season in the Caatinga occurs both temporally, between years, and spatially between its nine recognised ecoregions, which favours its phytophysiognomic diversity (Velloso et al., 2002) (Figure R-1b). The dominant vegetation in the Caatinga varies from open woodlands with spaced shrubs to tall, dry forests, as well as different intermediate vegetation compositions and some humid enclaves, represented mainly by the Chapada Diamantina Complex and by relicts of humid forests found in high-altitude regions (up to 1000 metres), known as Brejos de Altitude (Highlands) (Queiroz et al., 2017).

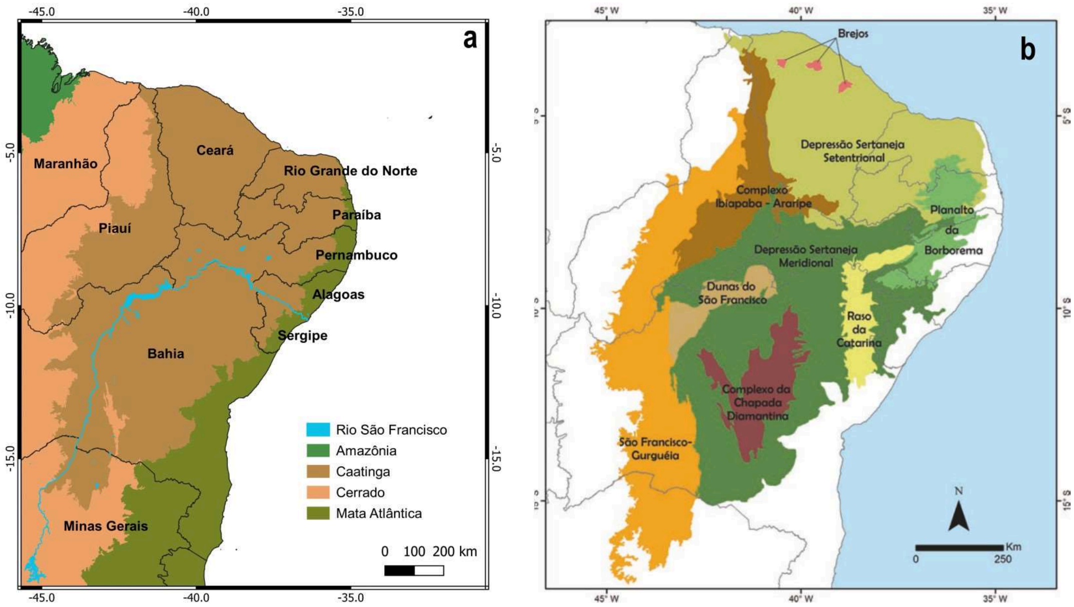

Figure R-1: Map of the Caatinga, its neighbouring biomes and the location of the São Francisco River (a); and ecoregions of the biome (b). Figure R-1b modified from Silva et al., 2017.

The phytophysiognomic diversity of this exclusively Brazilian biome is reflected in the biota as a whole, so that the Caatinga has the greatest biodiversity among the semiarid areas of the world, with a unique biota and high levels of endemism in the region (Albuquerque et al. 2012). There are around 3,150 species of angiosperms, 23% of which are endemic (Queiroz et al. 2017); 371 species of fish, 203 of which are endemic (Lima et al. 2017); 177 species of lizards and amphibians, 58 of which are endemic (Garda et al. 2017, Mesquita et al. 2017); 548 birds (Araujo and Silva 2017) and 182 species of mammals, 10 of which are endemic (Carmignotto and Astúa 2017, Costa-Pinto et al. 2023).

Despite all these unique characteristics, currently around 9% of the Caatinga is officially protected by Conservation Units (MMA 2022), while the biome has already lost half of its original cover and continues to be impacted by anthropogenic disturbances such as deforestation, logging, grazing and fire (Antongiovanni et al. 2020). In addition to these issues, climate change is already causing longer and more frequent droughts in the Caatinga, favouring the advance of the desertification process (Seddon et al. 2016, IPCC 2021). All these factors have direct and indirect consequences for the persistence and distribution of species; but the consequences of climate change on fauna, especially considering the vulnerability of certain species to this phenomenon (Albuquerque et al., 2012), is still a major gap. When it comes to mammals, for example, these gaps include more basic information, given that the mastofauna of the Caatinga biome is still the least studied in Brazil (Carmignotto and Astúa 2017).

5.3. Small mammals

In Brazil, small non-flying mammals are considered to be all marsupials (Order Didelphimorphia, Family Didelphidae) and rodents (Order Rodentia) weighing less than 2 (two) kilograms (small mammals from now on). These animals play a fundamental role in natural ecosystems, acting as a food source for predators and controlling populations of other animals (Wright 2003), helping to maintain and recover forest balance (Robinson and Redford 1986), and playing an important role in the recruitment of plant species through pollination, seed dispersal, and even herbivory (Chiarello 1999). They have different species that move through all forest strata and many are sensitive to anthropogenic disturbances, providing indications of changes in landscapes and habitats (Pardini and Umetsu 2006).

They are also useful for understanding responses to climate change. Because they have limited dispersal movements, especially when compared to medium and large mammals or even flying mammals, small mammals will be less able to reach suitable climatic refuges, making it difficult for populations to keep up with climate change (Schloss et al. 2012, Hope et al. 2017). On the other hand, they are sensitive to the availability of resources (Costa-Pinto et al. 2023a) and body heating, and will need to change their behaviour and seek thermally suitable microclimates in their habitats (Fuller et al. 2021) in response to environmental and climate change.

Studies that seek to predict and quantify future changes in environmental suitability, including changes in the distribution limits of small mammal species, are not so common (Beever et al., 2003; Mccain & King, 2014; Myers et al., 2009; Santoro et al., 2017; Szpunar et al., 2008), and only one includes small mammals in arid/semiarid regions (Costa-Pinto et al. 2024).

5.4. Niche Modelling and Spatial Prioritisation

Ecological Niche Modelling (ENM) - also known as Species Distribution Models (but see Sillero, 2011) or Habitat Suitability Models - is a statistical tool that uses information about the known occurrence of species and the environmental conditions existing at those sites to estimate the environmental suitability of unstudied sites (Guisan and Zimmermann 2000, Elith and Leathwick 2009). In recent years, it has been widely used to explore how the suitability of sites is susceptible to anthropogenic global changes, estimating future changes in environmental suitability or species distribution and their impacts on biodiversity (Araújo et al. 2011, Guisan et al. 2013, Kujala et al. 2015). Through the use of modelling, for example, reductions in range and loss of suitable climatic conditions have already been predicted for marsupial species in Brazil (Loyola et al. 2012, Costa-Pinto et al. 2024). The MNE has also become a widespread tool for nature conservation and management, particularly within Systematic Conservation Planning (SCP) (Margules and Pressey 2000, Muscatello et al. 2021).

Biodiversity conservation requires decisions on how to allocate resources in space in order to protect, restore or manage areas in a landscape (Muscatello et al. 2021). In this sense, SCP guides cost-effective conservation actions through a multi-step procedure in which current gaps in habitat and ecosystem protection are first identified and then priorities for additional protection are established (Margules and Pressey 2000). Spatial conservation prioritisation analyses help to identify priority areas where protection results in the greatest benefit for the greatest number of species and habitats (Moilanen et al. 2009). Spatial prioritisation software such as Marxan (Possingham et al. 2000) and Zonation (Moilanen et al. 2005, 2022) are commonly used to carry out these analyses which, in short, identify priority areas for biodiversity conservation.

5.5. References

See page 26.

6. OBJECTIVES

To understand the potential effects of climate change on the distribution of small non-flying mammals in the Caatinga, seeking to develop adaptive conservation strategies in the medium and long term in the face of future climate change scenarios.

6.1 Specific objectives

- To gather information on records of small mammal species in the Caatinga biome, focusing on geographical accuracy, taxonomic confidence, and biometric data;
- Identify climatically suitable areas for small mammals in the Caatinga today and predict which ones would be suitable under future climate scenarios;
- Quantify the potential extent of these changes in climatically suitable areas in the face of climate change;
- Identify priority areas for the preservation of small mammals in the Caatinga under current climate and land use scenarios, and under future climate change scenarios;
- Verify how much of these priority areas are currently in Protected Area territory, identifying ways to improve this protection.

7. CAPÍTULO 1: Pequenos mamíferos da Caatinga: um banco de dados para o bioma semiárido brasileiro

7. CHAPTER 1: Small mammals from the Caatinga: A dataset for the Brazilian semiarid biome

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Small mammals from the Caatinga: a dataset for the Brazilian semiarid biome

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Author Statement: All authors that contributed with unpublished data were listed in alphabetical order according to their surname, except the first, second and last authors.

Open Research Statement:

The complete data set is available as Supporting Information at: [to be completed at proof stage]. Associated data is also available at Figshare: https://doi.org/10.6084/m9.figshare.20063267.v2

Introduction

Ecological datasets are essential resources that have a multitude of uses in ecology and conservation, including studies of population and community ecology (Marjakangas et al. 2020), forest fragmentation and defaunation (Bovendorp et al. 2018), areas of endemism and conservation strategies (Dalapicolla et al. 2021), climate change effects (Freitas-Oliveira et al. 2021) and spatial conservation prioritization (Kujala et al. 2018).

Nevertheless, publicly available ecological datasets on mammals, especially those focused on small mammals, are relatively scarce with most published work appearing over the last 5 years (see Bovendorp et al. 2017, Figueiredo et al. 2017, Gonçalves et al. 2018). To date, there is no public data paper on small mammals from any arid or semiarid regions of the world. This is especially problematic for the semiarid (Caatinga) region of northeast Brazil, that has already lost half its original cover and continues to be impacted by chronic and acute anthropogenic disturbance (Antongiovanni et al. 2018, 2020). In addition, the mammalian fauna in the Caatinga biome is the least studied in Brazil (Carmignotto and Astúa 2017) with a handful of historical studies (Willig and Mares 1989, Oliveira et al. 2003, Carmignotto et al. 2012, Carmignotto and Astúa 2017) supplemented with more recent field-based work (Geise et al. 2010, Delciellos 2016, Cruz et al. 2017, Conceição and Bocchiglieri 2021, among others).

Here, we address this shortfall by collating the first small mammal dataset for the Caatinga biome. Specifically, we (1) gather detailed information from reliable records of small mammals (Didelphimorphia, Rodentia) from the Caatinga biome, focusing on richness, composition and some biometric data, and (2) identify geographic sampling gaps for the group. Due to the paucity of information available in the scientific literature and the low reliability of online databases (Maldonado et al. 2015), we created a dataset that includes factors associated with data quality such as coordinate accuracy, presence of vouchers associated with the records and biometric data.

Based on records from mammal collections, papers, theses, books, unpublished data, and prioritizing records with vouchers housed in scientific collections, 3133 records from 816 locations were gathered, resulting in a richness of 47 native species (12 marsupials and 35 rodents, plus three exotic rodents, *Rattus rattus*, *Rattus norvergicus* and *Mus musculus*).This is the most extensive small mammal dataset for the Caatinga biome with potential applications in a wide range of studies on subjects as diverse as habitat use, landscape ecology, macroecology, biogeography and conservation.

Metadata

CLASS I. DATA SET DESCRIPTORS

A. Data set identity

Title: Small mammals from the Caatinga: a dataset for the Brazilian semiarid biome

B. Data set identification code

Caatinga_SM_loc.csv and Caatinga_SM_rec.csv

C. Data set description

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II. Abstract: The Caatinga is an exclusively Brazilian biome, and is the largest and most biodiverse Seasonal Tropical Dry Forest in the world. Despite that, the mammalian fauna, especially small mammals, is the least studied of all Brazilian biomes. In order to fill gaps and provide detailed information on small mammals (Didelphimorphia, Rodentia) in the Caatinga biome, we compiled reliable records focusing on richness, composition and some biometric data. These records came from mammal collections, papers, theses, books, and unpublished data, prioritizing records with vouchers housed in scientific collections. We compiled a total of 3133 records from 816 locations, resulting in a richness of 47 native species (12 marsupials

and 35 rodents, plus three exotic rodents, *Rattus rattus*, *Rattus norvergicus* and *Mus musculus*). This dataset includes records of three new species for the biome and its transition zone: the rodents *Calomys mattevii*, *Holochilus oxe* and *Nectomys squamipes*. Of the total number of records, 1808 (57.71%) are from consulting activities, 95 (3.03%) are from zoonoses studies and 104 (3.32%) are from the National Plague Service (SNP). All nine Brazilian states with territory in the Caatinga have sampling data for small mammals, but the number of records and localities are unevenly distributed, with the state of Rio Grande do Norte having the lowest number of records and locations sampled. Our dataset is the first of its kind for the Caatinga biome and has considerable potential value for studies of habitat use, landscape ecology, macroecology, biogeography and conservation.

D. Key words: Data paper; Marsupials; Neotropics; Rodents; Seasonal Tropical Dry Forest; species composition; species richness.

CLASS II. RESEARCH ORIGIN DESCRIPTORS

A. Overall project description

a. Identity

Compilation of non-flying small mammals' occurrence in the Caatinga biome, providing richness, composition and biometric data.

b. Originators

'Small mammals from the Caatinga' was coordinated by Anna Ludmilla da Costa-Pinto, who performed the data standardization, taxonomic nomenclature review and metadata writing. Collaboration on the metadata writing was performed by Ana Cláudia Delciellos, Ricardo S. Bovendorp and Richard J. Ladle. All other co-authors contributed by providing unpublished data for the data set.

c. Period of study

The data presented were collected from 1942 to 2021. The process to organize and produce the current data set took place from 2021 to 2022.

d. Objectives:

Our goal was to gather detailed ecological information on small mammals (Didelphimorphia, Rodentia) in the Caatinga biome, focusing on a) species richness, composition and biometric data; and b) identifying geographic sampling gaps for the group in the Caatinga biome.

e. Abstract

See section Class I. C. II. Abstract.

f. Sources of funding

Fundings were provided by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior/CAPES (ALCP, AKRA, FHM and LG), Conselho Nacional de Desenvolvimento Científico e Tecnológico/CNPq (LG, RMFB and GG), Dossel Ambiental Consultoria e Projetos Ltda., State Grid Brazil Holding (ACD), Fundação de Amparo à Pesquisa do Estado de São Paulo/FAPESP and Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro/FAPERJ (LG), Fundação Cearense de Apoio ao Desenvolvimento Científico e Tecnológico/Funcap (AC), Secretaria Nacional de Segurança Hídrica/SNSH do Ministério do Desenvolvimento Regional/MDR (LSO, ICGV, JVAF, LCMP and PAN).

B. Specific subproject description

1. Site description: The Caatinga has an area of 912,529 km², corresponding to 10.7% of the Brazilian territory. It is the largest ecological region, or biome, in Northeastern Brazil and the largest Seasonal Tropical Dry Forest of the world (Silva et al. 2017a). The biome has a long, intense, and irregular dry season, with precipitation that can vary less than 40 mm/year to about 700 mm in a single month (Andrade et al. 2017). The Caatinga is an exclusively Brazilian biome with the highest biodiversity among semiarid areas of the world, an unique biota and high levels of endemism in the region (Albuquerque et al. 2012). The phytophysiognomies of the Caatinga range from lands of open shrubs, dry forests and arboreal-shrubby Caatinga, to islands of Atlantic Forest-like vegetation found in small highlands ("Brejos de Altitude") and in the Chapada Diamantina region in the state of Bahia (Queiroz et al. 2017). Despite all these unique features, the Caatinga has already lost half its original cover and continues to be impacted by chronic and acute anthropogenic disturbance (Antongiovanni et al. 2018, 2020) while it is the least known biomes in Brazil (Lessa et al. 2019).

2. Data collection: This dataset is based on records from mammal collections, papers, theses, books and unpublished data. Records with vouchers housed in scientific collections were prioritized. Only those records of non-flying small mammals inside the current limits of the Caatinga (sensu, IBGE 2019), with a 10 km buffer, were considered. This includes records from the transition area along the border with the Atlantic Forest (known as Agreste) and with the Cerrado.

3. Research criteria: Taxonomic nomenclature was based on the updated checklist of Brazilian mammals by the Taxonomy Committee of the Brazilian Society of Mastozoology (Abreu et al. 2021) in addition to other specific studies: Gurgel-Filho et al. (2015) for *Calomys*; Prado et al. (2021) for *Holochilus*; Paixão et al. (2021) for *Rhipidomys*; Nascimento et al. (2013) for *Thrichomys*; Pessôa et al. (2015) for *Trinomys*; Cunha-Filho (2019) for *Wiedomys*; Carmignotto and Monfort (2006) for *Thylamys*. In addition, we call the black-eared opossums from the state of Ceará *Didelphis marsupialis* (but we reinforce the need for a taxonomic review of these specimens – see Carmignotto and Astúa 2017); *Euryoryzomys* specimens from Ceará and Paraíba are called *E. russatus* (but see Prado and Percequillo, 2013); *Oligoryzomys fornesi* were treated as *O. mattogrossae* (Weksler et al. 2017).

Specimens identified at the genus level (sp.) were accepted only when voucher is present, so it would be possible to contact the collection for future identification. A list of Brazilian Mammal Collections can be found in Chiquito et al. (2021). As studies with different objectives can use different scales, such as macroecology and habitat selection, we consider as distinct locations any sampling points with different coordinates, regardless of the distance between them. To this end, in this dataset there are columns referring to where the coordinates were taken and their accuracy (in meters or kilometers). Lack of information was identified by the initials NA.

CLASS III. DATA SET STATUS AND ACCESSIBILITY

A. Status

Latest update: April 2022

Latest Archive date: April 2022

Metadata status: Last update on August 02, 2022, version submitted

Data verification: All localities were checked for accuracy and precision. The taxonomic status of the species was verified by the expert authors. In the bibliographic records, the taxonomic update was made based on the most recent literature (see 'Research criteria' topic) regarding the biogeographic distribution and karyotype description.

B. Accessibility

a. Storage location and medium

The complete data set is available as Supporting Information at: [to be completed at proof stage]. Associated data is also available at Figshare: https://doi.org/10.6084/m9.figshare.20063267.v2.

b. Contact person: Anna Ludmilla da Costa-Pinto, Setor de Mastozoologia, Museu de História Natural da Universidade Federal de Alagoas, Maceió, Alagoas, 51060-010, Brazil. E-mail: ludmilla.nascimento@mhn.ufal.br.

c. Copyright restrictions: None.

d. Proprietary restrictions: Please cite this data paper when the data are used in publications. We also request that researchers and teachers inform us of how they are using the data.

e. Costs: None.

CLASS IV. DATA STRUCTURAL DESCRIPTORS

A. Data set file

1) Caatinga_SM_loc.csv

2) Caatinga_SM_rec.csv

Format and storage mode: comma-separated values (.csv)

Header information: See Table 1 in section B for column descriptions.

Data Anomalies: Body measurements marked with * have additional information in the Remarks column. Information not available was indicated as 'NA'.

B. Variable information

1) Table 1. Description of columns of .csv files.

2) Table 2. Acronyms for cited Scientific Collections and Protected Areas (PA).

3) Table 3. Systematic list of small non-flying mammals' species from the Caatinga.

4) Figure 1. Distribution of the small mammal localities records on the Caatinga biome.

5) **Figure 2.** Number of sampled localities and small mammals' records in the Caatinga by states.

CLASS V. SUPPLEMENTAL DESCRIPTORS

A. Results description: This dataset raised 47 native species (Table 1) (plus three exotic rodents, *Rattus rattus*, *Rattus norvergicus* and *Mus musculus*), 12 marsupials and 35 rodents, in 3133 records from 816 localities (Figure 1). All the species recorded have specimens in a scientific collection. The last checklist of mammals from the Caatinga (Carmignotto and Astúa 2017) presented 48 species of small non-flying mammals (35 rodents and 13 marsupials) and our studies have a few differences in species composition. *Rhipidomys cearanus*, *Guerlinguetus brasiliensis, Cavia aperea* and *Metachirus nudicaudatus* are present on Carmignotto and Astúa (2017) list. However, we treat *R. cearanus* as a synonym of *R. mastacalis* (Paixão et al. 2021), although there has been a consensus that specimens from Serra de Ibiapaba (CE) may represent a new species (Tribe 2015, Paixão et al. 2021). *Guerlinguetus brasiliensis* was not included because it is cited on literature (Sousa et al. 2004, Pereira and Geise 2009) only as interview record. Similarly, we did not find any voucher from *C. aperea* in Caatinga. The record of *M. nudicaudatus* is from an area now classified as Cerrado according to the new limits of the Caatinga (Silva et al. 2017b, IBGE 2019). On the other hand, our inventory has three different rodents: *Calomys mattevii*, *Holochilus oxe* and *Nectomys squamipes*. *Calomys expulsus* cited for Caatinga in Northeastern Brazil may be, in fact, *C. matevii* which was described a few years ago (Gurgel-Filho et al. 2015). *Holochilus oxe* was recently described (Prado et al. 2021) and occurs on Northeastern Brazil, apparently on the northern bank of São Francisco River. The record of *N. squamipes* is from unpublished data (thesis of Chiquito, E.D.A.) from Serra de Itabaiana National Park, Sergipe State, an Atlantic Forest border with Caatinga. Vouchers are deposited at the Museu Paraense Emílio Goeldi (MPEG 24550, 24551, 24552).

The 10 species with the highest number of records are, respectively: *Wiedomys cerradensis* (n=415), *Monodelphis domestica* (368), *Thrichomys laurentius* (362), *Gracilinanus agilis* (309), *Didelphis albiventris* (291), *Marmosops incanus* (156), *Calomys* *mattevii* (150), *Thrichomys apereoides* (126), *Cerradomys vivoi* (102) and *Kerodon rupestris* (102; Figure 2).

According to our dataset, the marsupial *Caluromys philander* and the rodents *Nectomys rattus*, *Makalata didelphoides* and *Phyllomys lamarum* in the Caatinga used to occur in forest islands ("Brejos de Altitude") and forest patches along the São Francisco River, however, there is no recent record (less than 50 years) of its occurrence in the biome. Of the species with recent occurrence, three are included in the National List of Endangered Species (MMA, 2022): *Kerodon rupestris* (VU – Vulnerable), *Oligoryzomys rupestris* (EN - Endangered), *Trinomys yonenagae* (EN; MMA 2022). Of these, we highlight the conservation priority needed for the torch-tail spiny rat (*T. yonenagae*), a fossorial and desert-dwelling rodent, endemic to a restricted region of semiarid sand dunes along the left bank of the São Francisco River, near Ibiraba, Bahia State, and whose threats involve habitat loss, especially extraction of sand (Lacher et al. 2020). There is no specific 'red list' for the Caatinga biome.

Among the records, 1808 (57.71%) are related to consulting activities, reinforcing the importance of these activities in the generation of scientific data. Besides, 95 (3.03%) records are related to zoonoses study and 104 (3.32%) to the National Plague Service (SNP), which is linked to the importance of this group of mammals in public health issues, especially rodents. Of the total records, 1820 (58.09%) are published in papers (n=1346; 42.96%) or held in scientific collections. Among the unpublished records (n=1787; 57.04%), 1243 are from consulting activities, 474 are in scientific collections, 242 are cited in theses and 41 are from SNP. These categories, of course, are not exclusive, since a record may be from consulting activity, have a voucher in a collection, but not be cited in a paper, for example.

Most of the records related to consulting activities (n=1243; 68.75%) are unpublished data. However, it is important to reinforce that in this type of activity, after collecting testimonial specimens, it is common to release other captured individuals of the same species. The records related to zoonoses study, on the other hand, are all from data published in papers.

All nine states with territory in the Caatinga have sampling for small mammals, but both the number of sampled localities and the number of records are unequal (Figure 3). The state with the fewest locations and records is Rio Grande do Norte followed by Piauí (Figure1).

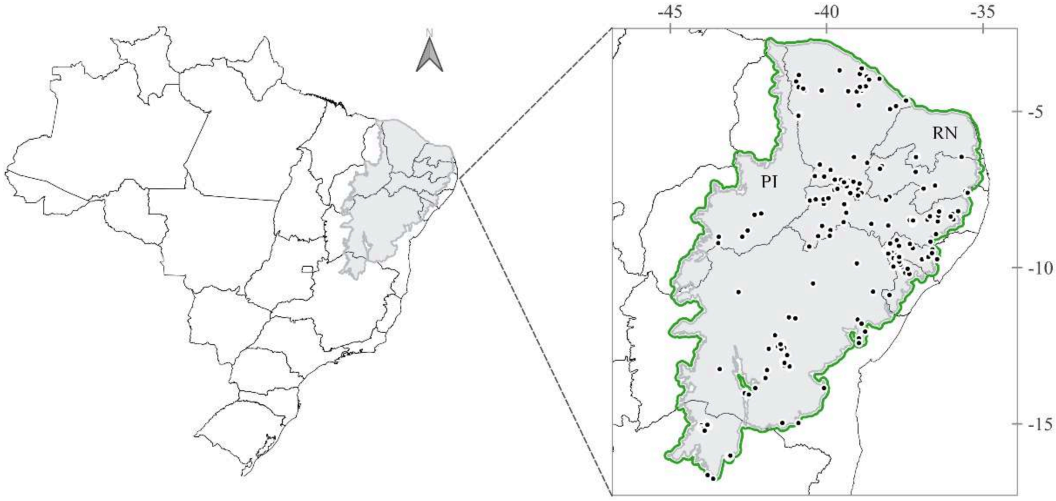

Figure 1. Map of Brazil, with the location of the Caatinga biome. Highlighted the distribution of the small mammal localities records on the biome. The Caatinga is in grey and the green line represents its limit with a 10km buffer. Black dots are the dataset locations. Gray lines are the Brazilian states boundaries, but only the initials of Piauí (PI) and Rio Grande do Norte (RN) are shown.

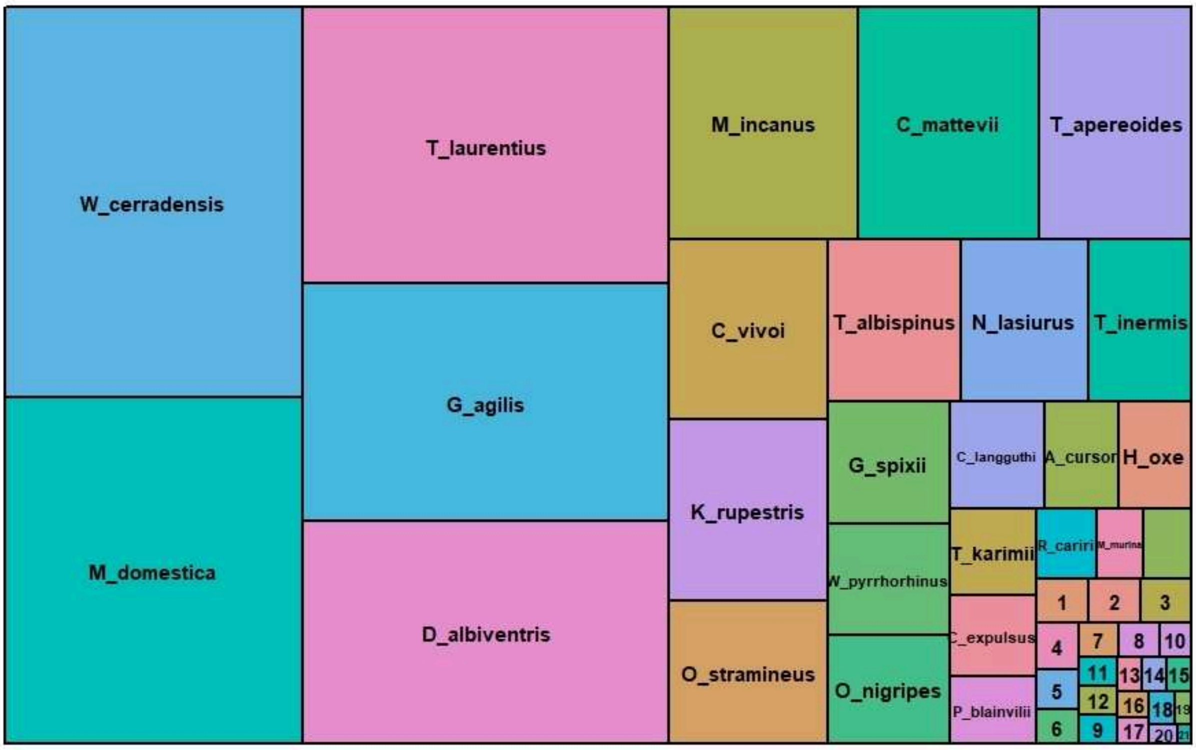

Figure 2. Number of records of small mammal species in the Caatinga. For each species, the size of the box is proportional to the number of records in the present dataset. Numbers represent species with less than 10 records (1- *E. russatus*, 2- *M. demerarae*, 3- *O. delator*, 4- *C. philander*, 5- *O. mattogrossae*, 6- *C. agricolai*, 7- *H. megacephalus*, 8- *M. americana*, 9- *G. microtarsus*, 10- *H. sciureus*, 11- *N. rattus*, 12- *R. mastacalis*, 13- D. marsupialis, 14- N. squamipes, 15- O. catherinae, 16- *O. rupestris*, 17- *P. lamarum*, 18- *P. simplex*, 19- *M. didelphoides*, 20- *O.dasytrichus*, 21- *T. yonenagae*).

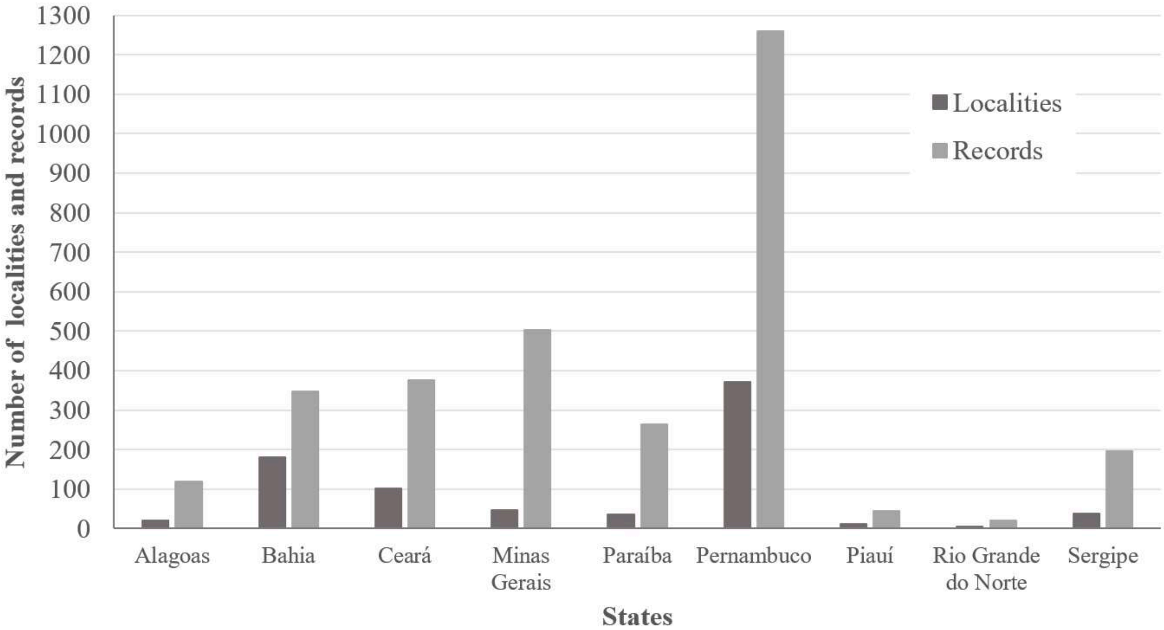

Figure 3: Number of sampled localities and small mammals’ records in the Caatinga biome by Brazilian states.

B. Final suggestions: Given the current possibility of supplementary material in scientific articles, we suggest the inclusion of tables with voucher number, date of collection, more accurate geographic coordinates and basic body measurements: head and body length (HBL), tail length (TL), feet length with/without claws (F) and ear internal length (E), all in millimetres and body weight (W) in grams. For studies in the Caatinga, we also suggest including information on the climatic season, as it can vary between years and regions in the biome (Andrade et al. 2017), in addition to being a key factor in understanding behavioural, ecological and species distribution issues.

As basic as the study is, when dealing with small mammals, it is important to have voucher specimens housed in scientific collections. As mentioned, this is a group with several taxonomic uncertainties, especially rodents. Therefore, through vouchers it is possible to update or correct taxonomic issues. Inform the date, at least the year of registration, in studies including those based on vouchers from scientific collections. These data are important for temporal analysis of occupation, and may be references for local population extinctions. Informing more accurate and precise geographic coordinates of the collection sites is important because, with GIS advances, coordinates and their accuracy make data useful for studies in many levels, from habitat use to biogeography. Finally, in inventories, provide date of collection, voucher numbers and, when possible, basic body measurements (HBL-TL-F-E-W). This information is important for studies with landscape ecology, functional diversity, among others.

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TABLES

Table 1. Description of columns of .csv files

Caatinga_SM_loc.csv	
Locality_Code	Code given to each locality
Locality	Locality of the locality
Municipality	Municipality of the locality
State	State of the locality
Lat	Decimal coordinates of the locality
Long	Decimal coordinates of the locality
Datum	Geodetic coordinate system
Coordinate_Location	Reference from where the coordinate was obtained
Accuracy	Measure of coordinate accuracy (in meters or kilometers)
Environment:	Caatinga habitat as described by the researcher or on paper (when available)
Sampling_design:	Design used to capture small mammal
Trap type:	Type of traps used to capture or record small mammals
Total trap:	Number of traps used per night sampled
Sampling nights:	Number of nights sampled per excursions/campaign
Number of excursions:	Number of excursions/campaigns in the locality
Start month and year:	Month and year when the survey started (MM.YYYY)
Final month and year:	Month and year when the survey finished (MM.YYYY)
Remarks:	Any other information
Caatinga_SM_rec.csv	
Record_Code:	Code given to unique records of small mammal
Locality_Code	Code given to unique locations, which links each record to the location where it was obtained
Date:	Date when the record was obtained (DD.MM.YYYY)
Order:	Order taxonomic classification
Genus:	Genus taxonomic classification

Species_on_source:	Species taxonomic classification reported by the researcher or on paper
Species_actual:	Species taxonomic classification after review
State	State of the record
Lat:	Decimal coordinates of the record
Long:	Decimal coordinates of the record
Datum:	Geodetic coordinate system
Coordinate_Location	Reference from where the coordinate was obtained
Accuracy	Measure of coordinate accuracy (in meters or kilometers)
Weather_season	Climate season during the record
Trap_type:	Type of traps used to capture or record the small mammal
Trap_height:	Height of the trap in which the small mammal was recorded
HBL_mm:	Head and body length in millimeters;
TL_mm:	Tail length in millimeters;
F_mm:	Feet length with/without claws in millimeters, or with claws when only one value appears;
E_mm:	Ear internal length in millimeters;
W_g:	Body weight in grams;
Collector_number:	Field number given by the collector
Voucher_number:	Voucher number given by the scientific collection to the specimen
Collection/Institution:	Scientific collection and Institution housing the specimen
Bibliographic_reference:	The reference of the paper in which the small mammal record was found
Researcher:	Researcher who provided the unpublished data
Remarks:	Any other information

Table 2. Acronyms for cited scientific Collections and Protected Areas (PA)

Institutions of Scientific Collections	
BMNH	British Museum of Natural History
CMUFS	Coleção de Mamíferos from Universidade Federal de Sergipe
LBCE	Laboratório de Biologia e Parasitologia de Mamíferos Reservatórios Silvestres from Instituto Oswaldo Cruz
MCFM	Museu de Fauna da Caatinga from Universidade Federal do Vale do São Francisco
MHNC-MAM	Museu de de História Natural do Ceará Prof. Dias da Rocha from Universidade Estadual do Ceará
MHNUFAL	Museu de História Natural from Universidade Federal de Alagoas
MN or MNRJ	Museu Nacional
MNHN	Muséum National d'Histoire Naturelle
MPEG	Museu Paraense Emílio Goeldi
MVZ	Museum of Vertebrate Zoology from University of California
MZUSP	Museu de Zoologia from Universidade de São Paulo
UFC	Coleção de Mamíferos from Universidade Federal do Ceará
UFMG	Universidade Federal de Minas Gerais
UFPB	Coleção de Mamíferos from Universidade Federal da Paraíba
UFSC	Coleção de Mamíferos; Universidade Federal de Santa Catarina
USNM	United States National Museum
UZMC	Universitäts Zoologisk Museum; Copenhagen
Protected Areas (PA)	
APA	Environmental Protection Area
ESEC	Ecological Station
FLONA	National Forest
ReBio	Biological Reserve

RPPN	Natural Heritage Private Reserve

Table 3: Small non-flying mammals' species from the Caatinga.

DIDELPHIMORPHIA	
Didelphidae	
	Caluromys philander (Linnaeus, 1758)
	Cryptonanus agricolai (Moojen, 1943)
	Didelphis albiventris Lund, 1840
	Didelphis marsupialis Linnaeus, 1758
	Gracilinanus agilis (Burmeister, 1854)
	Gracilinanus microtarsus (Wagner, 1842)
	Marmosa (Micoureus) demerarae (Thomas, 1905)
	Marmosa murina (Linnaeus, 1758)
	Marmosops incanus (Lund, 1840)
	Monodelphis americana (Müller, 1776)
	Monodelphis domestica (Wagner, 1842)
	Thylamys karimii (Petter, 1968)
RODENTIA	
Caviidae	
	Galea spixii (Wagler, 1831)
	Kerodon rupestris (Wied-Neuwied, 1820)
Cricetidae	
	Akodon cursor (Winge, 1887)
	Calomys expulsus (Lund, 1840)
	Calomys mattevii Gurgel-Filho, Feijó & Langguth, 2015
	Cerradomys langguthi Percequillo, Hingst-Zaher & Bonvicino, 2008
	Cerradomys vivoi Percequillo, Hingst-Zaher & Bonvicino, 2008
	Euryoryzomys russatus (Wagner, 1848)
	Holochilus sciureus Wagner,1842
	Holochilus oxe Prado, Knowles & Percequillo, 2021
	Hylaeamys megacephalus (Fischer, 1814)
	Necromys lasiurus (Lund, 1840)
	Nectomys rattus (Pelzeln, 1883)

Nectomys squamipes (Brants, 1827)

Oecomys catherinae Thomas,1909

Oligoryzomys mattogrossae (Allen, 1916)

Oligoryzomys nigripes (Olfers,1818)

Oligoryzomys rupestris Weksler and Bonvicino, 2005

Oligoryzomys stramineus Bonvicino and Weksler, 1998

Oxymycterus dasytrichus (Schinz 1821)

Oxymycterus delator Thomas, 1903

Pseudoryzomys simplex (Winge, 1887)

Rhipidomys cariri Tribe, 2005

Rhipidomys macrurus (Gervais, 1855)

Rhipidomys mastacalis (Lund 1840)

Wiedomys cerradensis Gonçalves, Almeida & Bonvicino, 2005

Wiedomys pyrrhorhinos (Wied-Neuwied, 1821)

Echimyidae

Makalata didelphoides (Desmarest, 1817)

Phyllomys blainvilii (Jourdan, 1837)

Phyllomys lamarum (Thomas, 1916)

Thrichomys apereoides (Lund, 1839)

Thrichomys inermis (Pictet, 1843)

Thrichomys laurentius Thomas, 1904

Trinomys albispinus (I. Geoffroy St.- Hilaire, 1838)

Trinomys yonenagae (Rocha, 1995)

8. CAPÍTULO 2: Para onde eles poderiam ir? Distribuição potencial de pequenos mamíferos na Caatinga sob cenários de Mudanças Climáticas

8. CHAPTER 2: Where could they go? Potential distribution of small mammals in the Caatinga under Climate Change scenarios

Costa-Pinto, A.L. da, Bovendorp, R.S, Heming, N.M., Malhado, A.C., Ladle, R.J., 2024. **Where could they go? Potential distribution of small mammals in the Caatinga under Climate Change scenarios**. *Journal of Arid Environments* 221:105133.

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Where could they go? Potential distribution of small mammals in the Caatinga under climate change scenarios

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ABSTRACT

Many organisms will respond to climate change by shifting their ranges while pursuing potential climatically suitable areas. Predicting these area changes is important especially in dry areas such as the Brazilian semiarid biome, the Caatinga. Here we identified which Caatinga areas would be climatically suitable for small mammal species under different climate change scenarios; and quantified how much of these potential suitable areas would be gained or lost for each species under each scenario by 2050 and 2070. The small mammal species fall into two main ecological groups: 1) arid-adapted species with good climatic suitability for most of the Caatinga (four rodents were predicted to experience gain in their total suitable areas, while there was loss of suitable areas for all marsupials and two other rodents) and 2) species with good suitability for highlands or transitions areas with the Atlantic Forest (typically more vulnerable to climate change, experiencing loss of suitable area). These are the first predictions of climatically suitable area potentially lost and gained for the Caatinga small mammals during future climate change scenarios. Our results reinforce the need to ensure that conservation strategies are in place to deal with the unavoidable climate change consequences in this unique biome.

1. Introduction

The average temperature on Earth is expected to rise to at least 1.5 °C above pre-industrial levels by 2030 and could rise by as much as 4.4 °C by 2100 (IPCC, 2021). Climate change affects biodiversity in different ways, from populations to ecosystems (McCarty, 2001). One of the most conspicuous and wide-ranging impacts will be changes in species distribution and community composition (Bellard et al., 2012; Williams and Blois, 2018), which leads to new species interactions and ecosystem function changes (Parmesan, 2006).

Reduced precipitation and an increase in extreme weather events, both known consequences of climate change, can affect population dynamics and the suitability of species occurrence, either indirectly through changes in primary productivity or directly through changes in reproductive rates (Mason-Romo et al., 2018). More broadly, some species may not be adapted to the new climate niche spectrum and, in response, may disperse to more climatically suitable areas or, when this is not possible, their populations may be reduced and even extirpated (Bellard et al., 2012). Thus, the potentially suitable area of a species may be reduced in some locations but other, previously unsuitable regions, may now be able to support sustainable populations (Mccain and King, 2014; Parmesan, 2006).

In this context, the overview of potential suitable areas and range shifts of a species under future climate change is often predicted using Ecological Niche Modelling (ENM), sometimes called Species Distribution Models (Kujala et al., 2015). In ENMs, current species occurrences are related to environmental variables, such as climate, in order to infer the variables ranges that are suitable for the species occurrence (Elith and Leathwick, 2009). Modelling has some limitations, such as not considering biotic interactions or dispersal processes (Guisan and Zimmermann, 2000), but it can perform well in characterising the environmental niche and indicating areas that are climatically suitable areas for the species, especially when attention is paid to the input data (from the taxonomic accuracy of species and their points of occurrence to the significance of environmental variables) and algorithm settings (Elith and Leathwick, 2009; Sillero et al., 2021).

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Although range shift is a well know response of animals to historical climate change, predicting and quantifying future changes in distribu- tion is still challenging. A review of mammalian responses to recent climate change identified local population extirpations, range contrac- tions, range shifts, and also no response at all (Mccain and King, 2014). However, small mammals, in specific, may be less able to track climate change as they are less mobile than large or flying mammals and will therefore be less able to reach suitable climate refuges (Schloss et al., 2012).

Small mammals have typically been less intensively researched than larger, more conspicuous mammal species (Santos et al., 2020). More specifically, studies on the effects of recent climate change on small mammal distributions are very scarce (Beever et al., 2003; Mccain and King, 2014; Myers et al., 2009; Santoro et al., 2017; Szpunar et al., 2008), and do not include studies of small mammals in arid/semiarid regions.

One such region, the northeastern semiarid region of Brazil, domi- nated by the Caatinga Seasonally Dry Tropical Forest, has been strongly affected by climate change (Vieira et al., 2015), and is predicted to experience further increases in temperatures, reductions in precipitation and more frequent drought events over the course of the century (IPCC, 2021). This is particularly worrying as the Caatinga has a unique biota among the arid, semiarid, dry sub-humid regions of the world (Silva et al., 2017), in part because it is limited in the West by the Brazilian savanna, the Cerrado (CE), and in the East by the Brazilian coastal rainforest, the Atlantic Forest (AF), both hotspots of biodiversity in Brazil (Myers et al., 2000).

We hypothesize that typical Caatinga small mammals (Rodentia and Didelphimorphia) and those shared with the Cerrado are drought adapted and therefore would gain climatically suitable areas in the CE and AF, which could increase their potential range of occurrence (Franchito et al., 2014; Rajaud and Noblet-Ducoudré, 2017; Sales et al., 2020). Conversely, species sha red with the Atlantic Forest, with mar- ginal distribution in the Caatinga or restricted to humid enclaves in the biome may lose climatically suitable habitat resulting in a more restricted distribution. The main questions are: Where could these spe- cies go? Which areas would be climatically suitable for their occurrence? The objectives of the current study are therefore: i) to identify which areas may be climatically suitable for small mammal species in the Caatinga at present; ii) to forecast which areas would be climatically suitable under future climate scenarios (IPCC, 2021), and; iii) quantify the extent of potential change in the projected climatically suitable area in the face of climate change.

2. Materials and methods

2.1. Study area

The Caatinga as an ecological region covers 912,529 km^2 and en- compasses the xeric vegetation in open scrublands, the dry forests areas, and also the highlands - enclaves of humid tropical forest, known as "Brejos de Altitude". The biome is crossed by the São Francisco River (SFR), the largest and most important perennial river of the North- eastern Brazil (Silva et al., 2017). It is an exclusively Brazilian biome with the highest biodiversity among semiarid areas of the world, it has a unique biota and high levels of endemism of the region (Albuquerque et al., 2012). However, the Caatinga is impacted by acute and chronic anthropogenic disturbance, whereas only 7.4% of the region is covered by protected area and it is still a biome with many knowledge gaps (Silva et al., 2017; Silva and Barbosa, 2017).

2.2. Ecological niche models (ENM)

Niche modelling analysis was performed using Maxent algorithm (Phillips et al., 2017) version 3.4.4 through R software version 4.1.2.

2.2.1. Small mammal occurrence data

The selection of species was based on the large dataset of small mammals from Caatinga (Costa-Pinto et al., 2023), considering those with records within the current limit of the biome (according to IBGE, 2019) and dated after 1960. Additional occurrence data, outside Caa- tinga limits, of the selected species were obtained from mammal col- lections, papers (Supplementary Material S1), and unpublished data collected by us, prioritizing records with vouchers housed in scientific collections. We checked coordinates and only occurrences with a maximum accuracy error of 5 km were used. We did not use data from online public databases as they typically have low accuracy and a high level of taxonomic uncertainty due to misidentification and outdated nomenclature (Maldonado et al., 2015), especially for small mammals. Taxonomic nomenclature follows (Abreu et al., 2021) in addition to other specific studies (for details, see Costa-Pinto et al., 2022). For the purposes of interpreting the results, the species were grouped into widely distributed in different ecoregions of the Caatinga (Silva et al., 2017) or endemic to the biome (Group 1), and species with marginal distribution, closer to more mesic biomes or restricted to humid enclaves (Group 2; Table S1).

We use the R package CoordinateCleaner to remove duplicated re- cords, occurrences falling in the sea, and wrong or impossible co- ordinates. We then spatially filter occurrences with a minimum distance apart 5 km from each other using the spThin R package (Aiello-Lammens et al., 2015). Only species with more than 12 records were modelled (Pearson et al., 2007). Databases with fewer occurrences but less bias have better predictive power than larger databases with more bias (Kujala et al., 2015; Varela et al., 2014).

2.2.2. Climate variables

As predictor variables, 11 bioclimatic variables from WorldClim version 2.1 were used (BIO02, BIO03, BIO05-07 and BIO12-17), with a resolution of 2.5 arcminutes (~5 km). These variables were selected based on best biological significance for the small mammal group (Fuller et al., 2021). Bioclimatic variables BIO18 and BIO19 were not included because, after visual inspection, they present truncated values in the study area (Sillero et al., 2021). The calibration area was generated for each species by adding a 1.5 decimal degree buffer to the convex polygon obtained from their occurrence points, the predictor variables were cut to the calibration area and the least correlated were selected (Spearman correlation, cutoff of 0.75).

2.2.3. Modeling

The Maxent models were set with the following configurations: feature classes (FC) linear (L), quadratic (Q), product (P), hinge (H) and combinations (LQ, LP, PQ, LH, PH, QH, LQP, LQH, LPH and QPH); regularization multipliers (RM) values of 0.5, 1.5, 2, 2.5, 3.5, 4 and 4.5; selection of points for calibration and cross-validation by Jackknife for $N < 15$ occurrences and by block for $N \geq 15$. These cross-validation settings are important when modelling process is based on small sam- ple sizes (Morales et al., 2017). A total of 98 models per species were generated and these were selected by the Ensemble of the Best Per-forming Models metric (EBPM), which selects the 10% models with the best values of Area Under the Curve (AUC, set to > 0.75) and Omission Rate (OR) (Boria et al., 2017). The final model is a consensus of the best performing models.

The latest Coupled Model Intercomparison Project - phase 6 (CMIP6) produces projections with different greenhouse gas emission scenarios, called Shared Socio-economic Pathways (SSP) (IPCC, 2021). For future climate change scenarios, we opted to use a more optimistic (SSP 245) and more pessimistic (SSP 585) scenarios, with data projected for the 2050s (2041–2060) and 2070s (2061–2080). The Global Circulations Models (GCMs) IPSL-CM6A-LR and MIROC6 were selected, as they present better performances for South America (Cannon, 2020). The suitability projections were generated by an ensemble of the GCMs. All the consensus models were geographically projected onto the limits of the Caatinga (according to IBGE, 2019) adding a 1 decimal degree buffer in order to identify possible changes in suitability at the western and dry edge with the Cerrado, and at the eastern and wetter edge with the Atlantic Forest.

2.2.4. Suitable area

In order to map and quantify the total suitable area (TSA) in the Caatinga for each species in all scenarios and periods, the continuous suitability values were categorized into "not suitable" and "suitable" using the Minimum Training Presence (mtp) as threshold. This choice was based on the fact that most of the occurrence data we use comes from a dataset (Costa-Pinto et al., 2023) in which most of the studies or samplings are punctual and geographically biased, which underestimates the distribution range of the species. Therefore, mtp is a better choice because as it is less conservative at indicating suitable areas, it avoids underestimating the projections on areas where the species can occur but were never sampled. Given the nature of the geographical distribution of sampling effort for these species, more restrictive thresholds are prone to bias the projections of suitable areas towards a few better sampled regions. The suitable area calculation was performed within the biome boundary (no buffer added). Since species can lose climatically suitable area in one region while gaining in another, we check these predicted areas of change in climate suitability and balance between these losses and gains to determine the increase, decrease, or stability of TSA for the species in each future scenario and decade using the current as a reference.

We used the R packages ENMwizard (Heming et al., 2018), ENMeval (Muscarella et al., 2014), and others packages to generate the ecological niche models.

3. Results

Of the 34 species of small mammals modelled, 24 (9 marsupials and 15 rodents) had models with AUC >0.75 (model results Supplementary Material S1) and had their climatically suitable area described here. Common species throughout the Caatinga (Group 1) and the most

frequent in more mesic areas in the biome (Group 2) presented patterns of current climatically suitable areas as expected: the first group with good suitability in most of the biome, while the second one with better suitability in specific areas, such as highlands or transitions areas with the Atlantic Forest (Fig. 1; Figure S1).

All species were predicted to undergo changes of climatic suitability enough to change the TSA in the future scenarios and time steps. Species from Group 2 would be more vulnerable to climate change and would experience more loss of suitable area in all scenarios and decades. This is also true for the majority species from Group 1, including all marsupials. However, four species, all of them rodents from Group 1, are expected to increase their TSA, including in areas from CE and AF biomes, with some areas losing climate suitability, especially in the worst-case scenarios (Fig. 2, Figure S3 and S4).

After contrasting the TSA in each scenario with the present, our results predict a reduction in this parameter inside the Caatinga limits for 83.3% (N = 20) of species modelled in all future scenarios and time steps (Table 1). *O. delator* is expected to lose more than 90% of its current total suitable area in all scenarios and *T. albispinus* in the SSP 585 scenario. No marsupials are expected to gain TSA in a future of climate change, although some of them gain suitable areas outside their original (baseline) TSA (Fig. 2, S3 and S4). *M. domestica*, in particular, is the only Group 1 marsupial predicted to experience no gain in climate suitability under any scenario, contradicting our hypothesis that all species adapted to aridity would have their climatic areas increased. In fact, 14 out of 24 species had no predicted gain in their suitable areas in all scenarios: the marsupials *M. demerarae*, *M. murina, M. incanus, M.americana* and *M. domestica*; and the rodents *A. cursor*, *C. langguthi*, *E. russatus*, *H. megacephalus*, *N. lasiurus*, *O. nigripes*, *O. dasythrichus*, *O. delator*, *R. mastacalis* and *T. albispinus.* No species is predicted to experience no loss in climate suitable areas in all scenarios and decades, regardless of the final TSA gain or loss.

Considering all species, the average area predicted to be gained is always smaller than the area predicted to be lost in all cases, and the amount of area lost may be higher in the SSP 585 scenario and for the year 2070 (Table 2). There is also a large variation in the value of lost or gained area between species (high SD) (Table 2).

4. Discussion

We provide the first forecasts and quantifications of climate change impacts on climatically suitable areas for small mammals in the most biodiverse semiarid area in the world. Although most mammal species found in the Caatinga are climatically adapted to the biome, all species in our study are expected to undergo shifts in suitable climate space due to the biome getting hotter and drier.

While identifying the current suitable areas of small mammal species in the Caatinga, we were able to fill some gaps of potential occurrence in areas with deficient sampling for the group, such as the eastern and western extremes on the north of the biome, where the states of Rio Grande do Norte and eastern Piauí are located. These states have the lowest sampling effort for small mammals in Northeast Brazil, as well as the lowest number of records for the group (Costa-Pinto et al., 2022). Therefore, our findings reinforce to where sampling efforts could be directed, with the aim of mitigating the status of being the least known semiarid region in the world (Albuquerque et al., 2012).

As anticipated, species of mammal with different ecologies are likely to respond differently to future climate change. Species that are more common in the Atlantic Forest (AF) and which are more adapted to interior highlands or transitional areas (Group 2) are predicted to be more vulnerable to climate change, and will lose more climatically suitable areas not only inside the limits of the Caatinga, but also in the AF itself (Fig. 2 and Figure S4) leading to the loss of their Total Suitable Area (TSA). In contrast, some species that are more adapted to the current biophysical conditions of the Caatinga (Group 1) are predicted to gain suitable habitat in current areas of the Cerrado (CE) and AF. Our results clearly indicate how the semiarid climate would expand over neighbouring biomes, accompanied by the potential "invasion" of savanna-dwelling small mammal species but also some potential Savannization foci in the AF, a trend also predicted for some areas in the Amazon (Sales et al., 2020). This so called "faunal savannization" forces a community redistribution, creating new negative interspecific relationships for forest-specialist species that already are undergoing range contraction (Sales et al., 2020; Santoro et al., 2017).

The predominance of xerothermophilic species in small mammal communities has been a persistent result on long-term monitoring studies in regions under climatic pressure in Italy (Szpunar et al., 2008) and Spain (Santoro et al., 2017). For instance, in the Doñana National Park (southwest Spain), the rodent most adapted to dry conditions *Mus spretus* has increased in abundance as the number of extremely hot days has increased in the preceding autumn, while species less adapted to dry conditions have declined markedly in recent years (Santoro et al., 2017). Similarly, more plastic species such as the common American opossums, *Didelphis virginiana* (closely related to the common South American opossum, *D. albiventris*), extended its distribution into the northern United States (where it was not recorded until the second half of the 20th century), presumably due to recent climate change (Myers et al., 2009). However, *D. albiventris* and *M. domestica* - both ecologically flexible species that can withstand wide limits of temperature and precipitation throughout its distribution – are predicted to lose TSA in our forecasts. This may imply that they are already living in their climatic limits, and that the current biophysical conditions of the Caatinga are the upper limits of the climatic tolerance for the species. The extinction risk is expected to be lower for mammals that already experience greater seasonality in temperature and precipitation as they may have potential adaptive flexibility (Pacifici et al., 2017), but in the case of *D. albiventris*

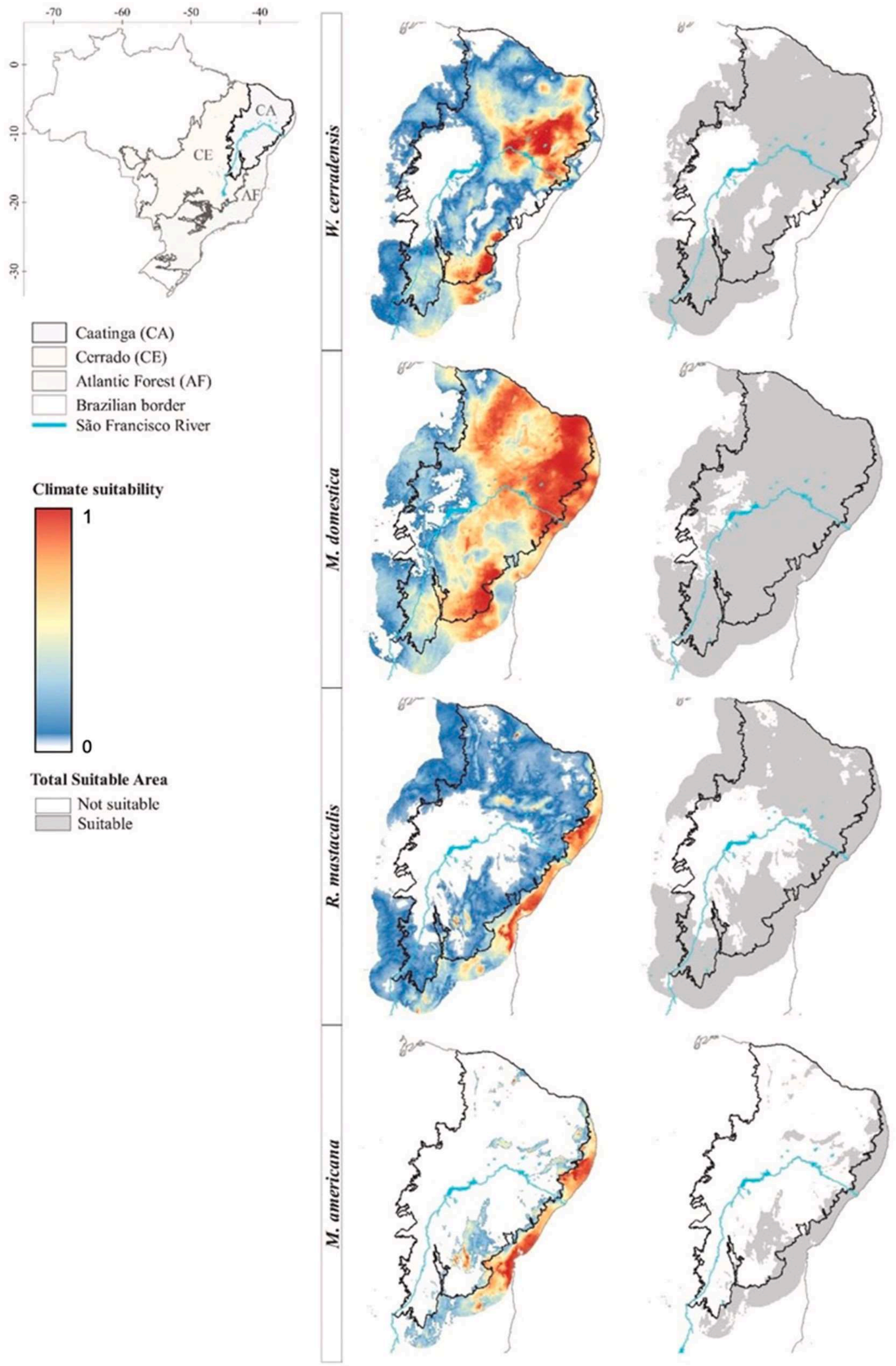

Fig. 1. Projection in geographic space of the current climatic suitability of four species of small mammals in the Caatinga (with a buffer of 1 decimal degree). On the left, maps with continuous suitability values after (threshold applied); on the right, the Total Suitable Area (TSA); binary suitability after application of the minimum presence threshold). *W. cerradensis* and *M. domestica* are exemplifying the species of Group 1, while *R. mastacalis* and *M. americana* are exemplifying those of Group 2. For all species, see Figures S1 and S2 in Supplementary Material 2.

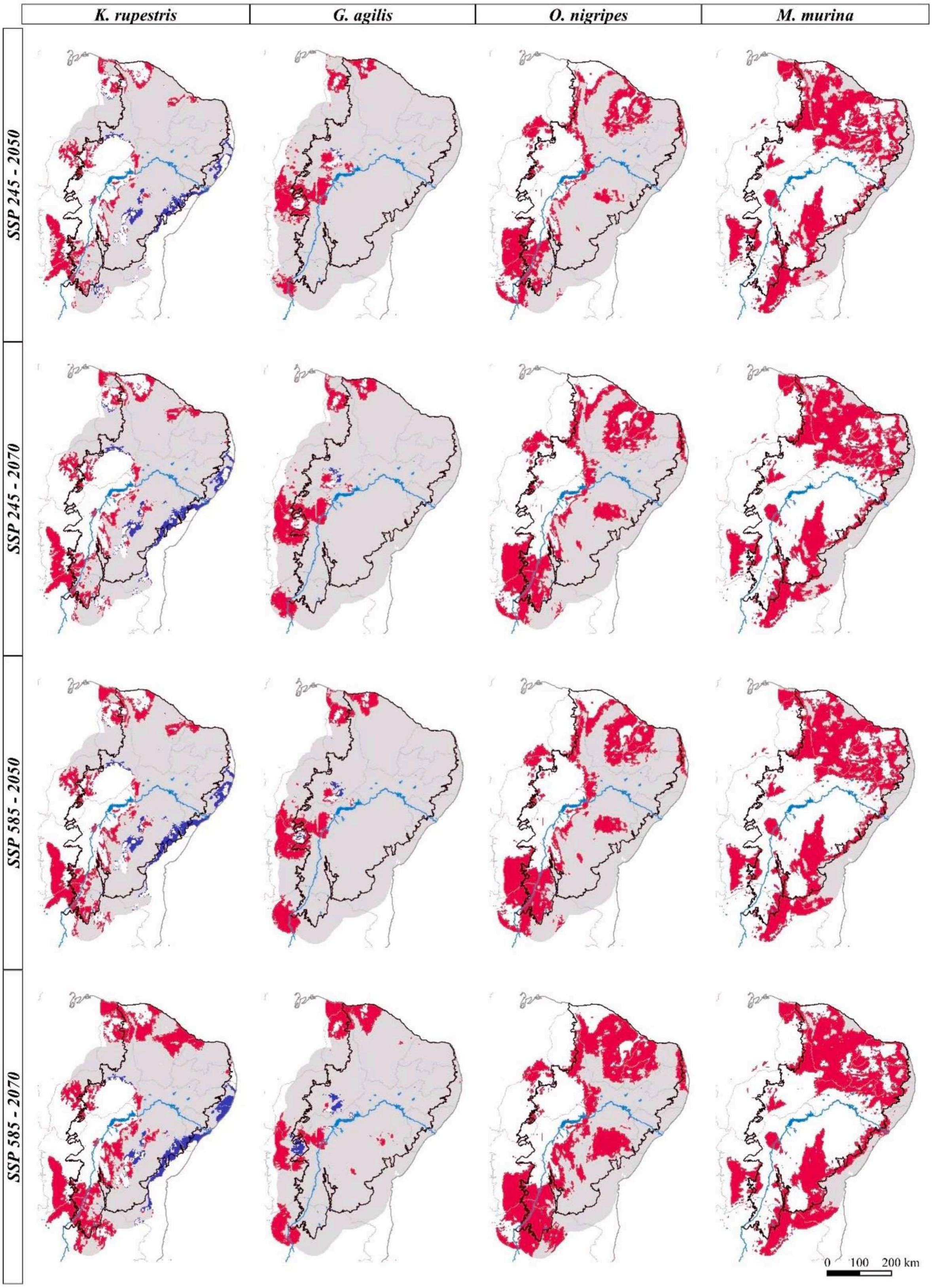

Fig. 2. Predicted areas of change in climate suitability between present and future models for four small mammals′ species. In grey, the current Total Suitable Area (TSA); in red, areas with loss of suitability; in dark blue, areas with suitability gain. The Caatinga border is represented by a black line and the São Francisco River by a light blue outline. *K. rupestris* and *G. agilis* are exemplifying the species of Group 1, while *O. nigripes* and *M. murina* are exemplifying those of Group 2. For all species, see Figures S3 and S4 in Supplementary material 2.

Table 1
Total suitable area (km²) in the present, used as baseline, and the predicted change in TSA (gain in bold and lost with negative values) for each small mammal species in the Caatinga limits for both optimistic (SSP 245) and pessimistic (SSP 585) scenarios at each decade.

	Present	SSP 245		SSP 585	
		2050	2070	2050	2070
DIDELPHIMORPHIA					
Cryptonanus agricolai	368,665.9	-29,709.6 -8%	-17,842.9 -5%	-26,666.2 -7%	**32,347.5** **9%**
Didelphis albiventris	841,806.2	-14,197.3 -2%	-17,093.5 -2%	-18,602.4 -2%	-22,164.9 -3%
Gracilinanus agilis	851,635.3	-48,014.9 -6%	-44,349.8 -5%	-43,473.3 -5%	-42,194.9 -5%
Gracilinanus microtarsus	347,957.0	-145,999.4 -42%	-160,506.1 -46%	-167,928.0 -48%	-174,412.6 -50%
Marmosa demerarae	421,586.4	-226,952.7 -54%	-269,318.4 -64%	-283,960.0 -67%	-339,996.7 -81%
Marmosa murina	374,800.0	-298,225.0 -80%	-320,024.1 -85%	-323,771.0 -86%	-348,668.1 -93%
Marmosops incanus	593,009.8	-35,885.8 -6%	-49,149.2 -8%	-89,883.4 -15%	-102,441.0 -17%
Monodelphis americana	107,012.6	-81,272.9 -76%	-91,907.2 -86%	-94,025.0 -88%	-104,903.7 -98%
Monodelphis domestica	794,434.2	-139,526.0 -18%	-157,652.7 -20%	-163,140.9 -21%	-202,451.7 -25%
RODENTIA					
Akodon cursor	299,427.5	-137,291.3 -46%	-156,495.9 -52%	-165,236.8 -55%	-195,597.3 -65%
Calomys expulsus	248,921.4	**31,457.5** **13%**	**29,914.2** **12%**	**14,810.3** **6%**	**6408.6** **3%**
Calomys mattevii	792,182.3	**10,012.5** **1%**	**6502.3** **1%**	**5701.8** **1%**	-13,833.5 -2%
Cerradomys langguthi	681,852.9	-342,683.6 -50%	-417,871.9 -61%	-426,907.3 -63%	-585,303.3 -86%
Euryoryzomys russatus	172,161.3	-87,484.2 -51%	-112,278.7 -65%	-112,610.9 -65%	-146,233.0 -85%
Hylaeamys megacephalus	509,916.2	-320,600.4 -63%	-392,755.3 -77%	-399,612.0 -78%	-483,455.5 -95%
Kerodon rupestris	644,339.6	-36,366.3 -6%	-56,732.5 -9%	-68,262.7 -11%	-128,790.5 -20%
Necromys lasiurus	660,899.7	-274,014.6 -41%	-333,554.6 -50%	-350,731.6 -53%	-442,101.3 -67%
Oligoryzomys nigripes	651,755.0	-151,330.6 -23%	-207,113.7 -32%	-207,242.5 -32%	-306,840.1 -47%
Oxymycterus dasytrichus	77,481.8	-58,188.2 -75%	-64,973.5 -84%	-66,658.1 -86%	-72,725.1 -94%
Oxymycterus delator	48,447.9	-44,540.9 -92%	-45,869.8 -95%	-46,274.3 -96%	-47,190.1 -97%
Rhipidomys mastacalis	542,360.4	-256,968.6 -47%	-317,902.9 -59%	-338,057.1 -62%	-425,718.6 -78%
Thrichomys laurentius	797,518.0	**46,248.3** **6%**	**44,171.0** **6%**	**45,029.3** **6%**	**43,014.2** **5%**
Trinomys albispinus	233,854.6	-194,496.9 -83%	-212,137.7 -91%	-213,143.8 -91%	-229,694.5 -98%
Wiedomys cerradensis	642,980.0	**115,827.9** **18%**	**123,661.8** **19%**	**131,383.5** **20%**	**129,521.8** **20%**

Table 2
Total potential suitable area changes, using present as baseline, considering all small mammals' species in the Caatinga limits for both optimistic (SSP 245) and pessimistic (SSP 585) scenarios at each decade.

Scenario	Decade	Area loss (km2)			Area gain (km2)		
		N (%)	Mean	SD	N (%)	Mean	SD
SSP 245	2050	20 (83.3%)	147,876.1	106,125.0	4 (16.6%)	50,886.5	45,778.7
	2070		174,107.3	128,434.3		51,062.3	50,829.8
SSP 585	2050		182,104.5	130,482.5		49,231.2	57,289.5
	2070		222,685.0	167,634.5		52,823.0	53,393.1

and *M. domestica* this flexibility may be reaching its limit. In fact, the reduction of current suitable areas for native, arid adapted species in the Caatinga when considering future projections of climate change has been expected for species of plants (Silva et al., 2019) and birds (Gonçalves et al., 2023).

All 14 species in our study that are predicted to have no gains in climate space under future scenarios and decades are common in the Atlantic Forest (Group 2), with the exception of the marsupial *M. domestica* and the rodent *N. lasiurus*. When considering all species with TSA loss, this number rises to 20. In other words, the vast majority of small mammal species lose regions that could be climatic refuges for maintaining populations. It should be noted that the only modelled species threatened with extinction is the endemic rock cavy *Kerodon rupestris* (known as 'mocó'), which is in the Vulnerable-VU category on the recent Brazilian National Red List (MMA, 2022). The mocó is widely hunted and associated with rocky outcrops, such as inland cliffs and mountain peaks (Conceição and Bocchiglieri, 2021). The combination of climatically suitable area loss, its strong association to a specific habitat and high hunting pressure makes this species a conservation priority and one that may require additional protection measures to avoid the worst consequences of future climate change.

For species more adapted to the biophysical conditions of the Atlantic Forest and even the Cerrado, dispersing eastwards may be the only option to keep their populations within climatically suitable areas. Populations in the highlands (islands of humidity in the semiarid) may be particularly at risk, being driven to move upwards until they have nowhere to go. This trend, known as 'the escalator effect' (Marris, 2007), is already reported for recent climate change with small mammals inhabiting the Arctic (Prost et al., 2013), high-mountain habitats (Beever et al., 2003; Mccain and King, 2014; Moritz et al., 2008) and even some species at tropical dry forests in Western Mexico (Mason-- Romo et al., 2018). Although species may be able to shift their distri- bution tracking climatic conditions they are adapted to, in these "new" areas there is a possibility that other abiotic variables and biotic interactions may not be suitable for the species to fill their fundamental niche (Visser, 2008).

A factor not addressed in this study, but that may influence species displacement into new potential suitable areas are geographical barriers (Soberón et al., 2017). The Caatinga has a major biogeographic barrier, the São Francisco River, which shapes the current distribution of some small mammal species and may play a major barrier to these species moving to climatically suitable areas on the opposite bank. For instance, some species have a restricted distribution to the North or South of this river: *G. microtarsus*, *M. incanus*, and *T. albispinus* on the South side, *W. cerradensis* and *C. langguthi* on the North. Therefore, without human intervention these species would not be able to reach potential climatic areas on the opposite side of their current occurrences.

More generally, there is no guarantee that populations will be able to disperse towards suitable areas, either due to conditions in the matrix to be crossed, geographic barriers, the ability of these species to disperse and move, or the speed of these climate changes compared to rate of dispersal (Schloss et al., 2012). Studies that take these variables into account can provide more realistic (and often more pessimistic) fore- casts. Sales et al. (2020) predicted more frequent and greater magnitude range reduction if dispersal constraints were included in models of the future distribution of mammalian species in tropical rainforests. Po- tential distribution changes due to climate change would also lead to new conformations of communities (some of which may be non-analogue communities), affecting coexistence between species as well as changing the provision of ecosystem services.

Climate change would affect the suitability of small mammals in the Caatinga in the not-so-distant future. Whether under pessimistic or optimistic scenarios, the climate boundaries for the survival of many small rodents and marsupials in the Caatinga will be severely chal- lenged. In this study we outlined some of the consequences of this in terms of expected shifts in species suitable climate space and pinpoint suitable areas potentially lost and gained for small mammals, leading to loss and gain of TSA in the most biodiverse semiarid area in the world. As for the initial question "Where could these species go?", as far as climate is concerned, now we know where they could go. Unfortunately, our models suggest that, for the vast majority of these species, the area of bioclimatically suitable habitat is shrinking or will be practically inac- cessible, highlighting the need for large scale conservation planning in this unique biome.

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CRediT authorship contribution statement

Anna Ludmilla da Costa-Pinto: and. **Ricardo S. Bovendorp:** conceived the manuscript, and. **Neander M. Heming:** wrote the script and provided full support during the analyses. ALCP collected and analysed the data, created the figures and wrote the manuscript, gave significant contributions to the discussion and general review. **Ana Cláudia Malhado:** and. **Richard James Ladle:** edited and review the manuscript. All authors approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Research data are already published as Costa-Pinto et al. (2022) or at the Supplementary material

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Appendix A. Supplementary data

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MATERIAL SUPLEMENTAR - CAPÍTULO 2

SUPPLEMENTARY MATERIAL – CHAPTER 2

Supplementary material - S1

Manuscript "*Where could they go? Potential distribution of small mammals in the Caatinga under climate change scenarios*"

List of additional references used for small mammals' occurrence besides Costa-Pinto et al. (2022)

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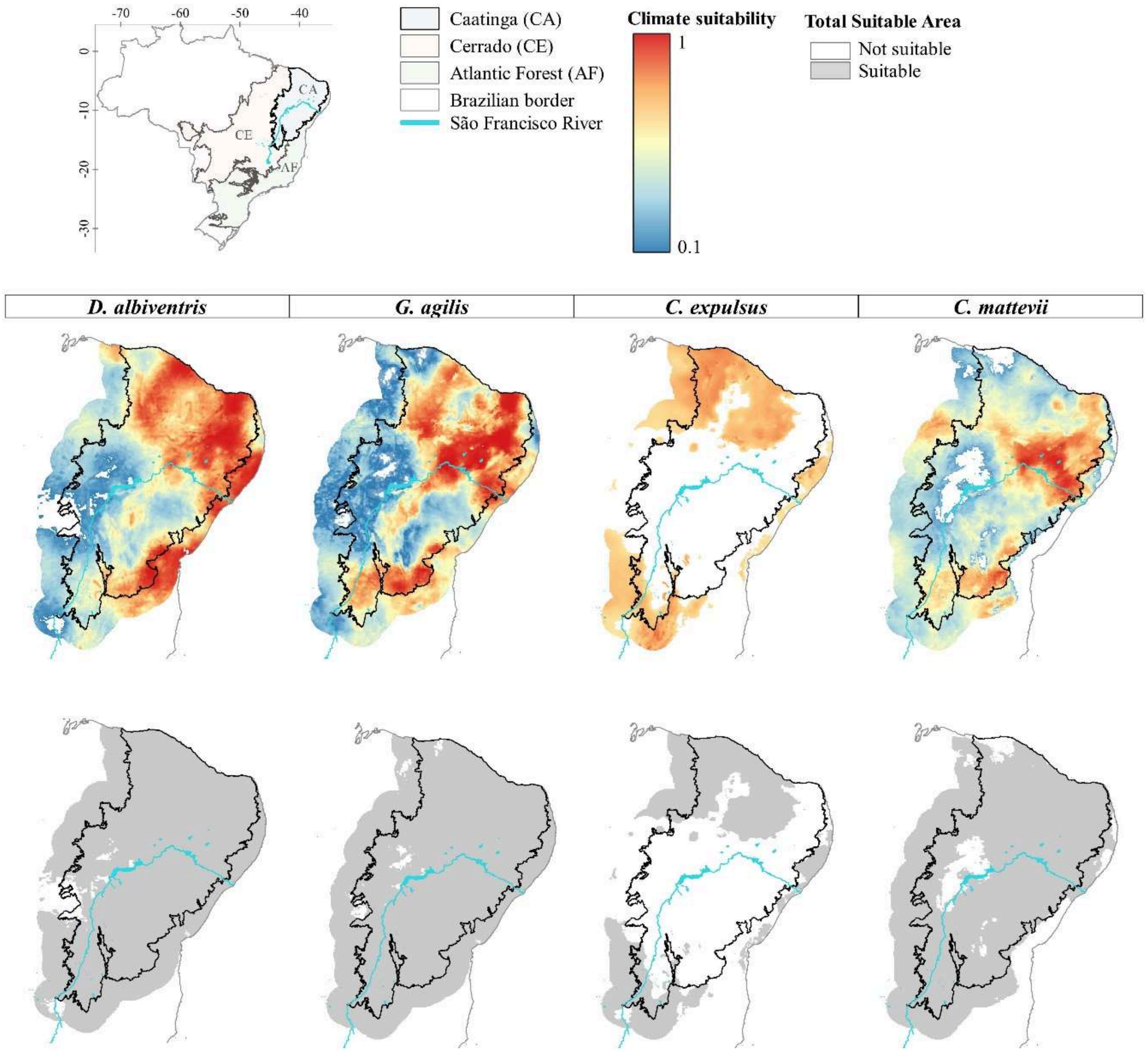
Table S1: Species modelled summary. Group of distribution (**1**, common to Caatinga; **2**, mostly restricted to more mesic environments of the biome, see main text); number of initial records; number of records after Coordinate Cleaner and SpThin packages; Cross Validation Method (calibration technique); AUC and OR values; and if the species was analysed (Yes/No) based on AUC > 0.75.

Species	Group	Inicial N	Coordinate Cleaner	SpThin	Cross Validation Method	AUC	OR	Analyzed
DIDELPHIMORPHIA								
Cryptonanus agricolai (Moojen 1943)	2	20	18	16	Block	0.77	0.09	Yes
Didelphis albiventris Lund, 1840	1	349	158	117	Block	0.81	0.00	Yes
Gracilinanus agilis (Burmeister, 1854)	1	334	156	107	Block	0.82	0.00	Yes
Gracilinanus microtarsus (Wagner, 1842)	2	45	45	37	Block	0.78	0.12	Yes
Marmosa (Micoureus) demerarae Thomas, 1905	2	33	30	25	Block	0.92	0.00	Yes
Marmosa murina (Linnaeus, 1758)	2	50	47	39	Block	0.93	0.03	Yes
Marmosops incanus (Lund, 1840)	2	206	94	57	Block	0.77	0.00	Yes
Monodelphis americana (Müller, 1776)	2	34	33	32	Block	0.83	0.02	Yes
Monodelphis domestica (Wagner, 1842)	1	362	169	102	Block	0.81	0.00	Yes
Thylamys karimii (Petter, 1968)	1	32	18	15	Jackknife	0.43	0.07	No
RODENTIA								
Akodon cursor (Winge, 1887)	2	71	64	46	Block	0.82	0.06	Yes
Calomys expulsus (Lund, 1840)	1	36	27	19	Block	0.75	0.00	Yes
Calomys mattevii Gurgel-Filho, Feijó & Langguth, 2015	1	153	88	49	Block	0.78	0.02	Yes
Cerradomys langguthi (Percequillo et al. 2008)	2	44	24	22	Block	0.86	0.09	Yes
Cerradomys vivoi Percequillo et al. 2008	2	107	70	16	Block	0.57	0.00	No
Euryoryzomys russatus (Wagner, 1848)	2	23	23	20	Block	0.84	0.05	Yes
Galea spixii (Wagler, 1831)	1	59	46	41	Block	0.73	0.00	No
Holochilus oxe Prado, Knowles & Percequillo, 2021	1	12	10	NA	NA	NA	NA	NA
Hylaeamys megacephalus (Fischer, 1814)	2	21	19	19	Block	0.78	0.06	Yes
Kerodon rupestris (Wied Neuwied, 1820)	1	103	27	24	Block	0.77	0.07	Yes
Necromys lasiurus (Lund, 1840)	1	101	79	64	Block	0.78	0.01	Yes

Oecomys catherinae Thomas,1909	2	32	31	24	Block	0.56	0.00	No
Oligoryzomys nigripes (Olfers,1818)	2	91	74	60	Block	0.76	0.00	Yes
Oligoryzomys stramineus Bonvicino and Weksler, 1998	1	76	27	23	Block	0.62	0.00	No
Oxymycterus dasytrichus (Schinz 1821)	2	20	20	18	Block	0.81	0.18	Yes
Oxymycterus delator Thomas, 1903	2	19	17	16	Block	0.94	0.10	Yes
Rhipidomys macrurus (Gervais, 1855)	2	22	17	13	Jackknife	0.69	0.08	No
Rhipidomys mastacalis (Lund 1840)	2	41	41	36	Block	0.84	0.04	Yes
Thrichomys apereoides (Lund, 1839)	1	132	30	13	Jackknife	0.74	0.08	No
Thrichomys inermis (Pictet, 1843)	1	58	44	10	NA	NA	NA	NA
Thrichomys laurentius Thomas, 1904	1	360	149	91	Block	0.77	0.02	Yes
Trinomys albispinus (I. Geoffroy St.- Hilaire, 1838)	2	83	18	12	Jackknife	0.80	0.08	Yes
Wiedomys cerradensis Gonçalves et al. 2005	1	392	191	75	Block	0.88	0.00	Yes
Wiedomys pyrrhorhinos (Wied-Neuwied, 1821)	1	44	24	18	Block	0.39	0.25	No
Total	-	3565	1928	1276	-	-	-	-

Supplementary material – S2

Manuscript "Where could they go? Potential distribution of small mammals in the Caatinga under climate change cenarios"



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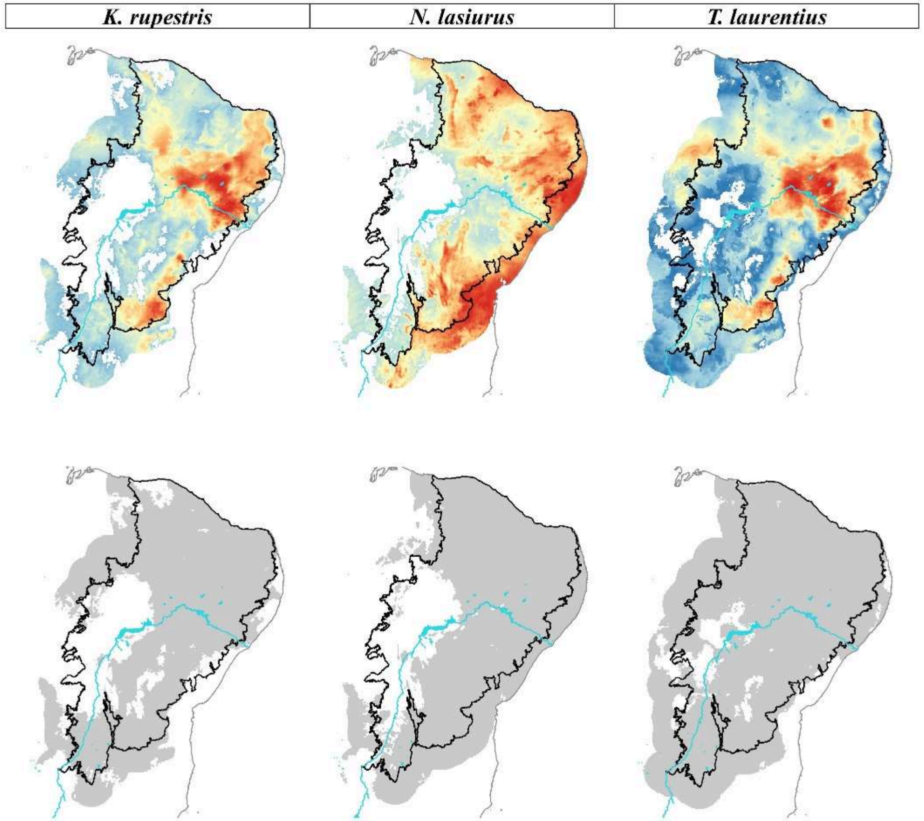
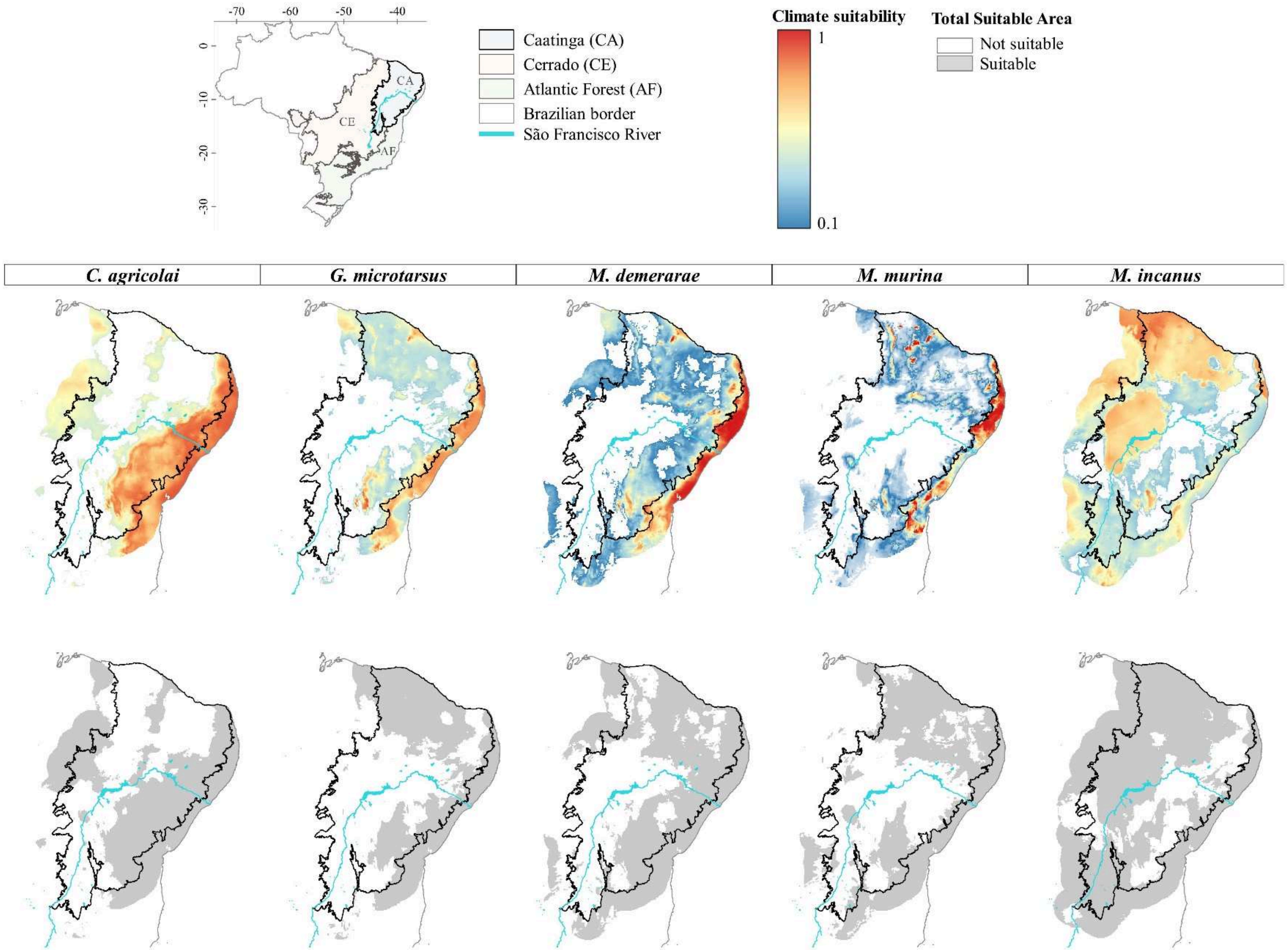
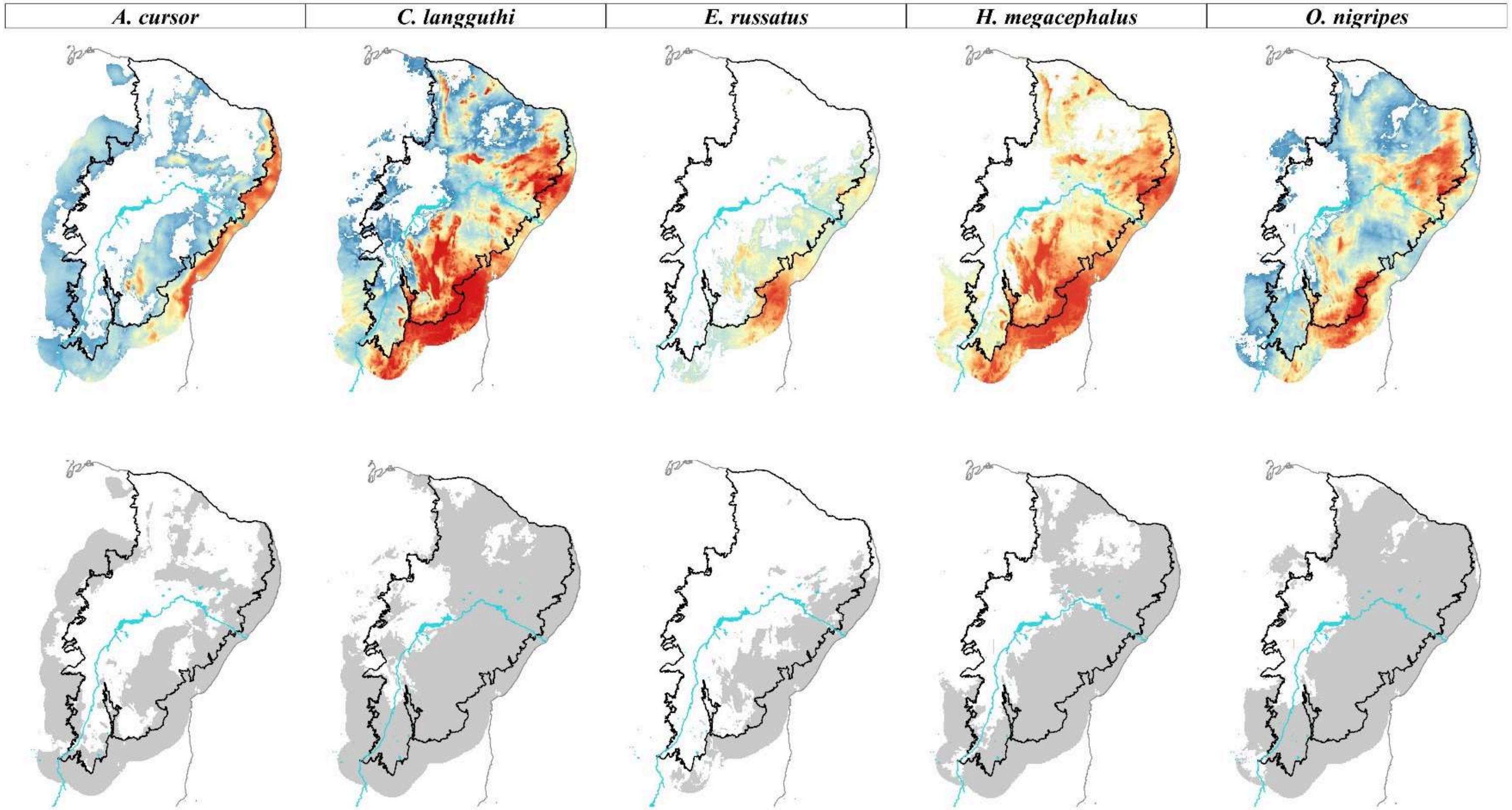


Figure S1: Projection in geographic space of the current climatic suitability of areas in the Caatinga (with a buffer of 1 decimal degree) for species of small mammals from Group 1. On the top, maps with continuous suitability values (threshold applied), and on the bottom, binary suitability after application of the minimum presence threshold.


-70
-60
-50
-40
0
-10
-20
-30
CA
CE
AF
Caatinga (CA)
Cerrado (CE)
Atlantic Forest (AF)
Brazilian border
São Francisco River
Climate suitability
1
0.1
Total Suitable Area
Not suitable
Suitable
C. agricolai
G. microtarsus
M. demerarae
M. murina
M. incanus

(cont.)



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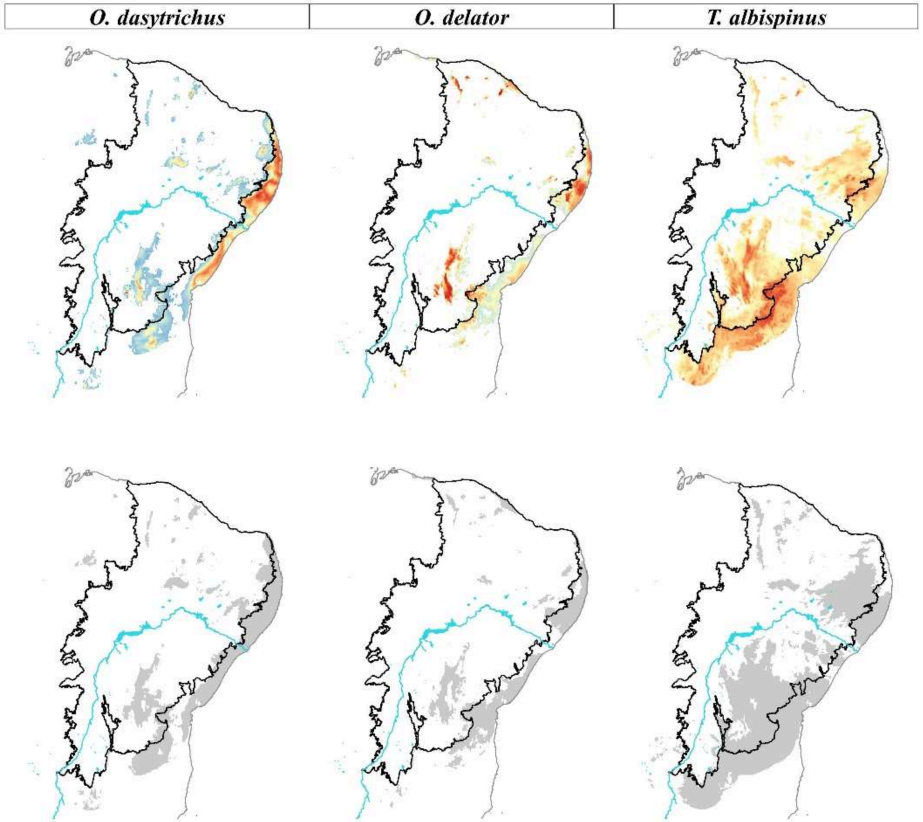
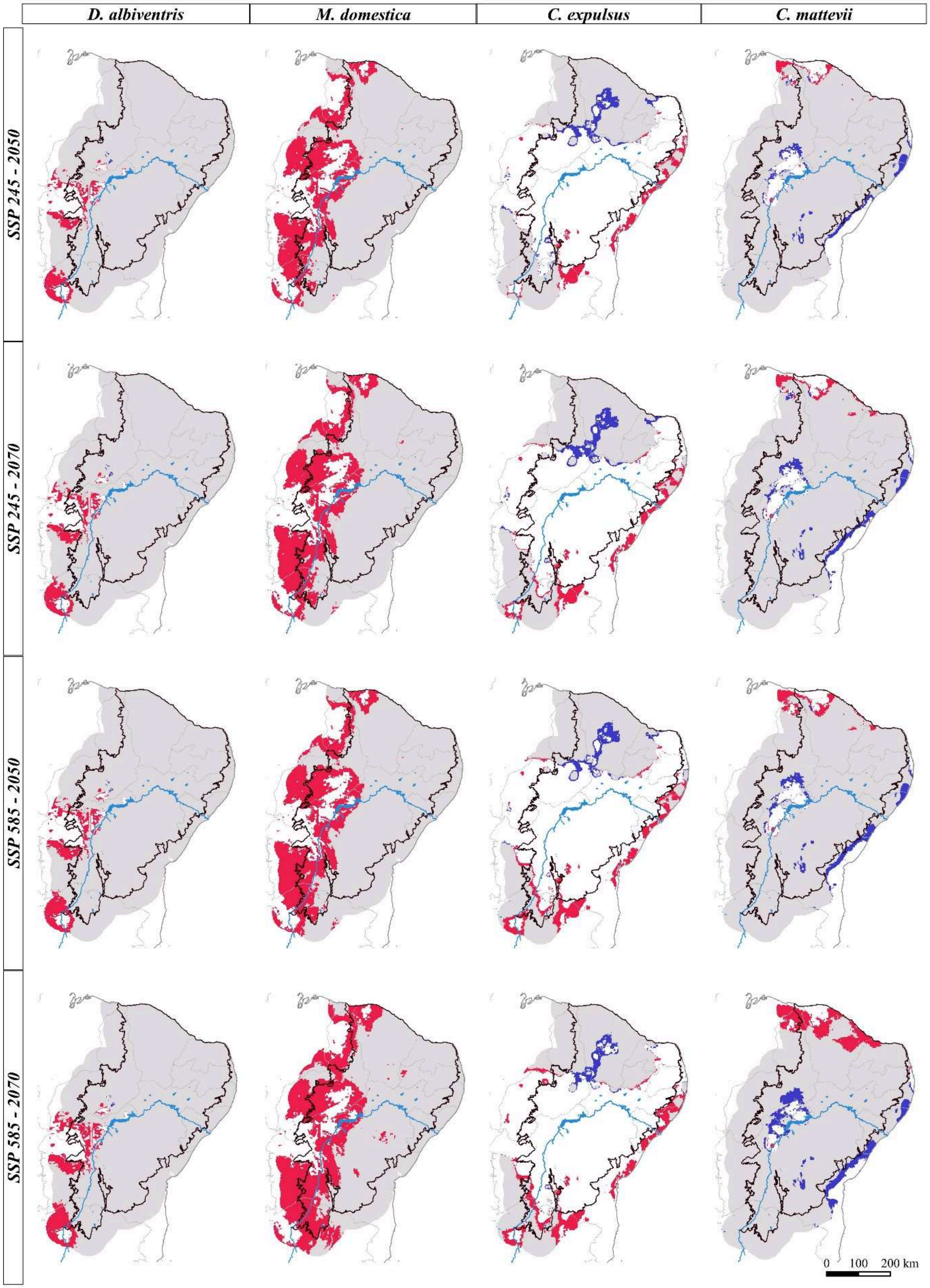


Figure S2: Projection in geographic space of the current climatic suitability of areas in the Caatinga (with a buffer of 1 decimal degree) for species of small mammals from Group 2. On the top, maps with continuous suitability values (threshold applied), and on the bottom, binary suitability after application of the minimum presence threshold.


D. albiventris
M. domestica
C. expulsus
C. mattevii
SSP 245 - 2050
SSP 245 - 2070
SSP 585 - 2050
SSP 585 - 2070
0 100 200 km

(cont.)

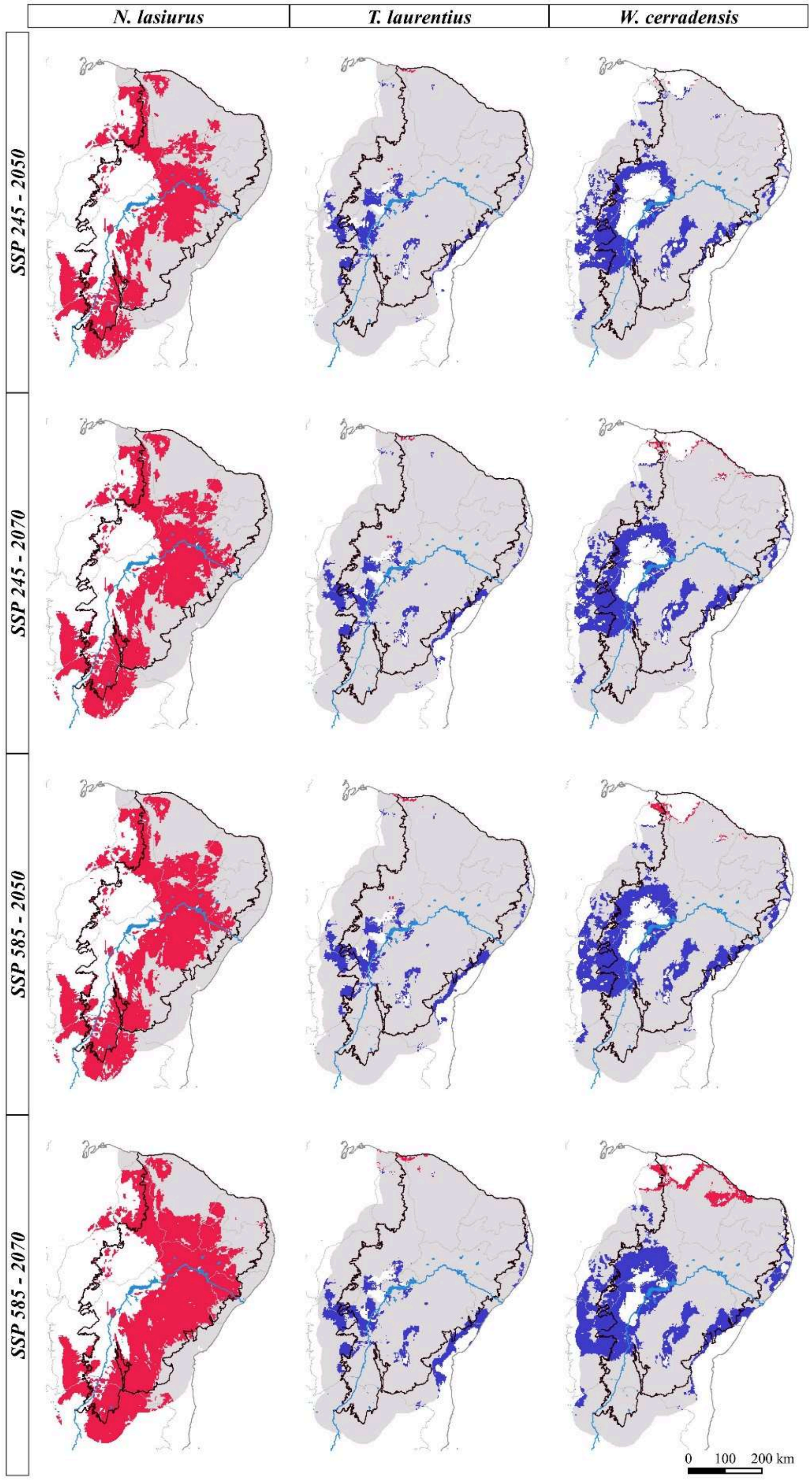
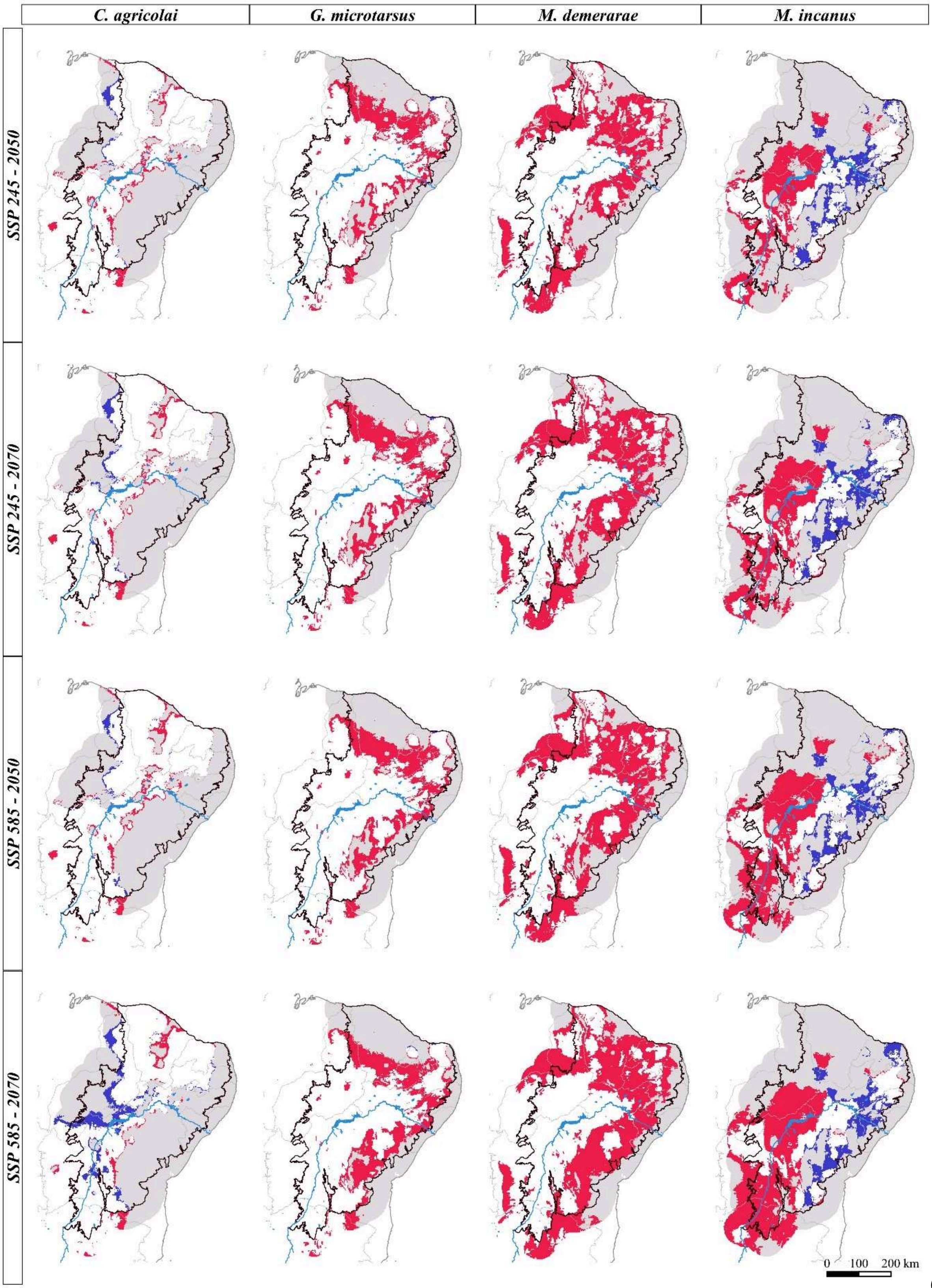
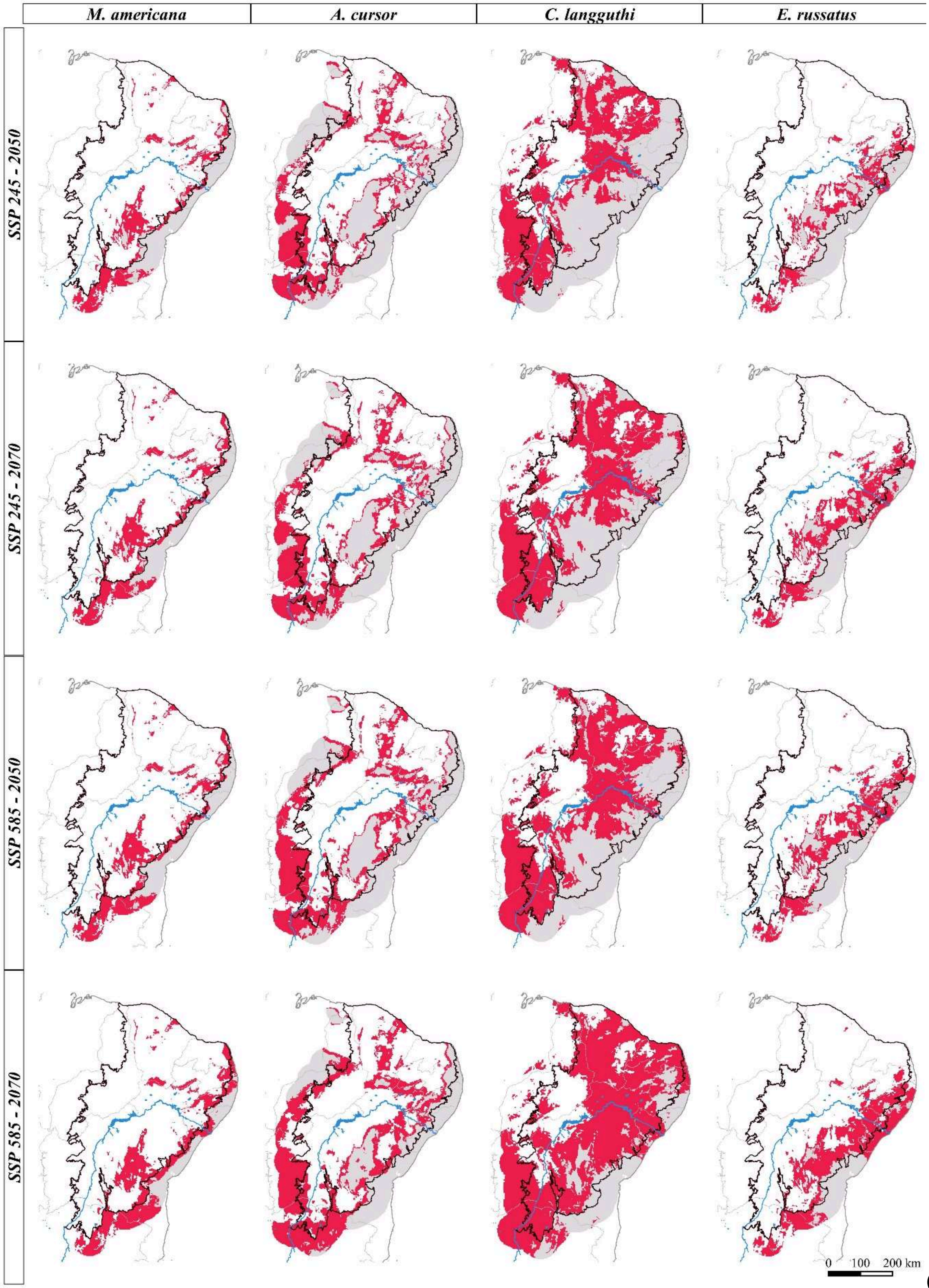


Figure S3: Predicted areas of change in climate suitability between present and future models for small mammals' species from Group 1. In grey, the current suitability; in red, areas with loss of suitability; in blue, areas with suitability gain. The Caatinga Border is represented by a black line and the São Francisco River by a light blue outline.

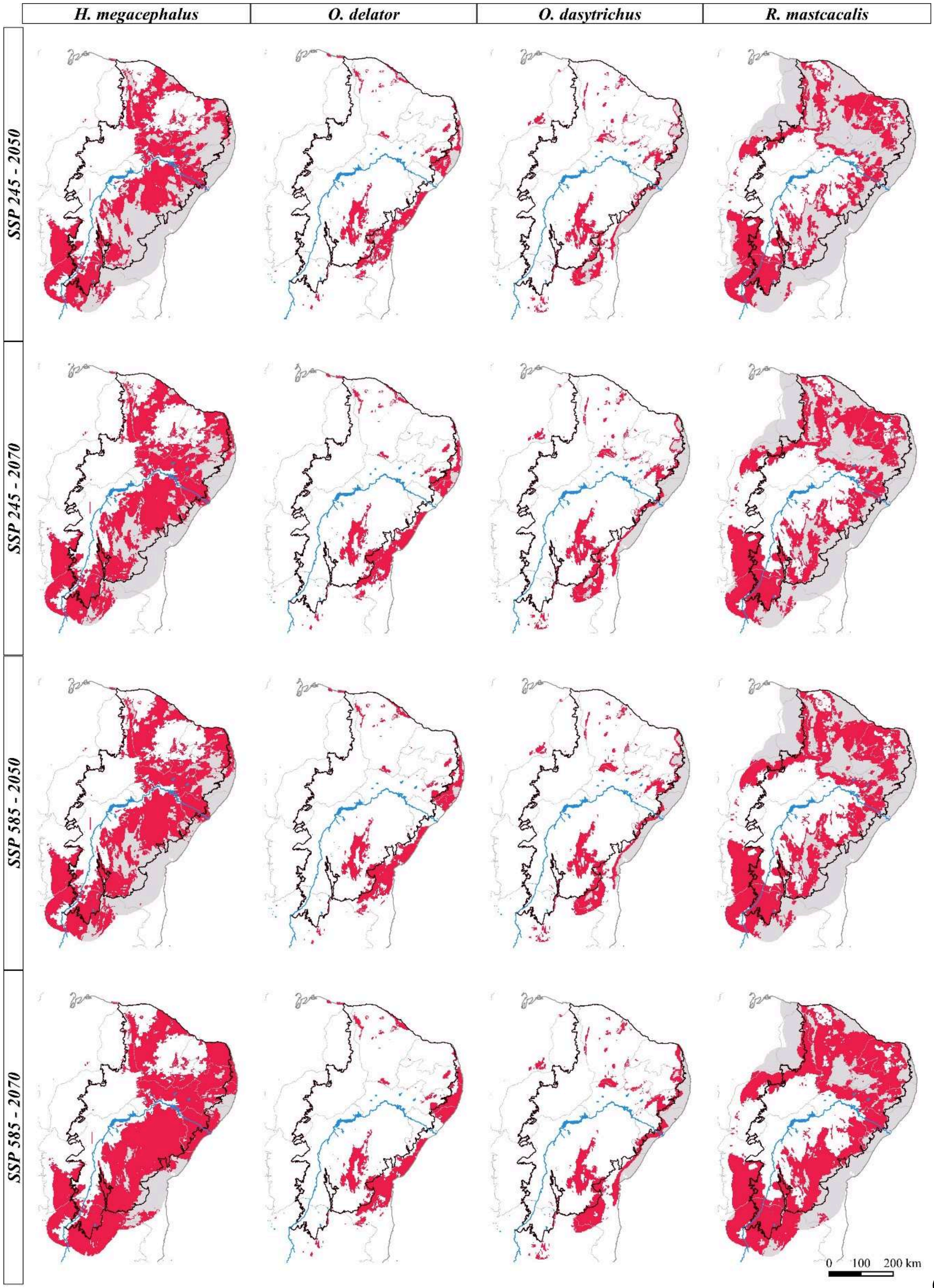

C. agricolai
G. microtarsus
M. demerarae
M. incanus
SSP 245 - 2050
SSP 245 - 2070
SSP 585 - 2050
SSP 585 - 2070
0 100 200 km

(cont.)



M. americana
A. cursor
C. langguthi
E. russatus
SSP 245 - 2050
SSP 245 - 2070
SSP 585 - 2050
SSP 585 - 2070
0 100 200 km

(*cont.*)


H. megacephalus
O. delator
O. dasytrichus
R. mastcacalis
SSP 245 - 2050
SSP 245 - 2070
SSP 585 - 2050
SSP 585 - 2070
0 100 200 km

(cont.)

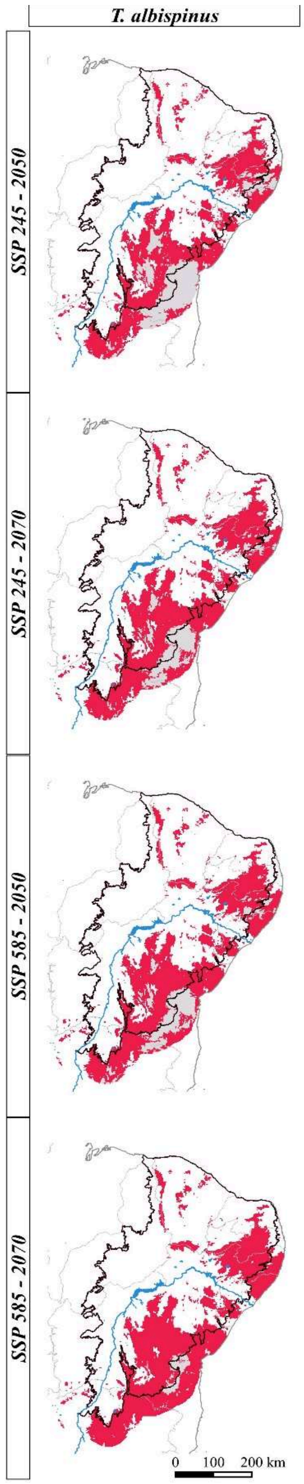


Figure S4: Predicted areas of change in climate suitability between present and future models for small mammals' species from Group 2. In grey, the current suitability; in red, areas with loss of suitability; in blue, areas with suitability gain. The Caatinga Border is represented by a black line and the São Francisco River by a light blue outline.

9. CAPÍTULO 3: Planejando para um futuro de mudanças: priorizando áreas para conservação de pequenos mamíferos na Caatinga

9. CHAPTER 3: Planning for a future of changes: prioritizing areas for conservation of small mammals in the Caatinga

Costa-Pinto, A.L., Kujala, H., Bovendorp, R.S., Malhado, A.C., Ladle, R.J., 2023. **Planning for a future of changes: prioritizing areas for conservation of small mammals in the Caatinga**. [Under review] Diversity and Distributions.

Running title: Prioritising small mammals in the Caatinga

Abstract

Aim

Human land-use and climate change are two of the main threats affecting biodiversity, especially in arid/semiarid regions. The most effective way to protect the species in these ecosystems against these threats is through the delimitation of Protected Areas (PAs). However, such PAs need to be targeted cost-efficiently and consider future climate change. We identify priority areas to preserve small mammal species in the Caatinga in the present and in a future of climate changes. We also evaluate how well these priority areas are protected by currently PAs and identify ways forward to improve their protection.

Location

The Caatinga Dry Forest, Northeast Brazil.

Methods

We use ecological niche models and Zonation spatial prioritisation software to identify the top 30% priority areas to preserve small mammal species under current climate and land use scenarios, besides considering optimistic and pessimistic scenarios of future climate change. We also evaluate how much these priority areas are covered by current PAs, identify ways to further improve their protection using hierarchical mask analysis, and by evaluating species mean distribution coverage.

Results

Climate change will not hugely shift the distribution of priority areas for species conservation in the Caatinga. Around 13% of the identified priority areas overlap with current PAs, and planning the expansion of PAs considering integral protection areas increases the coverage of priority areas to more than 18% and captures more than 72% of species suitable area.

Main conclusions

Our prioritisations take into account climate change and provide low risk if conducted as a "no-regrets" conservation action. These priority areas are poorly supported by the Brazilian PA system, and need of further protection. One cost-effective option could be to upgrade some Sustainable Use PAs into more restrictive ones. Securing these priority areas helps preserve the long-term ecosystem functioning and to prevent biodiversity loss in a changing world.

Keywords: Climate Change, Didelphimorphia, Dry Forest, Protected Areas, Rodentia, Zonation.

Introduction

Anthrophogenic land use and climate change are major threats to global biodiversity (Newbold 2018, IPCC 2021). Considering that both are critical planetary boundaries that humanity is heading for overcoming, and that climate change is also a core boundary (Lade et al. 2020), it is a ultimatum for biodiversity conservation actions to start now. Climate change threatens biodiversity by transforming parts of current ranges of species climatically unsuitable, forcing them to either adapt or migrate to avoid extinction (Parmesan 2006). Advancing at a faster rate than any known climate event in the history (Loarie et al. 2009, Diffenbaugh and Field 2013), anthropogenic climate change poses major challenges to species that are forced to shift their distributions in order to track their climatically suitable niche, particularly species with poor dispersal capabilities and/or little overlap between their present and future climate niches (Parmesan 2006). Combined with unprecedented levels of landcover change, which create additional dispersal barriers and reduce adaptation potential of species through habitat loss and fragmentation, human land use and climate change put species in double-jeopardy (Travis 2003, Jetz et al. 2007). Furthermore, climate change may weaken previous conservation efforts by forcing already protected species to shift their distributions outside currently protected areas (Araújo et al. 2011).

The standard approach to estimate future species distribution shifts and their impacts on biodiversity is through ecological niche models (ENMs), also known as species distribution models or habitat suitability models, (Araújo et al. 2011, Guisan et al. 2013, Kujala et al. 2015). ENMs are statistical and machine learning tools that use information on species known occurrence and associated environmental conditions to estimate the environmental suitability of unsurveyed locations (Guisan and Zimmermann 2000, Elith and Leathwick 2009). They can be used to explore how the suitability of locations might change under changing climatic conditions. For instance, using ENMs, Ribeiro et al. (2016) estimated that 85% of mammal species in Brazilian Amazon are likely to be exposed to novel climatic conditions in more than 80% of their current distribution by 2070.

The backbone of biodiversity conservation is the preservation of natural habitats and ecosystem functions through the establishment of Protected Areas (hereafter PAs) as they protect species against habitat loss and habitat fragmentation besides other human-induced threats (Lovejoy 2006). PAs are areas recognized by law, and with great value not only for biodiversity conservation, but also for ecosystem services and sustainable use (Fonseca et al. 2017). Because of the scarcity of conservation resources and the urgency of stopping biodiversity decline (Watson et al. 2014), it is vital that conservation actions such as the delimitation of PAs are targeted to maximize conservation impact and minimize costs. This in turn requires robust identification of areas where protection will result in the best possible conservation benefits.

Systematic conservation planning (Margules and Pressey 2000) guides cost-effective conservation actions through a multi-step procedure, where current gaps in the protection of habitats and ecosystems are first identified and priorities for additional protection are then established. Within this framework, spatial conservation prioritisation analyses help to identify priority areas where protection results in the greatest benefit for the greatest number of species and habitats (Moilanen et al. 2009). Spatial prioritisation software such as Marxan (Possingham et al. 2000) and Zonation (Moilanen et al. 2005, 2022) are commonly used to conduct such analyses. Selecting priority areas for conservation is, therefore, one of the first steps to create PAs. However, these prioritisations rarely consider the changes in the climate suitability of these areas in the long or even medium term (Araújo 2009), but focus instead on the present distribution patterns of species. A good strategy to preserve biodiversity would be to make prioritisations sensitive to potential changes in climate suitability for species, so that PAs delimited now will also be able to protect climatically suitable areas for species in a future of climate change (Kujala et al. 2013).

Anthrophogenic land use and climate change are of particular concern for arid and semi-arid regions in the world, such as the Caatinga, a Seasonally Dry Tropical Forest, the major biome in Northeast Brazil (Seddon et al. 2016, Silva et al. 2017). Although the Caatinga has the highest biodiversity among semiarid areas of the world, with an unique biota (Albuquerque et al. 2012), the biome has already lost half its original cover and continues to be impacted by chronic and acute anthropogenic disturbance (Antongiovanni et al. 2020). Additionally, climate change has already been causing longer and more frequent droughts in this water-limited biome, leading to desertification (Seddon et al. 2016, IPCC 2021). All these factors have direct and indirect consequences for the persistence and distribution of species. For instance, a widespread and common Caatinga marsupial (Didelphidae, Didelphinae), *Monodelphis domestica* (Wagner, 1982), is predicted to suffer reduction of climatically suitable areas in the Caatinga and may expand into neighbouring less arid biomes, such as the Atlantic Forest and Cerrado, as a result of reaching its climatic limit with the warming and reduced precipitation predicted for the Caatinga (Costa-Pinto et al., 2024). Small mammal species - represented in Brazil by all marsupials and rodents under 2 kg – play important roles in the ecosystem as predators, prey and seed dispersers, and are also useful for understanding responses to environmental and climate change (Hope et al. 2017). This group of mammals have limited movement (Schloss et al. 2012), are sensitive to the availability of resources (Costa-Pinto et al. 2023) and to body heating, so they must change their behaviour and seek thermally suitable microclimates within their habitats (Fuller et al. 2021) in response to the environmental and climate changes. The consequences of a changing future can be minimised by protecting small mammal suitable habitats and, therefore, their microhabitats.

Currently, approximately 9% of the Caatinga is officially protected (MMA 2022a). In Brazil, the term Protected Areas refers to conservation units, indigenous lands and other natural areas established by law, such as riverbanks. There are 12 categories of conservation units gathered into two main types: sustainable use (SU), which are more flexible regarding sustainable use of natural resources, and integral protection (IP), whose main goal is to preserve biodiversity, being more restricted to human use (MMA 2011). The SU type is larger in number and territorial size, encompassing categories such as Environmental Protection Area (APA - Área de Proteção Ambiental, in Portuguese) where private ownership is allowed, towns can be maintained and natural resources exploited within its boundaries The IP type includes categories such as Ecological Stations (ESEC - Estação Ecológica) where only scientific research and preservation-oriented management activities are allowed (MMA 2011, 2022a). For the purposes of this work, we consider Protected Areas (PA) to be synonymous with conservation units.

Here, we identified priority areas to preserve 40 small mammal species in the Caatinga under current climate and land use scenarios, and priority areas to protect their habitats in the biome under future climate change. To do so, we modeled the expected distribution shifts of species and analyse how this affects their conservation needs in the future. We also evaluate how well these priority areas are protected by currently PAs and identify ways forward to improve their protection.

Methods

Study area

The Caatinga occupies 11% of Brazilian territory and most of the Northeast region (Silva et al. 2017). It is located between two Brazilian Hotspot of biodiversity biomes (Myers et al., 2000), the Cerrado on the west and the Atlantic Forest on the east, and it is crossed by the São Francisco River, an important biogeographic barrier (Figure 1). As a semiarid biome, the Caatinga is characterised by a long and intense dry season which varies in its duration both temporally among years, and spatially among its nine recognised ecoregions, favouring its phytophysiognomic diversity (Velloso et al. 2002). The dominant vegetation in the Caatinga ranges from open scrublands to tall, dry forests with different intermediate vegetational compositions, besides some wet enclaves, represented mainly by the Chapada Diamantina Complex and wet forest relicts, the highlands known as “Brejos de Altitude” (Queiroz et al. 2017).

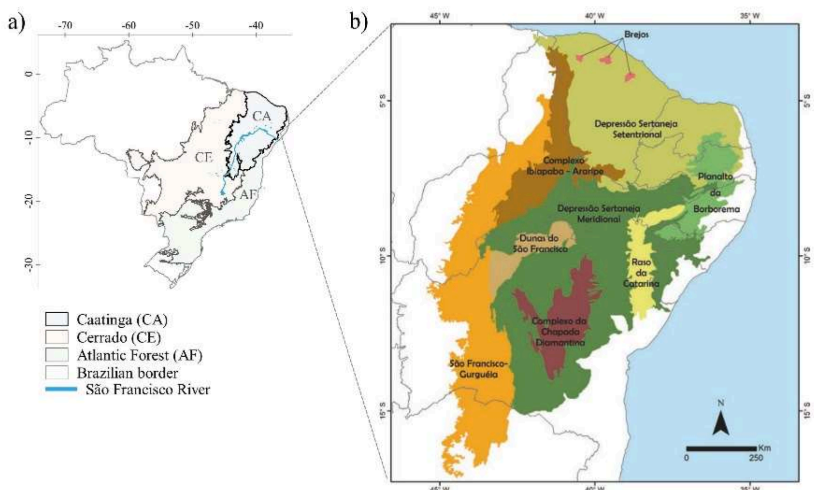


Figure 1. Caatinga biome (according to IBGE, 2019): a) location and its surrounding biomes and b) Caatinga ecoregions (adapted from Silv*a et* al., 2017).

According to the National Registry of Conservation Units (CNUC, in Portuguese) the Caatinga has 193 PAs, of which 126 are for Sustainable Use (SU) and 67 for Integral Protection (IP). In terms of coverage, 9% of the Caatinga is covered by PAs, of which 7% are SU and only 2% are IP (MMA 2022a).

Small mammal records

Small mammal records were gathered from the recent database published by Costa-Pinto *et al.* (2023), together with additional records from papers and scientific collections, filtering out occurrences older than 1990 and with spatial accuracy less than 5km. Details about taxonomic issues can be found in (Costa-Pinto et al. 2023). We gathered a total of 3,641 records of 40 small mammal species (30 rodents and 10 marsupials) (Table S1.1) of which five are endemic to the biome and three are categorised as threatened by the Brazilian latest National List of Endangered Species (Portaria MMA Nº148/2022): the rodents *Kerodon rupestris* (Wied-Neuwied, 1820) – VU (Vulnerable), *Phyllomys blainvilii* (Jourdan, 1837) – LC (Least Concern), *Rhipidomys cariri* Tribe, 2005 – VU, *Trinomys yonenagae* (Rocha, 1995) – EN (Endangered), and *Wiedomys pyrrhorhinus* (Wied-Neuwied, 1821) – LC. The small mammals of the Caatinga can be grouped into two main ecological groups, arid adapted and non-arid adapted species, the latter with better suitability for highlands or transitions areas with the Atlantic Forest (Costa-Pinto et al. 2024). The non-arid adapted species are predicted to be more impacted by climate change, losing much climatically suitable area in the Caatinga, and also in transition areas with the Brazilian Cerrado and Atlantic Forest (Costa-Pinto et al. 2024).

We used the *CoordinateCleaner* package in R version 4.1.2 to search for and remove any duplicates. In order to reduce sampling bias, we spatially filtered occurrences with a minimum distance apart of 5 km using the *spThin* package (Aiello-Lammens et al. 2015). After data cleaning and filtering, there were a total of 1,262 records left, ranging from 10 to 117 between species (Table S1.1). For 32 species with 12 or more records, we used ecological niche models to estimate their present and future habitat suitability under climate change (see section Ecological niche modelling). For the remaining eight species, we used their occurrence records to inform the conservation prioritisation in two alternative ways: For all other species than *Trinomys yonenagae*, the occurrence records of the species were rasterized to a uniform grid at 2.5' (arc minute) resolution, where grid cells with occurrence points marked known presences. *Trinomys yonenagae*, which had only one occurrence record, is a rodent species known to be confined to a specific area of the sand dune habitat on the left bank of São Francisco River (Figure 1). We therefore used the polygon of the APA "Dunas e Veredas do Baixo Médio São Francisco", a PA covering the particular sand dune region, and filtered out the local urban areas within the APA

(IBGE, 2019) plus a 500m buffer around them. The resulting polygon was then rasterized and used to represent the area of suitable habitat for *T. yonenagae* in the spatial prioritisation.

Ecological niche modelling

We produced environmental suitability maps with ecological niche models for 32 of the 40 species using the Maxent algorithm (Phillips et al., 2017) version 3.4.4 through R version 4.1.2, and packages *ENMwizard* (Heming et al., 2018) and *ENMeval* (Muscarella et al., 2014). Maxent is known as the best algorithm to perform at low sample sizes (Wisz et al. 2008) specially when finetuning feature classes and regularization multiplier parameters (Morales et al. 2017).

We used spatial data at 2.5 arc minutes (~5x5 km^2) resolution on elevation, climate and land use as model predictors. Elevation and Bioclimatic variables BIO 02, BIO 03, BIO 05-07, BIO 12-17 (WorldClim v.2.1; Table S1.2), which describe the mean, range, extremes and variability of annual temperature and precipitation, were pre-selected based on their biological relevance for the small mammals (Costa-Pinto et al., 2023; Fuller et al., 2021). In addition, we used the within pixel proportion of coverage of six land use/land cover (LULC) categories from Mapbiomas Project (Mapbiomas, 2022): natural vegetated area, pasture, agriculture, rocky outcrops, water and urban area (details on the predictors variables in Table S1.2). We used a convex polygon obtained from all filtered and cleaned species occurrence points buffered with a 1.5 decimal degree buffer to define our modelling area, which expands beyond the borders of Caatinga (Figure S1.1), and used this to randomly sample 10,000 background points for model building (Phillips et al. 2017). A broader modelling area was used for two reasons: to be able to include more species records, and therefore to build more informative models, and to better capture the environmental niche of each species. The predictor variables were cut to the modelling area and, to reduce problems with collinearity, we generate a correlation matrix, selecting one between two predictors with Sperman correlation − $r_s > 0.75$.

During the Maxent model building, options for feature classes (linear, quadratic, product, hinge) and their combinations were restricted according to species sample size, allowing more complex models to be built only for species with sufficiently many records (Muscatello et al., 2021; Phillips et al., 2017; Table S1.1 and Table S1.4). Because many species had a small number of records, the models were further fine-tuned by testing all combinations of allowed feature classes and a set of regularization multipliers (0.5, 1.5, 2, 2.5, 3.5, 4 and 4.5) (Morales et al. 2017), and selecting the best model based on the Area Under the Curve (AUC) (Table S1.1). All model variants were cross-validated using jackknife for species with $N \leq 15$ occurrences and blocks for species with $N > 15$. For species for which no models reached the test AUC > 0.75 in the cross-validations, we rejected the ENMs and reverted to using only point records. For species with test AUC > 0.75, the final parsimonious models were achieved by iteratively removing variables with less than 1% of contribution importance (Williams et al., 2012) (Table S1.3). Finally, we apply the minimun training presence (mtp) threshold to the final models.

Using the final models, we projected species future distributions for years 2050 (2041-2060) and 2070 (2061-2080) under optimistic (SSP245) and pessimistic (SSP585) climate change scenarios from Shared Socio-economic Pathways with CMIP6 (Eyring et al. 2016). We used the Global Circulations Models (GCMs) IPSL-CM6A-LR and MIROC6, as they have been shown to perform better for South America (Cannon 2020). As our aim was to understand which areas should be protected today, under current land use conditions, to better support biodiversity under future of climate change, we use the same current LULC predictors for the future projection models. Projections were generated as an ensemble mean of the GCMs for each time period and scenario. All models were geographically projected to the Caatinga, however, for species for which the São Francisco River is considered to act as a biogeographic barrier, the models were further restricted to the North/South side of the river based on the known current range of the species. Since based on the known records of *Rhipidomys macrurus* in North Caatinga this species does not co-occur with other species of *Rhipidomys*, suggesting a likely inter-specific biotic filtering, we post-process the model projections of this species using a minimum bounding hull plus 2º buffer as a mask.

Spatial conservation prioritisation

We used the spatial conservation prioritisation software Zonation v.5 (Moilanen et al. 2022) to identify priority areas for protection in the Caatinga region. Zonation is a maximum-utility type optimisation tool that produces a priority ranking of each spatial unit (here 2.5 x 2.5 arc minutes grid cells) based on feature data (present and future maps for each species), ordering the grid cells from least to most important for conservation in a manner that maximises the representation of all features in the top ranked grid cells. Consequently, a set of top ranked priority areas together typically capture high value areas for all input features.

The final parametric choices behind the prioritisations were made after initial testing and comparison of results. Perhaps the most central user-defined setting in Zonation is how the feature values in each cell are aggregated into one value, which the Zonation algorithm then uses to compare and rank the grid cells (so called marginal loss rule; Moilanen et al., 2022). We compared the prioritisation outputs of runs using marginal loss rules ABF, CAZMAX, CAZ1 and CAZ2. Of these, we chose the latter (CAZ2) as for each fraction of the top ranked grid cells, it retained relatively high average coverage of feature distributions without compromising the performance of the "worst-off features" (Figure S1.2).

We ran the prioritisations first separately for each time-step and emission scenario to understand how conservation priorities might shift in the Caatinga region because of climate change. We then ran all the time-periods together, i.e., including three temporally different maps for each species in the same prioritisation, so to produce a climate robust priority solution, where the top priority sites together protect the core habitats of each species at all time-steps. From each prioritisation, we identified the highest 30% ranked areas as priorities (henceforth 'priority areas') for protection in the Caatinga. This value was stipulated by Target 3 of the Kunming-Montreal Global Biodiversity Framework, to enable at least 30% of terrestrial ecosystems to be effectively under a system of protected areas or other effective area-based conservation measures by 2030 (CBD 2022). Since the future predicted distributions of species are inherently more uncertain than species present distribution (Kujala et al. 2013), we explored the trade-offs of splitting conservation resources between present and future priorities. We conducted a sensitivity analysis, where we assigned different weights for each present (T_1), 2050 (T_2) and 2070 (T_3) distributions of the features: the weights for present, $w(T_1)$, was always 1, and weights for future, $w(T_2)$ and $w(T_3)$, increased incrementally from 0 by 0.25 at each iteration so that $w(T_1) \geq w(T_2) \geq w(T_3)$ (Table S1.5). The sensitivity analysis was done separately for each emission scenario (SSP245 and SSP585). Focusing on the top 30% ranked areas, we then identified the maximum weights that could be given the T_2 and T_3, before we started to lose average protection of current distributions (Table S1.5). The final weights were $w(T_1) = 1$; $w(T_2) = 0.5$; $w(T_3) = 0.25$ for both scenariosSSP245 and SSP585.

Considering that small mammals from the Caatinga can be organised into species adapted and not adapted to the arid environment (Costa-Pinto et al. 2024), we also analysed the prioritisations result separately for these two groups (which we called 'arid' and 'non-arid' species). We overlapped the top 30% priority areas with the polygons of the Caatinga ecoregions (proposed by Silva et al., 2017) to analyse their distribution. Also, to understand how the priority areas are covered by the current PA network and to assess the potential conservation gap, we calculated the overlap of the priority areas and current protected areas, using the polygons of the Brazilian PAs (MMA 2022a), and separating the results for IP and SU protected areas.

To verify which areas should be prioritised in order to expand the current PA system in the Caatinga, we ran additional hierarchical mask analysis with all time steps using all PAs (IP+SU), assigning different weights to each type (IP=2 and SU=1), and only IP PAs (no weigh added). We assigned different weights to the analyses with the two types of PAs, because IP PAs are more restricted to human use and, in general, tend to protect biodiversity more than SU PAs. In these prioritisations, the PAs (IP and IP+SU) are considered as already protected, and the unprotected areas are prioritized based on how well they complement the existing PA network, by accounting for how well or poorly species are already protected by the PAs and targeting areas with species of poor current protection. Finally, we overlap the top 30% priority outcomes of this analysis with polygons of Sustainable Use PA to verify how many percent of them would be inside SU PA limits or outside any PA. From the hierarchical mask prioritisations, we evaluated small mammals mean coverage inside IP, all PAs, and expansion areas.

All post-processing analyses were performed in QGIS software v.3.22.13.

Results

In the Caatinga, the highest priority areas for the conservation of small mammal species are spread across all ecoregions in the biome (Figure S2.1) and include areas climatically suitable for the species for both climate change scenarios. The priority areas showed only moderate shifts through time under climate change (Figure 2), and the priority areas of the three periods (T_1, T_2 and T_3) overlapped more than 69% and 61% in the SSP245 and SSP585 scenarios, respectively (Table 1). Prioritisations done with all periods together ($T_{1\text{-}3}$, 'joint prioritisation' from now on) better filled the gaps between these overlaps, improving the connectivity between time steps (Figure 2).

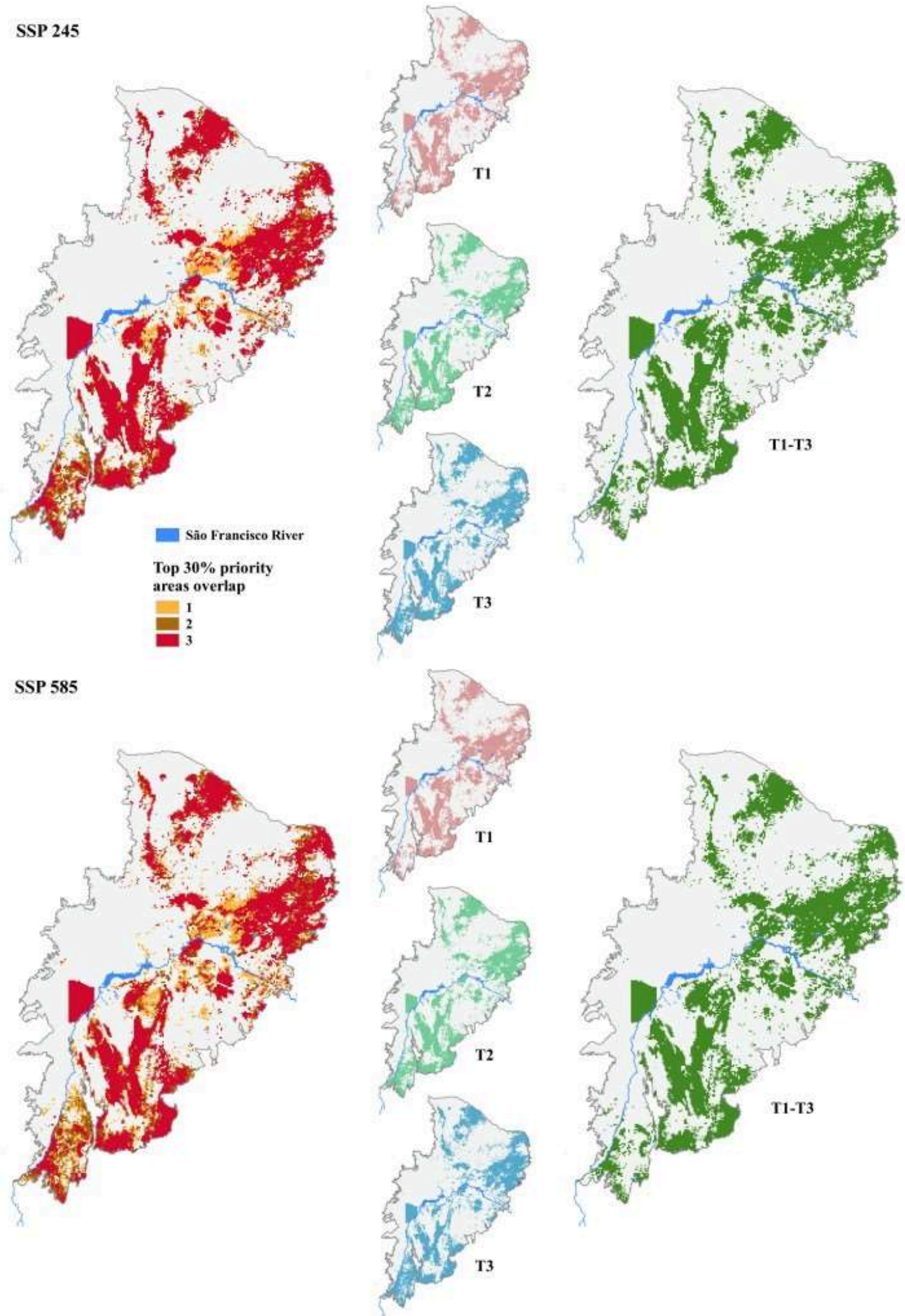


Figure 2. Maps of the overlap (left) of the priority areas for small mammal conservation in the Caatinga when the present (T_1), 2050 (T_2) and 2070 (T_3) potential distributions of species are considered separately (centre). Maps on the right show the priority areas when all periods are optimised together (T_{1-3}, right). The results are shown for climate change scenarios SSP245 and

SSP585. Red areas on the left-most maps represent areas where the prioritisation results of all three individual time periods overlap.

Table 1. Proportion of grid cells that are included in the top 30% priority areas for small mammals in the Caatinga in one, two or all three-time steps, when these are prioritised independently for each SSP scenario.

Top 30% prioritisation overlap	SSP245 (%)	SSP585 (%)
1	16.5	20.9
2	14.1	17.7
3	69.3	61.4

In all prioritisations, individual or joint ones, the priority areas are mostly located on highlands and high plateaus, including most of the Planalto da Borborema, Complexo da Chapada Diamantina and part of the Complexo Ibiapaba-Araripe ecoregions. These are also the ecoregions where priority areas are more stable through time (Figure 2). Together, the highland and high plateau ecoregions occupy 18.3% of the Caatinga territory, but have 26.7%, 26.9% and 27% of the priority areas in the present and in the joint prioritisations considering the optimistic and pessimistic climate change scenarios, respectively (Table S2.1). There is also some amount of important priority areas on the south of São Francisco Gurguéia and Depressão Sertaneja Meridional ecoregions, and some areas in the Raso da Catarina and Depressão Sertaneja Sententrional ones (Figure S2.1). However, we notice that in the Depressão Sertaneja Sententrional and in the south of São Francisco Gurguéia ecoregions there are more areas that are important only in one or two time steps (Figure 2).

In both scenarios, the priority areas captured on average >70% of species suitable areas, although this was higher for the non-arid species (~89%) than for the arid species (~58%) (Table 2).

Table 2. Mean coverage of biological features considering prioritisation of top 30% priority areas for small mammals in the Caatinga.

Prioritisation scenarios	**Mean of coverage**		
	All spp	**Arid**	**Non-arid**
SSP245 joint prioritisation	73.2%	57.7%	88.1%
SSP585 joint prioritisation	74.6%	58.9%	89.7%

The Brazilian Protected Areas system did not perform in protecting these priority areas for small mammal conservation in the Caatinga: around 13% of these important areas overlap with the PAs, and just around 3% are safeguarded by the most restrictive IP areas (Figure 3 and Table 3).

Regarding PA system expansion, when using IP PAs as hierarchic mask, more priority areas emerge in the centre of the Caatinga, especially in the São Francisco Gurgéia and Depressão Sertaneja Setentrional ecoregions (Figure 3). The amount of top priority areas inside SU PAs remains low and is almost the same in all scenarios (around 10%; Table 3), with emphasis on some APAs, such as APA Chapada do Araripe, Boqueirão da Onça and Dunas do São Francisco, where consistently were identified a large amounts of top priority areas. Lastly, when comparing prioritisations with and without IP PAs as hierarchical mask, priority areas outside any PA reduces in almost 5% in the former (Table 3), while the mean feature coverage by priority areas considering expansion with IP PAs mask increases (Table 4 and Figure S2.2).

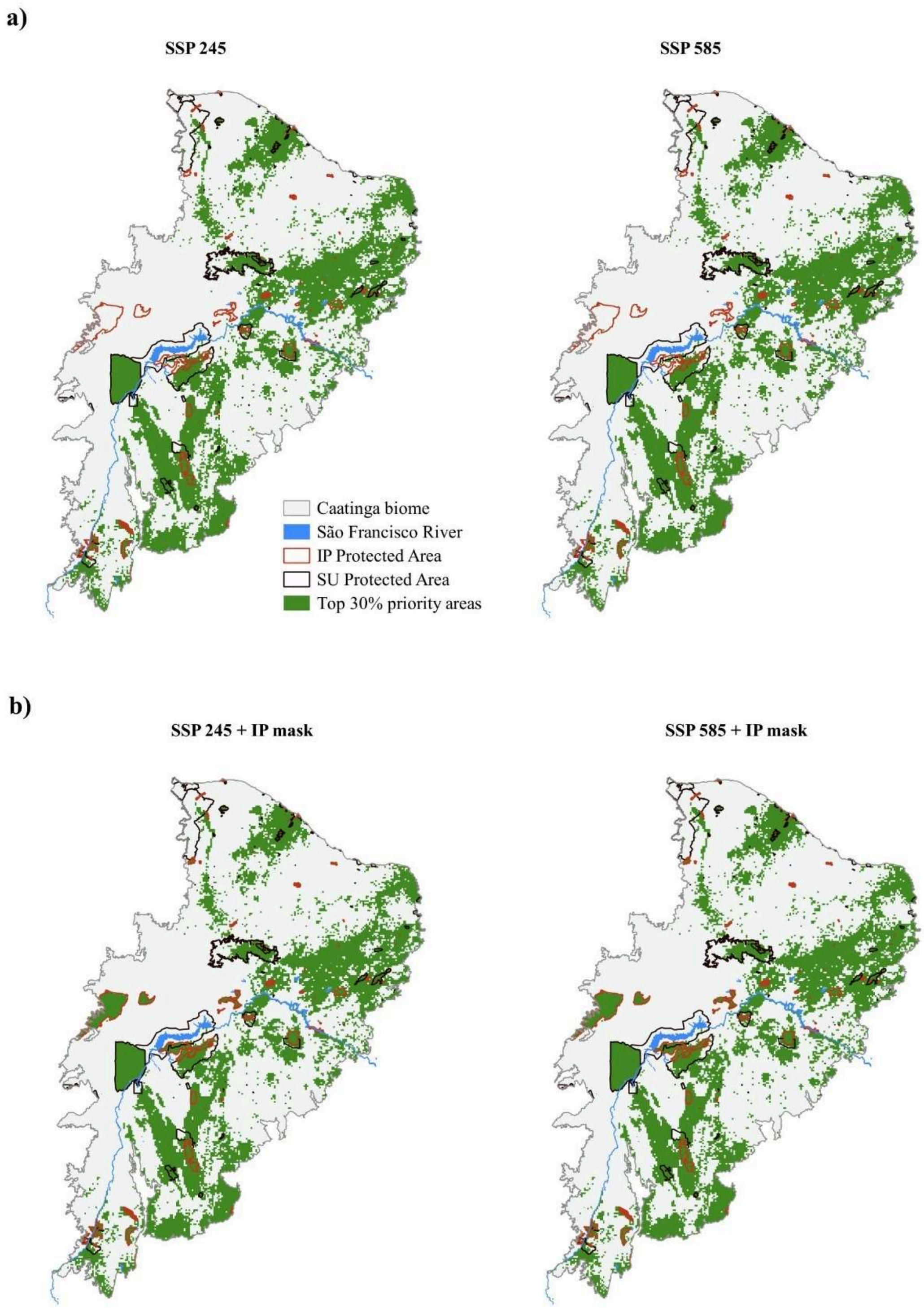


Figure 3. 30% highest Priority Areas for small mammals considering present and future of Climate Change and their distribution inside Integral Protection (IP) and Sustainable Use (SU) Protected Areas in the Caatinga. a) Prioritisations without hierarchic mask; b) Prioritisations with Integral Protection PA as hierarchic mask.

Table 3. Top 30% priority areas for small mammals in the Caatinga covered by: PA, any Protected Area; IP, Integral Protection, more restrictive ones; SU, Sustainable Use, very flexible ones; and outside any official Protected Area.

Prioritisations	**PA %**	**IP %**	**SU %**	**Outside PA %**
Current	13.71	3.32	10.39	86.29
SSP245 joint prioritisation	13.58	3.29	10.29	86.42
SSP585 joint prioritisation	13.58	3.28	10.30	86.42
SSP245 joint prioritisation + IP PAs mask	18.51	8.07	10.44	81.49
SSP585 joint prioritisation + IP PAs mask	18.48	8.07	10.41	81.52

Table 4. Mean coverage of species distributions at each time steps by the Integral Protection (IP) PAs, Sustainable Use (SU) PAs and their expansion areas in different prioritisations for small mammals in the Caatinga. $T_{1\text{-}3}$ refers to an average across time-periods (joint prioritisations). For IP+Expansion, the IP PAs were used as hierarchic mask, and for All PAs+Expansion, all PAs were used as hierarchic mask, with different values for each level of protection (IP and SU).

SSP245	**$T_{1\text{-}3}$**	**T_1**	**T_2**	**T_3**
IP	5.9%	7.25%	4.90%	5.31%
SU	15.7%	20.93%	12.12%	12.80%
IP+Expansion	72.4%	72.77%	71.21%	73.05%
All PAs+Expansion	69.9%	70.43%	68.59%	70.64%

SSP585	T1-3	T1	T2	T3
IP	6.4%	7.25%	5.35%	6.29%
SU	16.4%	20.93%	12.73%	14.39%
IP+Expansion	73.9%	72.73%	73.41%	75.75%
All PAs+Expansion	71.7%	70.41%	71.06%	73.99%

Discussion

Here we identify robust, future-proofed priority areas for protection of small mammal species in the Caatinga, taking into account scenarios of Climate Change, and reinforcing the PAs role in preserving the biodiversity. Although predicting future priorities under climate change always includes uncertainties (many emission scenarios, many modelling approaches, etc.), in the Caatinga change is predicted to be minimal in the core priority areas, irrespective of which time period or emission scenario is used. This implies that there is little risk in committing to the protection of these areas as they are likely to be climatically stable in the medium to long term. Prioritisations that take into account all three time periods together (T_{1-3}) are therefore a robust solution and a "no-regret" strategy for small mammals in the Caatinga, i.e., measures that can begin to be enacted now since its benefits will continue even if the effects of climate change are not as pessimistic as currently anticipated (Hallegatte 2009).

The high spatial overlap of priority areas between the time-periods can be partially explained by the fact that many of these areas are on highlands, high plateaus or ecotone areas within the Atlantic Rainforest (Figure 2). These high elevation and more humid regions inside the Caatinga biome harbour most of the non-arid species and are likely to keep more stable microclimate (Scheffers et al. 2014, Neves et al. 2017) and therefore remain suitable for most of the small mammal species in the Caatinga in the future (Costa-Pinto et al. 2024). Nevertheless, it is worrying that so many of the priority areas are located in these highlands and high plateaus, given that large proportions of these ecoregions are under strong human impact (Highlands - 90.1%; Chapada Diamantina - 75.7%; Planalto da Borborema - 62% and the Ibiapaba-Araripe Complex – 59.5%) through human induced fires, roads and deforestation (Silva and Barbosa 2017). This indicates that more attention needs to be paid to strategies to protect these regions.

In our analysis, some of the current PAs are of no or low priority for small mammal conservation (Figure 3 and Table 3), including some with strict protection. There are two main reasons for that. First, the PAs might have been established for other reasons. For instance, the Serra da Capivara National Park and Serra das Confusões National Park that were created to protect and preserve archaeological remains and ecosystems, respectively. Secondly, a global trend has been observed whereby PAs are not often placed in important biodiversity areas, but in areas that are easy to protect, e.g. poorly productive lands or mountains, simply because this is cheaper and socieconomically more doable (Margules and Pressey 2000, Pressey et al. 2002). It is also worth noting that we are only looking at a small fraction of biodiversity (small mammals) and also that we are referring to the top 30% of priority areas, which is a restricted percentage and does not mean that these PAs are not important for the conservation of small mammal in the Caatinga. However, due to limited conservation resource, priority should be given to areas that are most cost-effective for the conservation of those species in the biome.

In line with these spatial gaps in conservation, most Brazilian PAs have 0 to 0.01 species records per km^2 (Oliveira et al. 2017), revealing how much protected biodiversity is still unknown. This is controversial as, by law, all PAs need a management plan (MMA 2011) which include a species checklist in the area. However, only 551 out of 2,659 Brazilian Protected Areas have this document (MMA 2022a).

Based on the most recent assessment (MMA 2022a), only 9% of the Caatinga is protected by PAs. This lags far behind the Kunming-Montreal Biodiversity Framework Target 3 commitments to conserve at least 30% of all terrestrial ecosystems, which is the threshold for selecting priority areas used by us. Since Zonation ranks the entire analysis area, the selection of top fractions to focus on is somewhat arbitrary and other thresholds could have been used.

Our analysis suggests that there is a need to expand the protected areas system in the biome to support small mammal species to persist under climate change. A cost-effective starting point could be to upgrade SU PAs to some more restrictive IP PA category in those parts where they overlap with priority areas for small mammal conservation. This strategy saves costs in comparison to a land that currently has no protection becoming a PA, as SU PAs have the following characteristics: 1) officially they have some restrictions to their use, so increasing the restriction level would cause less economic harm; 2) although some categories allow private property within their limits, most of the territories of SU PAs are already owned by the government, so there is less need to buy the area from private land owners; and 3) they are supposed to have a management plan which is cheaper to upgrade than to newly create. In fact, our results show that, apart from saving resources, to expand PA in the Caatinga using IP areas as a starting point also increases the protection of the mean distribution of small mammal species in the biome.

An increase in legal restrictions governing human activities within the PA would be needed to enact our recommendations. For instance, use restrictions would have to be implemented in almost the entire APA Dunas e Veredas do Baixo-Médio São Francisco, on parts of the APA Boqueirão da Onça, APA Chapada do Araripe, APA da Ararinha Azul, APA Serra Branca, among others. The extensive high priority area in the middle west of the Caatinga (Figure 2) encompasses nearly the whole APA Dunas e Veredas do Baixo-Médio São Francisco, a Sustainable Use PA which is home to the endangered *Trinomys yonenagae*, a fossorial rodent specific to this unique sand dune region. *T. yonenagae* is endemic to the sand dune field of the

Caatinga on the west bank of the São Francisco River, an area with less than 5,000 km^2 under pressure from habitat loss through sand removal (Luchesi et al. 2019), highlighting the need to upgrade the level of protection. It is noteworthy that most of the SU PAs that need upgrading are currently categorised as APAs, which is the most permissive of the categories and, in practice, allows for urban constructions and/or soil removal activities. Unfortunately, more restrictive PAs such as the FLONA de Saracá-Taquera and FLONA do Amaná have failed to protect the areas from mining activities in the Amazon, the Brazilian biome that has the greatest visibility in the world. This highlights the risks associated to more permissive PAs, especially in a biome with less visibility such as the Caatinga.

We are aware, however, that this change of category is not as easy or as cheap as it may seem. The costs and processes involved in expropriation, drawing up management plans, maintaining infrastructure and staff at IP PAs can be major obstacles for PA category transfers. In this sense, categories such as Natural Monument ("Monumento Natural" - MONA) or Wildlife Refuge ("Refúgio da Vida Silvestre" - REVIS), which are IP PA options that allow the presence of privately owned land areas as long as the land and natural resource use are compatible with the conservation goals of the PA (MMA, 2011), can offer a more realistic pathway to improved protection. Another option, that does not involve upgrading PAs, would be to focus on zoning within the SU PAs, by establishing environmental territories (zones) organised in terms of biotic and abiotic protection, and regulating spatial use and occupation inside the boundaries of the SU PA based on environmental vulnerability.

Either way, perhaps the most important insight is for the PAs to function effectively, regardless of the type of restriction. This requires that the legally binding protection and sustainable use rules of PAs are respected and valued by the population and public authorities. Brazil has a history of PA downgrading, downsizing and degazettement (Pack et al., 2016), in addition to the constant attempts to change environmental protection laws (Ruaro et al., 2021). All these strands have been greatly intensified in recent years, including the persecution of government environmental officials and significant cuts in funding for the creation and maintenance of PAs (Ferrante & Fearnside, 2021; Ruaro et al., 2021).

We have shown that the current Brazilian Protected Area system only partially safeguards the diversity of small mammals in the Caatinga, and that it is not entirely equipped to support the survival of these species under future climate change. However, it is crucial to remember that

PAs bring many benefits that go beyond their limits or the goals for which they were created. When implemented, and especially when it is done with community engagement, PAs can also benefit the biodiversity in the surrounded areas by, for instance, supporting source populations or reducing hunting pressure (Campos-Silva et al. 2021, Brodie et al. 2023). More broadly, preserved fragments of the Caatinga biome sequestrate atmospheric CO_2 at rates comparable to rainforests so that, among dry forests in the world, the Caatinga can be considered a major carbon sink (Mendes et al. 2020). Finally, it has already been observed that IP PAs had higher productivity and considerable resilience to low levels of precipitation in the Caatinga, when compared to SU or unprotected areas (Salvatierra et al. 2017).

It is worth noting that in this study we only considered Protected Areas to be Conservation Units. However, there are other legal conservation mechanisms that go beyond these, such as Legal Reserves and Permanent Protection Areas (PPA). The former is an area located within a private rural property that must be set aside for conservation. The latter are, theoretically, untouchable natural areas, with strict limits on exploitation, designed to protect soils and, above all, riparian forests (Brazilian Forest Code, Law nº 12.651/2012). These areas play a complementary but very important strategic role in biodiversity conservation, both by connecting fragments and by maintaining or restoring native vegetation (De Marco et al. 2023). For instance, legal reserves and permanent protection areas can protect up to 14.48% of the distribution area of threatened vertebrate species in the Cerrado (De Marco et al. 2023), a savannah-like Brazilian biome that is also a biodiversity hotspot. It is important, however, that these areas are kept effectively protected as required by law, and are not at the mercy of activities such as deforestation and hunting.

We acknowledge that more comprehensive conservation results could be achieved with an analysis that, in addition to small mammals, included also other animal and plant groups, and which accounted for functional and phylogenetic diversity (Pollock et al. 2015, Brum et al. 2017). Regardless, we believe that the general results presented here, which highlight the importance of prioritising unique areas in the Caatinga, such as the Highlands and high plateaus, will likely remain true also in such expanded analysis as most of these areas are historical biodiversity refuges (Silva et al. 2017). Finally, we encourage smaller scale studies, e.g., at states level, where higher resolutions species and environmental data can improve the outcomes of prioritisations by producing more fine-scale solutions.

For the small mammals in the Caatinga, climate change will not hugely shift the distribution of their ecologically important areas, providing low-risk opportunities to protect their habitats now with long-term benefits. Although currently these areas are poorly supported by protected areas and they need further protection, we provide a cost-effective option for such which is the upgrading of some SU PAs. Here we offer practical suggestions for the conservation of small mammals in the Caatinga, providing transparent support, replicable methodology and strategies for expanding protected areas that can be discussed in conservation policies. As consequence, the efforts to secure these priority areas can help to preserve the long-term ecosystem functioning and to prevent biodiversity loss in a changing world.

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DATA ACCESSIBILITY STATEMENT

Species occurrence points are available at https://datadryad.org/stash/share/Ex0DCgbZ8f8pzSRCH0X9fgB_mR_jR85pWWtMrgtTwcU. The data and script sources are cited in the Methods section. Ecological niche model summary and Zonation input description can be found in Supplementary Material – S1.

SUPPORTING INFORMATION

Supplementary Material – S1: Additional method figures and tables.

Supplementary Material – S2: Additional result figures and tables.

MATERIAL SUPLEMENTAR - CAPÍTULO 3

SUPPLEMENTARY MATERIAL – CHAPTER 3

Supplementary Material – S1

"Planning for a future of changes: prioritizing areas for conservation of small mammals in the Caatinga"

Table S1.1. Small mammal species list and information about number of records (N) before, and after data cleaning processes; Ecological Niche Model (ENM) information regarding the cross-validation method, feature classes (FC) specific settings and the AUC values of the final model; species' ecological group; and the type of information used as feature input layers in Zonation. 'L' (linear), 'Q' (quadratic) and 'H' (hinge).

	Initial N	Coordinate Cleaner	SpThin	Cross-validation Method	FC[1]	AUC	Ecological group	Zonation input[2]
DIDELPHIMORPHIA								
Cryptonanus agricolai	21	18	16	block	L, Q and H	0.82	Non-arid	ENM suitability
Didelphis albiventris	363	160	117	block	All	0.85	Arid	ENM suitability
Gracilinanus agilis	333	154	105	block	All	0.89	Arid	ENM suitability
Gracilinanus microtarsus	44	44	36	block	L, Q and H	0.94	Non-arid	ENM suitability
Marmosa demerarae	38	31	25	block	L, Q and H	0.94	Non-arid	ENM suitability
Marmosa murina	56	48	39	block	L, Q and H	0.94	Non-arid	ENM suitability
Marmosops incanus	204	91	53	block	L, Q and H	0.91	Non-arid	ENM suitability
Monodelphis americana	35	33	32	block	L, Q and H	0.92	Non-arid	ENM suitability
Monodelphis domestica	365	169	102	block	All	0.90	Arid	ENM suitability
Thylamys karimii	34	20	17	block	L, Q and H	0.91	Arid	ENM suitability
RODENTIA								
Akodon cursor	71	61	43	block	L, Q and H	0.90	Non-arid	ENM suitability
Calomys expulsus	36	27	19	block	L, Q and H	0.88	Arid	ENM suitability
Calomys mattevii	153	88	49	block	L, Q and H	0.95	Arid	ENM suitability
Cerradomys langguthi	46	25	22	block	L, Q and H	0.95	Non-arid	ENM suitability
Cerradomys vivoi	107	70	16	block	L, Q and H	0.83	Non-arid	ENM suitability
Euryoryzomys russatus	23	23	20	block	L, Q and H	0.96	Non-arid	ENM suitability

cont.	Initial N	Coordinate Cleaner	SpThin	Cross-validation Method	FC[1]	AUC	Ecological group	Zonation input[2]
Galea spixii	62	47	41	block	L, Q and H	0.85	Arid	ENM suitability
Holochilus oxe	13	11	NA	NA	NA	NA	Non-arid	Occ records
Hylaeamys megacephalus	22	19	19	block	L, Q and H	0.79	Non-arid	ENM suitability
Kerodon rupestris	103	27	24	block	L, Q and H	0.90	Arid	ENM suitability
Necromys lasiurus	102	79	64	block	L, Q and H	0.86	Arid	ENM suitability
Oecomys catherinae	30	27	20	block	L, Q and H	0.89	Non-arid	ENM suitability
Oligoryzomys mattogrossae	10	9	NA	NA	NA	NA	Non-arid	Occ records
Oligoryzomys nigripes	91	73	59	block	L, Q and H	0.90	Non-arid	ENM suitability
Oligoryzomys rupestris	2	2	NA	NA	NA	NA	Arid	Occ records
Oligoryzomys stramineus	81	29	24	block	L, Q and H	0.83	Arid	ENM suitability
Oxymycterus dasytrichus	21	20	18	block	L, Q and H	0.96	Non-arid	ENM suitability
Oxymycterus delator	20	17	16	block	L, Q and H	0.96	Non-arid	ENM suitability
Phyllomys blainvilii	4	3	NA	NA	NA	NA	Arid	Occ records
Pseudoryzomys simplex	7	7	NA	NA	NA	NA	Arid	Occ records
Rhipidomys cariri	9	6	NA	NA	NA	NA	Arid	Occ records
Rhipidomys macrurus	22	17	13	jackknife	L and Q	0.78	Arid	ENM suitability
Rhipidomys mastacalis	41	40	35	block	L, Q and H	0.91	Non-arid	ENM suitability
Thrichomys apereoides	133	30	12	jackknife	L and Q	0.96	Arid	ENM suitability
Thrichomys inermis	58	44	10	NA	NA	NA	Arid	Occ records
Thrichomys laurentius	360	149	91	block	All	0.91	Arid	ENM suitability
Trinomys albispinus	83	18	12	jackknife	L and Q	0.97	Non-arid	ENM suitability
Trinomys yonenagae	1	1	NA	NA	NA	NA	Arid	PA-Urban area
Wiedomys cerradensis	393	192	75	block	L, Q and H	0.94	Arid	ENM suitability
Wiedomys pyrrhorhinus	44	24	18	block	L, Q and H	0.80	Arid	ENM suitability

[1] Input in raster format.

Table S1.2. Description of predictor variables, indicating which ones were used in the final ENMs.

	Predictors	**Description**	**Used (r_s<0.75)**
Climate	BIO 02	Mean diurnal range (mean of monthly max temp - min temp)	X
	BIO 03	Isothermality (BIO2/BIO7) (×100)	X
	BIO 05	Max temperature of warmest month	X
	BIO 06	Min temperature of coldest month	
	BIO 07	Temperature annual range (BIO5-BIO6)	
	BIO 12	Annual precipitation	
	BIO 13	Precipitation of wettest month	
	BIO 14	Precipitation of driest month	
	BIO 15	Precipitation seasonality (Coefficient of variation)	X
	BIO 16	Precipitation of wettest quarter	X
	BIO 17	Precipitation of driest quarter	
	Elevation	Elevation data	X
LULC*	Natural vegetated area	Naturally vegetated areas, from dense arboreal Caatinga and shrubby Caatinga to savanna-like vegetation	X
	Pasture	Area modified for raising cattle, goats and others	X
	Agriculture	Areas occupied with agricultural crops	X
	Rocky outcrops	Naturally exposed rocks without land cover	X
	Water	Rivers, lakes, dams and other bodies of water	X
	Urban area	Areas with significant density of buildings and roads	X

*Proportion of the pixel occupied by the category

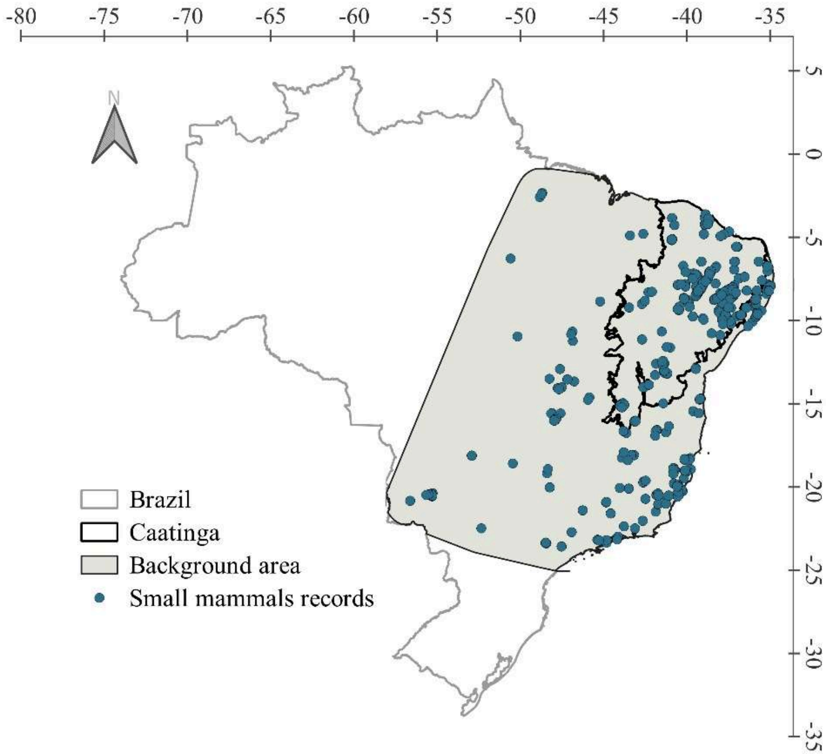

Figure S1.1. Occurrence records and background limits for the species ENMs.

Table S1.3. Feature classes settings. Abbreviations are 'L' (linear), 'Q' (quadratic), 'P' (product) and 'H' (hinge).

Sample size	Allowed Feature Classes
$x \geq 80$	All features and combinations
$79 \geq x \geq 15$	L, Q, H and combinations
$14 \geq x \geq 10$	L, Q and combinations

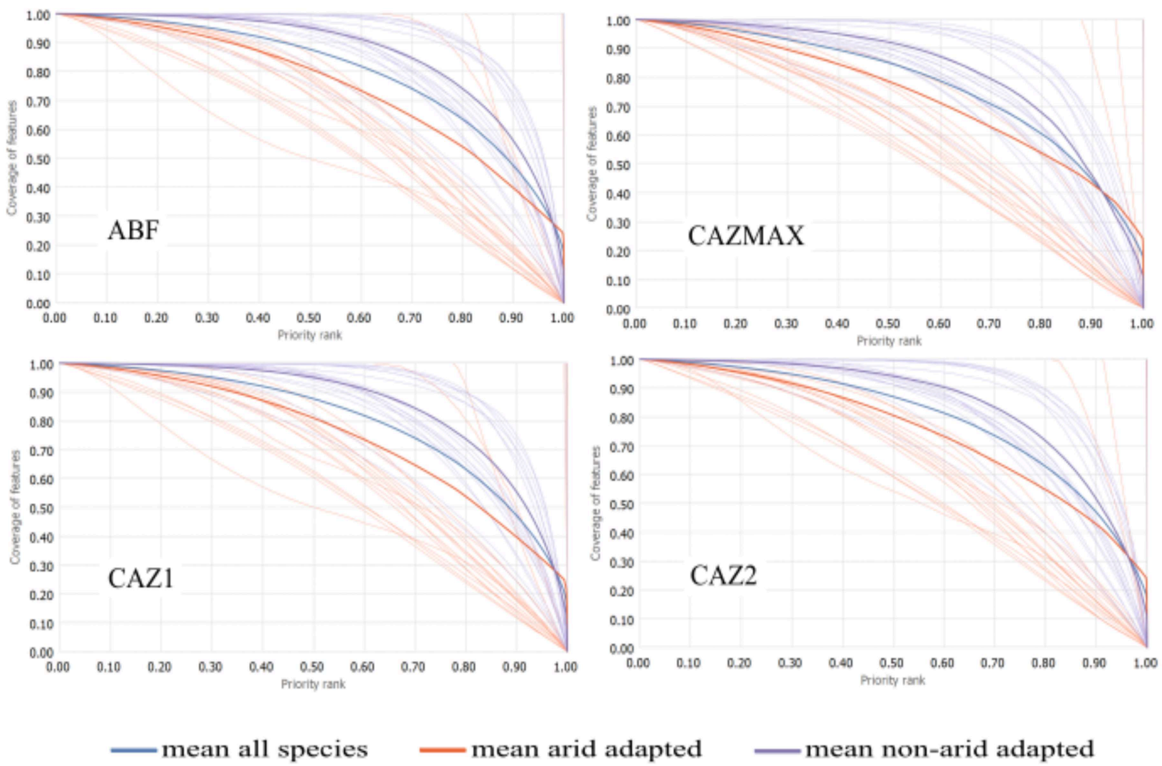

Figure S1.2. Performance curves of marginal loss rules choice using present only (T_1) data. ABF= Additive Benefit Function; CAZMAX, CAZ1, CAZ2 – variants of Core Area Zonation. Light lines represent performance curves of individual features.

Table S1.4. Impact of different weighting schemes on the mean coverage of species distributions at each time-period when priority rank equals 0.7. Bold numbers represent the threshold combination of weights where it is still possible to gain conservation value for the future (T_2, T_3) without losing it (negative values) for the present (T_1). [a] w(T_1) always = 1; [b] Baseline mean value, when weights are 1/0/0 for T_1/T_2/T_3.

Weights	**SSP 245**			**SSP 585**		
T_2/T_3[a]	ΔT_1	ΔT_2	ΔT_3	ΔT_1	ΔT_2	ΔT_3
0.0 / 0.0	0.7354[b]	0.7155[b]	0.7325[b]	0.7354[b]	0.7349[b]	0.756[b]
0.25 / 0.0	0.0003	0.0017	0.0018	0.0003	0.0022	0.0022
0.25 / 0.25	0.0004	0.0030	0.0033	0.0002	0.0036	0.0045
0.5 / 0.25	**0.0002**	0.0057	0.0061	**0.0000**	0.0069	0.0071
0.5 / 0.5	-0.0005	0.0072	0.0080	-0.0011	0.0084	0.0098
0.75 / 0.5	-0.0017	0.0087	0.0098	-0.0022	0.0107	0.0112
0.75 / 0.75	-0.0033	0.0096	0.0112	-0.0039	0.0112	0.0127
1 / 1	-0.0062	0.0109	0.0132	-0.0074	0.0125	0.0139

Supplementary Material – S2

"Planning for a future of changes: prioritizing areas for conservation of small mammals in the Caatinga"

Table S2.1. Proportion of the 30% highest priority areas in the present and long-term prioritizations for the SSP 245 and SSP 585 scenarios among Caatinga ecoregions.

Ecoregion	Caatinga's area [1]	Present[2]	SSP 245[2]	SSP 585[2]
Complexo da Chapada Diamantina	5.5%	12.1%	12.1%	12.0%
Planalto da Borborema	4.9%	9.5%	9.9%	10.1%
Dunas do São Francisco	2.9%	3.7%	3.7%	3.7%
Raso da Catarina	3.4%	4.0%	3.8%	3.8%
Depressão Sertaneja Setentrional	23.3%	19.8%	19.9%	20.0%
Brejos	0.3%	0.7%	0.7%	0.7%
Depressão Sertaneja Meridional	31.3%	36.6%	35.9%	35.6%
Complexo Ibiapaba - Araripe	7.6%	4.4%	4.3%	4.2%
São Francisco/Gurguéia	20.9%	5.7%	6.1%	6.1%

[1] According to Silva and Barbosa (2017).

[2] Since the ecoregion's polygon proposed by Silva et al. (2017) does not match entirely with the current limits of the biome (IBGE, 2019), the sum of the 30% highest priority areas percentage inside ecoregions is less than 100%.

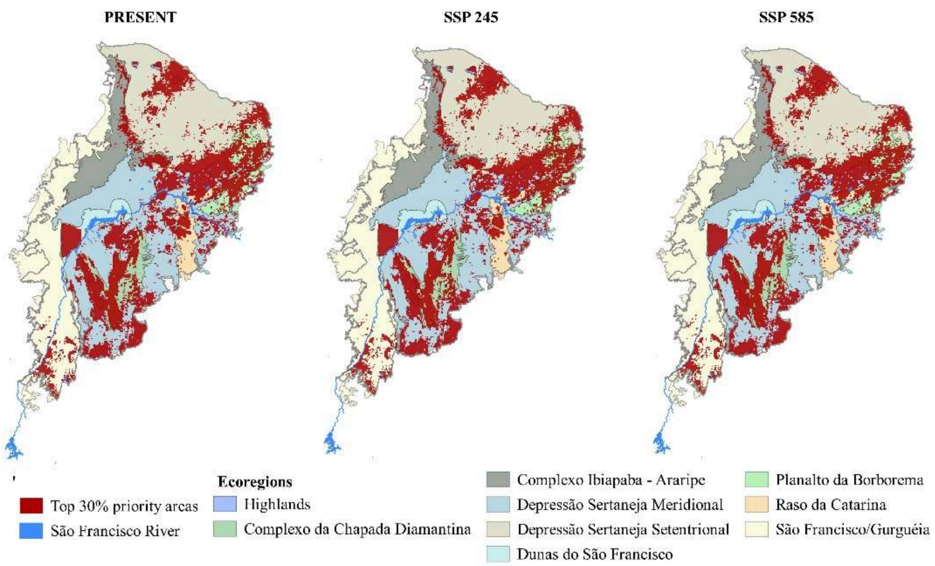

Figure S2.1. Distribution of the 30% highest priority areas in the present and long-term prioritizations for the SSP 245 and SSP 585 scenarios among Caatinga ecoregions. Since the ecoregion's polygon proposed by Silva et al. (2017) does not match entirely with the limits of the biome (IBGE, 2019), some of the priority areas appears outside ecoregions.

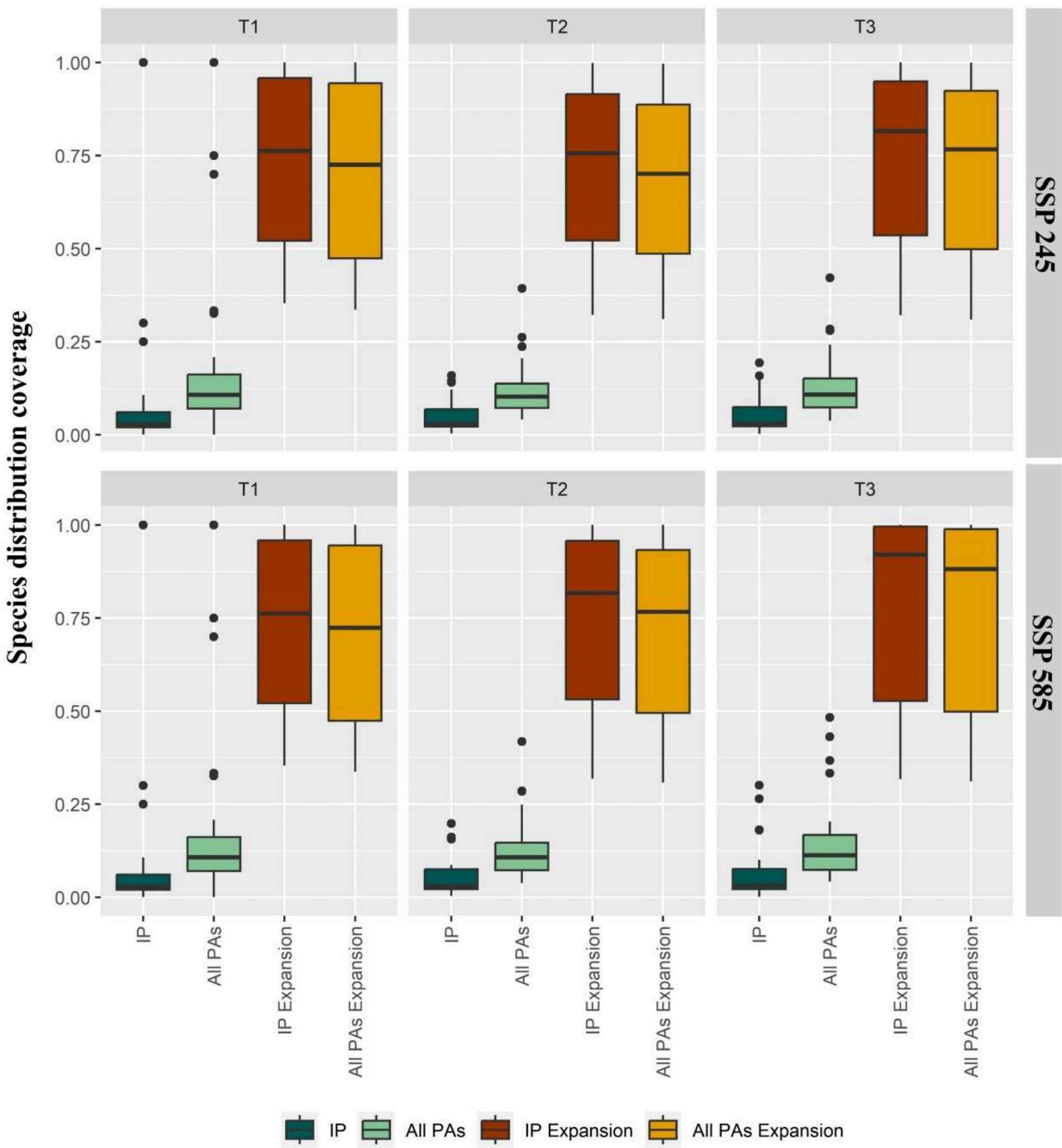

Figure S2.2. Comparison of species distribution coverage of joint prioritisations in PAs (IP or All PAs) with the use of hierarchical masking (for PA expansion). 'IP' and 'IP Expansion' refers

10. CONCLUSÕES

- O banco de dados é o primeiro para regiões áridas/semiáridas do mundo, contemplando 47 espécies nativas de pequenos mamíferos no bioma Caatinga (12 marsupiais e 35 roedores), em 3.133 registros de 816 localidades. Presando pela credibilidade taxonômica e geográfica, o banco de dados conta com os seguintes diferenciais: todas as espécies registradas possuem espécime tombado em uma coleção científica e são fornecidas informações de acurácia geográfica e dados biométricos;
- As áreas climaticamente adequadas para pequenos mamíferos não-voadores na Caatinga devem reduzir ou ficar praticamente inacessíveis às espécies, sendo aquelas mais adaptadas a ambiente mésicos as mais vulneráveis às mudanças climáticas;
- Das 24 espécies modeladas, 83,3% devem perder área climaticamente adequada em diferentes cenários de mudanças climáticas. Apenas quatro roedores adaptados a ambientes mais xéricos devem ganhar área climaticamente adequada;
- Os 30% de áreas mais prioritárias para conservação de 40 espécies de pequenos mamíferos não-voadores identificadas, levam em conta os cenários atuais de clima e uso da terra e incluem priorizações que consideram as incertezas das mudanças climáticas. Assim, oferecem baixo risco se forem implementadas como uma ação de conservação de não arrependimento (*no regrets measure)*;
- Considerando que as UCs atuais da Caatinga contemplam menos de 13% das áreas prioritárias identificadas, uma das estratégias com melhor custo-

11. CONCLUSIONS

- The dataset is the first for arid/semiarid regions in the world and includes 47 native species of small mammals in the Caatinga (12 marsupials and 35 rodents), 3,133 records in 816 localities. Striving for taxonomic and geographic credibility, the dataset includes species with vouchers, and provides geographic accuracy information as well as biometric data;
- Climatically suitable areas for small mammals in the Caatinga should be reduced or practically inaccessible to species, with those most adapted to mesic environments being the most vulnerable to climate change;
- Of the 24 species modeled, 83.3% are expected to lose climatically suitable areas under different climate change scenarios. Only four rodents adapted to more xeric environments are expected to gain climatically suitable area;
- The top 30% priority areas for the conservation of 40 species of small mammals identified take into account current climate and land use scenarios and include prioritisations that consider the uncertainties of climate change. As such, they offer low risk if implemented as a no regrets measure;
- Considering that the current Protected Areas in the Caatinga cover less than 13% of the priority areas identified, one of the most cost-effective strategies for expanding this coverage of priority areas for the conservation of small mammals in the biome is to transform certain existing Sustainable Use (or part of them) into Integral Protection, such as MONA or REVIS categories.

APÊNDICES

(divulgação científica)

APPENDICES

(scientific communication – in Portuguese)

- **Release da publicação do artigo referente ao Capítulo 1**

Este artigo representa o primeiro dataset sobre mamíferos para o bioma Caatinga. E o que é um dataset? Nada mais é que um compilado que forma um banco de dados de livre acesso para todo mundo. No caso deste nosso dataset, nós compilamos, ou seja, nós reunimos dados de ocorrência de pequenos mamíferos não-voadores (que seriam os roedores e os marsupiais), na maior e mais biodiversa Floresta Tropical Seca Estacional do mundo, que é a nossa Caatinga.

A ideia de se elaborar um dataset veio da escassez de dados para esse grupo na Caatinga. Na verdade, temos a junção de um dos biomas menos estudados no Brasil, a Caatinga, com os pequenos mamíferos não-voadores, que raramente são o tema desses poucos estudos sobre a biodiversidade deste bioma. Quando buscamos estudos científicos que tratam de zonas áridas e semiáridas no mundo, a Caatinga costumava ficar de fora ou suas informações eram extrapoladas e pouco precisas.

Como a gente tem pouca informação na literatura científica, o que nós fizemos foi entrar em contato com o máximo de pesquisadoras e pesquisadores que realizaram algum tipo de trabalho com pequenos mamíferos na Caatinga, além de contactar Coleções de Mamíferos e, claro, revisar os dados da literatura. Cada espécie foi revisada taxonomicamente, cada localidade foi checada e nosso intuito foi deixar esse banco de dados o mais preciso e informativo possível!

Este estudo ajuda a preencher algumas lacunas críticas de conhecimento, fornecendo informações importantes, como riqueza, composição, ou seja, quantas e quais as espécies de pequenos mamíferos e sua localização na Caatinga, além de trazer dados biométricos, como medidas corporais e peso de vários registros.

O resultado é inédito e tem implicações consideráveis para o uso em diversos

- **Release da publicação do artigo referente ao Capítulo 2**

MAIS DE 80% DAS ESPÉCIES DE PEQUENOS MAMÍFEROS DEVEM PERDER ÁREA CLIMATICAMENTE ADEQUADA NA CAATINGA POR CONSEQUÊNCIA DAS MUDANÇAS CLIMÁTICAS

Neste estudo nós verificamos como as Mudanças Climáticas poderiam afetar a distribuição das áreas climaticamente adequadas para as espécies de pequenos mamíferos na Caatinga, um bioma semiárido exclusivamente brasileiro e que já vem sofrendo com aumento dos períodos de seca e temperatura como consequências dessas mudanças.

No Brasil, os pequenos mamíferos não voadores são todos os marsupiais e roedores com menos de 2kg. Nesta pesquisa, além de verificar onde são as áreas climaticamente adequadas atualmente para 24 espécies de pequenos mamíferos, nós fizemos projeções para cenários climáticos em 2050 e 2070 e verificamos que mais de 80% das espécies devem perder área climaticamente adequada na Caatinga, algumas delas, inclusive, perdendo mais de 90% de sua área em todos os cenários. As espécies que a Caatinga compartilha com a Mata Atlântica são as que mais serão afetadas negativamente nesse sentido.

Apenas quatro roedores devem ter um aumento no total de área adequada, todos são espécies bem comuns na Caatinga, bem adaptadas à aridez, mas que para duas delas, esse aumento é de no máximo 2% de área climaticamente adequada em comparação com o que se tem atualmente. Em compensação, até o roedor exclusivo da Caatinga, ou seja, endêmico ao bioma, o mocó, deve perder área climaticamente adequada. Se somarmos a isso a pressão de caça que essa espécie sofre, temos ameaças preocupantes para esse roedor que está na lista de *adequada em todos os cenários que nós analisamos, indicando que esse marsupial deve estar vivendo já no seu limite climático e que o avanço das mudanças climáticas deve trazer consequências negativas para sua sobrevivência.*

Concluindo, percebemos que as mudanças climáticas devem afetar negativamente as espécies em um futuro não tão distante, com a maioria delas tendo seus ambientes bioclimaticamente adequados diminuindo ou praticamente inacessível, o que liga um alerta para que essas questões sejam levadas em consideração ao se planejar a conservação dessas espécies e da própria Caatinga.

- **Release do doutorado sanduíche para matéria da UFAL**

Priorização espacial e Mudanças Climáticas na Caatinga.

A doutoranda Ludmilla da Costa-Pinto foi para a Universidade de Helsinki, na Finlândia, para aprender análise de priorização espacial com o software Zonation, que foi desenvolvido por pesquisadores desta instituição. No período que esteve fora, Ludmilla identificou áreas prioritárias para conservação de 40 espécies de pequenos mamíferos não-voadores na Caatinga, algumas delas ameaçadas de extinção. A pesquisa envolveu ainda o contexto de Mudanças Climáticas e esse fator afeta tanto a seleção dessas áreas prioritárias como uma futura expansão de Áreas Protegidas pensando na conservação dessas espécies.

O doutorado sanduíche de Ludmilla foi uma parceria com a renomada pesquisadora Dra Heini Kujala, além de uma importante ponte de colaboração com o grupo de pesquisa C-BIG (Conservation Biology Informatics Group) que se destaca mundialmente na pesquisa com conservação e planejamento do uso do solo para

- **Links de matérias e vídeos online**

Reportagem da TV Caatinga sobre publicação do Dataset

https://www.youtube.com/watch?v=otFyqcQ3zEg

Reportagem da TV Pernambuco sobre publicação do Dataset

https://www.youtube.com/watch?v=1vvi1E6sGZE

Vídeo de divulgação do dataset no Youtube do Lacos 21

https://www.youtube.com/watch?v=oKfyrc1QYvw&t=13s

Reportagens sobre Capítulo 2

https://www.jornaldealagoas.com.br/geral/2024/03/04/22650-biologa-da-ufal-lidera-estudo-pioneiro-sobre-pequenos-mamiferos-que-vivem-na-caatinga

https://www.cadaminuto.com.br/noticia/2024/03/04/biologa-do-museu-de-historia-natural-da-ufal-lidera-estudo-pioneiro-sobre-pequenos-mamiferos-que-vivem-na-caatinga

Divulgação do Capítulo 2 no Instagram do Lacos 21

https://www.instagram.com/p/C4eDXD2Lntg/?igsh=MWh4Y2tzMDE2cmppcg==