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AVALIANDO OS IMPACTOS DAS MUDANÇAS CLIMÁTICAS E DO USO E COBERTURA DE SOLO NA ADEQUABILIDADE DE HABITAT PARA O TAMANDUÁ-BANDEIRA (*MYRMECOPHAGA TRIDACTYLA*, LINNAEUS, 1758)

Belo Horizonte

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Orientador: Dr. Rodrigo Lima Massara

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ATA DE DEFESA DE DISSERTAÇÃO

GUILHERME ANDRADE DAMASCENO

No dia 23 de julho de 2025, às 14:00 horas, sala 236, bloco I3, teve lugar a defesa de dissertação de mestrado no Programa de Pós-Graduação em Ecologia, Conservação e Manejo da Vida Silvestre, de autoria do(a) mestrando(a) Guilherme Andrade Damasceno, orientando(a) do Professor Rodrigo Lima Massara, intitulada: " Avaliando os Impactos das Mudanças Climáticas e do Uso e Cobertura de Solo na Adequabilidade de Habitat para o Tamanduá-bandeira (Myrmecophaga tridactyla, Linnaeus, 1758) ". Abrindo a sessão, o(a) Presidente da Comissão, Doutor(a) Rodrigo Lima Massara, após dar a conhecer aos presentes o teor das normas regulamentares do trabalho final, passou a palavra para o(a) candidato(a) para apresentação de seu trabalho. Estiveram presentes a Banca Examinadora composta pelos Doutores: Alessandra Bertassoni (UFG), Renata Guimarães Frederico (SEM VÍNCULO (ENCERRADO RECENTEMENTE COM A UFMA)) e demais convidados. Seguiu-se a arguição pelos examinadores, com a respectiva defesa do(a) candidato(a). Após a arguição, apenas os senhores examinadores permaneceram no recinto para avaliação e deliberação acerca do resultado final, sendo a decisão da banca pela:

(X) Aprovação da dissertação, com eventuais correções mínimas e entrega de versão final pelo orientador diretamente à Secretaria do Programa, no prazo máximo de 30 dias;

( ) Reprovação da dissertação

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***Conforme o disposto no Artigo 80 da Resolução Complementar do CEPE/UFMG Nº 02/2017, de 04 de julho de 2017, caso seja a primeira reprovação, poderá ser concedido, a critério do Colegiado de Curso, um prazo para a realização de nova defesa de tese.**

Nada mais havendo a tratar, o Presidente da Comissão encerrou a reunião e lavrou a presente ata, que será assinada por todos os membros participantes da Comissão Examinadora.

Belo Horizonte, 23 de julho de 2025.

Comissão Examinadora	**Assinatura**
Doutor(a) Rodrigo Lima Massara	
Doutor(a) Alessandra Bertassoni	
Doutor(a) Renata Guimarães Frederico	

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” Eu só queria que o mundo tivesse o dobro do tamanho e que metade dele ainda estivesse inexplorado.”

- David Attenborough

RESUMO

As mudanças climáticas e mudanças no uso e cobertura de solo são consideradas as principais ameaças para a biodiversidade, no presente e no futuro. Espera-se que diversas espécies percam habitats adequados no futuro, o que pode resultar em extinções locais e globais. Isso é ainda mais preocupante para espécies de nicho climático restrito e forte sensibilidade ao clima. Esse é o caso para o maior Xenarthra existente, *Myrmecophaga tridactyla*. Por ser basoendotérmica, *M. tridactyla* regula a temperatura corporal ajustando seu ritmo de atividade conforme o clima, a disponibilidade de habitats abertos e fechados e a presença humana. Alguns estudos avaliaram o efeito das mudanças climáticas sobre a espécie, porém nenhum incluiu mudanças de uso de solo em projeções futuras. Nesse estudo, desenvolvemos modelos de nicho ecológico para prever a adequabilidade de habitat para a espécie em sua área de distribuição, considerando dois cenários de emissão de gases de efeito estufa (SSP245 e SSP585)) nos intervalos 2041-2060 e 2061-2080. Esperávamos um decréscimo contínuo na adequabilidade de habitat para *M. tridactyla* tanto no cenário otimista SSP245 quanto no pessimista SSP585. Contudo, ao contrário do esperado, observamos um ganho líquido de adequabilidade durante 2041-2060, seguido por um forte declínio em 2061-2080. O mesmo padrão se manteve no cenário pessimista SSP585, mas com um declínio ainda mais acentuado em 2061-2080. Esse resultado pode gerar a falsa impressão de que a espécie se beneficia das mudanças climáticas e do uso da terra e pode levar à redução de esforços conservacionistas. Além disso, no segundo intervalo (2061-2080), as áreas mais favoráveis concentram-se em regiões densamente habitadas e em franca expansão agrícola e urbana. A alta adequabilidade climática nesses locais pode atrair indivíduos, intensificando conflitos antrópicos e configurando uma armadilha ecológica ("ecological trap") que compromete ainda mais a aptidão individual e populacional da espécie. Nossos achados ressaltam a importância de incorporar cenários de mudanças climáticas e de uso do solo no planejamento de conservação e de interpretar modelos de nicho ecológico em conjunto com cenários locais e regionais.

Palavras-chave: estratégias conservacionistas; espécies ameaçadas; nicho climático; temperatura; mamíferos neotropicais

ABSTRACT

Climate change and alterations in land use and cover have been considered major threats for present and future biodiversity. Many species are expected to lose suitable habitats in the future, which could result in local and global extinctions. This is even more concerning for species with restrict ecological niche and stronger climate sensitivity. This is the case of the largest extant Xenarthra, *Myrmecophaga tridactyla*. Being a basoendotherm species, *M. tridactyla* regulates its body temperature by adjusting activity patterns in response to climate, the availability of open and forested habitats, and human presence. Some studies have assessed the impact of climate change on species presence, but none included land use and cover in future predictions. In this study, we developed ecological niche models to predict habitat suitability across the species' historical distribution under two greenhouse-gas-emission scenarios (SSP245 and SSP595) for the periods 2041-2060 and 2061-2080. We expected a steady decline in suitability under both scenarios. However, contrary to our expectations, models revealed a net increase in suitable areas during 2041-2060, followed by a sharp decrease in 2061-2080, particularly pronounced in the pessimistic SSP595. This counterintuitive early gain may create a false impression that the species benefit from climatic and land-use changes, potentially reducing conservation efforts for the species at the time. Moreover, in 2061-2080 the areas of highest suitability concentrate in densely populated regions undergoing rapid agricultural and urban expansion, posing an ecological trap that could further compromise individual and population fitness. Our findings underscore the necessity of integrating both climate and land-use projections into conservation planning for the species, and of interpreting ecological-niche models in the context of local and regional processes

Keywords: conservation strategies; endangered species; climatic niche; temperature; neotropical mammals.

CONTEXTUALIZAÇÃO GERAL

O ritmo acelerado das alterações no clima e na paisagem, induzidas por atividades humanas, constitui uma das principais preocupações para a conservação da biodiversidade em escala global (Habibullah et al. 2022, Hetem et al. 2014, Levinsky et al. 2007). O aumento das temperaturas médias e a maior frequência de eventos climáticos extremos, diretamente relacionados às mudanças climáticas, têm sido responsáveis — de forma direta e indireta — pela simplificação das comunidades biológicas e pelo declínio populacional generalizado de diversas espécies (Habibullah et al. 2022, Pacifi et al. 2015, Sinervo et al. 2010). Paralelamente, a conversão de habitats florestais e abertos em áreas modificadas pelo ser humano, como terrenos agrícolas e zonas urbanas, é uma das principais causas de perda e fragmentação extensiva de habitats, contribuindo para processos de extinção e para a redução da biodiversidade (Jaureguiberry et al. 2022, Hanski 2011). Embora cada impacto possa produzir efeitos isolados, sua interação tende a amplificar as consequências negativas para a biodiversidade, comprometendo a capacidade das espécies de responder a essas mudanças em escalas regionais e globais (Selwood et al. 2015, Oliver & Morecroft 2014). Projeções futuras indicam que esses fatores serão determinantes para a perda de habitats adequados e para a extinção de inúmeras espécies (Moura et al. 2023, Sharma et al. 2022, Cuarón 2000).

De acordo com o Painel Intergovernamental sobre Mudanças Climáticas, cerca de 10% das espécies enfrentarão risco muito elevado de extinção diante de um aumento de 2 °C na temperatura média global, com impactos ainda mais acentuados em determinados grupos (IPCC 2022). Espécies terrestres de importância ecológica podem sofrer drásticas reduções de área de ocorrência e declínios populacionais nos trópicos (Moura et al. 2023, Ribeiro et al. 2016, Trisurat et al. 2014), favorecendo extinções locais, comprometendo funções ecológicas e acelerando a simplificação das comunidades biológicas (Newbold 2018, Lurgi et al. 2012). Compreender os efeitos desses fatores sobre a biodiversidade é, portanto, fundamental não apenas para mitigar impactos atuais, mas também para planejar estratégias de conservação frente a um futuro em que espécies ameaçadas — com baixa taxa reprodutiva e alta sensibilidade climática — possam estar à beira da extinção (Reside et al. 2018, Watson et al. 2012).

O tamanduá-bandeira (*Myrmecophaga tridactyla* Linnaeus, 1758), o maior representante vivo da ordem Xenarthra, é uma das espécies potencialmente mais afetadas pelas mudanças no uso e cobertura da terra e pelas alterações climáticas (Zimbres et al. 2012). Distribui-se em baixas altitudes a leste dos Andes — desde Honduras até a região do Gran Chaco, na Argentina, Bolívia e Paraguai — e a oeste dos Andes, na Colômbia e no Equador (Miranda et al. 2025). Classificada como Vulnerável pela União Internacional para a Conservação da Natureza (IUCN) e por diversas listas vermelhas nacionais e regionais (Miranda et al. 2015), a espécie apresenta declínio populacional acentuado em decorrência de ameaças antrópicas, como destruição de habitat, aumento da intensidade e frequência de incêndios, atropelamentos, caça e abate ilegal (Miranda et al. 2014, Diniz & Brito 2013). *M. tridactyla* alimenta-se principalmente de cupins e formigas, podendo consumir até 35.000 insetos por dia, desempenhando papel ecológico essencial no controle populacional desses invertebrados e na manutenção da integridade da vegetação (Rodrigues et al. 2008, Moeller 1990). Por sua natureza basoendotérmica (baixo metabolismo), possui capacidade limitada de ajustar-se fisiologicamente às variações de temperatura ambiental (McNab 1984). Assim, regula a temperatura corporal por meio da modulação dos padrões de atividade conforme as condições climáticas, utilizando habitats florestais e abertos para forrageamento e descanso, em função de variáveis como temperatura e precipitação (Giroux et al. 2023, Camilo-Alves & Mourão 2006). Essa característica torna a espécie particularmente sensível a mudanças ambientais de curto e longo prazo, aumentando a preocupação com seu estado de conservação atual e futuro em um contexto de rápidas transformações ambientais.

Estudos prévios indicam que *M. tridactyla*, assim como diversas outras espécies, deverá perder toda a sua área de habitat adequado no bioma Caatinga, uma floresta tropical sazonalmente seca do Brasil (Moura et al. 2023). Populações situadas em florestas tropicais, como a Amazônia, também devem ser severamente impactadas por transições para paisagens mais homogêneas e de baixa diversidade vegetal (Borges et al. 2023), especialmente fora de áreas protegidas (Zimbres et al. 2012). Além disso, a espécie encontra-se virtualmente extinta em porções de sua distribuição histórica — que se estendia da Guatemala ao norte do Uruguai —, restando apenas pequenas populações em declínio, sobretudo na América Central (Miranda et al. 2014). O cenário para a espécie é, portanto, pouco otimista, principalmente diante da rápida expansão agrícola, minerária e urbana, que poderá causar níveis sem precedentes de perda e fragmentação de habitat (Powers & Jetz 2019, Jantz et al. 2015).

No presente estudo, avaliamos de forma integrada os efeitos das mudanças no uso e cobertura da terra e das alterações climáticas, visando compreender o impacto combinado dessas variáveis sobre a espécie no presente e em projeções futuras. Para tanto, desenvolvemos modelos de nicho ecológico com os seguintes objetivos: 1) identificar os principais fatores ambientais que determinam a distribuição da espécie; 2) mapear a adequabilidade atual de habitat; e 3) projetar a adequabilidade futura sob diferentes cenários de emissão de gases de efeito estufa. Considerando a sensibilidade da espécie tanto a mudanças climáticas quanto a modificações antrópicas na paisagem (Miranda et al. 2015, Rodrigues et al. 2008), nossa hipótese é de que ambos os fatores provocarão redução líquida na adequabilidade de habitat para os períodos de 2041–2060 e 2061–2080, em comparação às condições atuais. Prevemos essa redução sob os cenários SSP245 (otimista) e SSP585 (pessimista), em função do aumento da temperatura e de alterações nos padrões climáticos (Gidden et al. 2019). Adicionalmente, buscamos identificar padrões espaciais de mudança na adequabilidade, de modo a localizar áreas com maior potencial para a persistência de populações futuras sob condições climáticas favoráveis.

SUMÁRIO

1. INTRODUCTION

The rising rate of human-induced changes in climate and landscape is a major concern for biodiversity conservation worldwide (Habibullah et al. 2022, Hetem et al. 2014, Levinsky et al. 2007). Increasing mean temperatures and frequency of climatic extremes directly related to climate change have been responsible - both directly and indirectly - for the simplification of biological communities and the widespread populational decline of some species (Habibullah et al. 2022, Pacifi et al. 2015, Sinervo et al. 2010). Furthermore, the conversion of forested and open habitats into human-modified landscapes, such as agricultural lands and urban areas, is a major cause of extensive habitat loss and fragmentation, currently driving extinction and biodiversity loss (Jaureguiberry et al. 2022, Hanski 2011). While each impact may have isolated effects, their combination can exacerbate the negative consequences on biodiversity and further undermine the ability of species to cope with such changes at both regional and global scales (Selwood et al. 2015, Oliver & Morecroft 2014). Tragically, future predictions indicate that these factors will be the main drivers of loss of suitable habitats and the extinction of several species (Moura et al. 2023, Sharma et al. 2022, Cuarón 2000).

According to the Internation Panel on Climate Change, about 10% of the species will be facing very high risk of extinction with a temperature increase of 2ºC, with greater risk to specific groups (IPCC 2022). For instance, some important terrestrial species may face drastic range contraction and population decline in the tropics (Moura et al. 2023, Ribeiro et al. 2016, Trisurat et al. 2014), which may promote local extinctions, compromise their ecological roles and accelerate the simplification of biological communities (Newbold 2018, Lurgi et al. 2012). Therefore, understanding the effects of these factors on biodiversity is essential not only to mitigate current consequences but specially to plan for a future in which endangered species - with low reproductive rates and greater climate sensitivity – may be on the verge of extinction (Reside et al. 2018, Watson et al. 2012).

The giant anteater (*Myrmecophaga tridactyla* Linnaeus, 1758), the largest living Xenarthra, is one of the species whose future may be compromised by land use and climate change (Zimbres et al 2012). The species can be found at low elevations east of the Andes - from Honduras to the Gran Chaco region of Argentina, Bolivia and Paraguay - and west of the Andes in Colombia and Ecuador (Miranda et al. 2025). Considered Vulnerable by the International Union for Conservation of Nature (IUCN) and many national and regional red lists (see Miranda et al. 2015), populations are facing rapid decline due to human-induced threats such as habitat destruction, increasing fire intensity and frequency, road mortality, poaching and hunting (Miranda et al. 2014, Diniz & Brito 2013). *M. tridactyla* prey mainly on termites and ants, consuming up to 35.000 insects daily, which makes this species essential to population control and vegetation integrity maintenance (Rodrigues et al. 2008, Moeller 1990). Due to its basoendothermic (low metabolic) nature, individuals have a limited capacity to adjust to environmental temperature fluctuations through physiological processes (McNab 1984). Consequently, individuals regulate body temperature by modulating their activity patterns according to climatic conditions, using both forested and open habitats for foraging and resting, depending on factors such as temperature and rainfall (Giroux et al. 2023, Camilo-Alves & Mourão 2006). This characteristic makes the species highly sensitive to both short and long-term climate and land use changes, which raises concerns about its current and especially future conservation status in a rapidly changing world.

The effects of climate change on *M. tridactyla* have already been investigated. The species, along with many others, is expected to lose all its suitable habitat in the Caatinga Biome, a Brazilian Tropical Dry Forest (Moura et al. 2023). Additionally, populations located in tropical forests, such as the Amazon, are expected to be strongly impacted by current and future transitions toward more homogeneous, low-diversity vegetations landscapes (Borges et al. 2023), particularly those outside protected areas (Zimbres et al. 2012). In addition to expected future population declines, the species is virtually extinct in areas within its historical range, that ranged from Guatemala to northern Uruguay, and some locations, especially in Central America, only have small, declining populations remain (Miranda et al. 2014). It is evident that prospects for the species are not optimistic, especially in a future of rapid agricultural, mining and urban expansion, which may drive unprecedented levels of habitat loss and fragmentation (Powers & Jetz 2019, Jantz et al. 2015).

In the present study, we incorporated the effects of land use and cover change alongside climate change to better understand the effect of both variables on the species in the present and in the future. To evaluate these impacts on *M. tridactyla*, we developed ecological niche models aiming to: 1) identify the primary environmental drivers of its distribution, 2) map present-day habitat suitability, and 3) forecast future suitability under alternative greenhouse-gas emission scenarios. Given the species' sensitivity to climate and human-driven landscape changes

(Miranda et al. 2015, Rodrigues et al. 2008), we expected that both land use and cover change and climate change would result to a net decrease in habitat suitability for 2041-2060 and 2061-2080, relative to current conditions. We anticipated this decline under both the SSP245 (optimistic) and SSP585 (pessimistic) emission scenarios, due to rising temperature and changes in climatic patterns (Gidden et al. 2019). Additionally, our study aimed to identify spatial patterns of change in habitat suitability to pinpoint areas where future populations may persist under favorable climatic conditions.

2. METHODS

2.1 Study Area and Species Data

We used the IUCN 's historical geographical range for the species (Miranda et al. 2025) as our study area to encompass a great variability of the species niche. Species occurrence data were obtained from the Neotropical Xenarthrans dataset (Santos et. al. 2021), the Camera trap surveys of Atlantic Forest Mammals Dataset (Franceschi et al. 2024) and Colombia's Biodiversity Information System (SiB Colombia 2020). The compiled data represented a total of 11,738 presence records for the species.

To select precise presence records, we adopted several criteria. First, aiming to target more recent habitat availability in the modelling process, we excluded data collected before 2000. Then, to ensure that the coordinates provided by the studies were sufficiently precise, we excluded records with less than 1 kilometer of precision or without reported precision values. We only used records obtained through camera traps or human observations, whether from opportunistic encounters or monitoring programs, to avoid potential false positives. Finally, we merged the four datasets into a single dataset containing only records that met all these criteria, resulting in a total of 2,943 records. All previous and subsequent procedures were performed using R Statistical Software v4.4.2 (R Core Team 2013).

Then, we removed duplicate records and those with erroneous coordinates (*e.g,.* those placed at city centroids or in the sea) using the *CoordinateCleaner* R package (Zizka et al. 2019). To reduce sampling bias and spatial autocorrelation, we used the *spThin* R package (Aiello- Lammens et al. 2015), excluding records that were less than 10.77 km apart. We chose this distance on an estimated mean individual home range derived from values reported by

Bertassoni & Ribeiro (2019). After the spatial filtering, a total of 485 records remained and were used in subsequent modelling steps (Fig. 1).

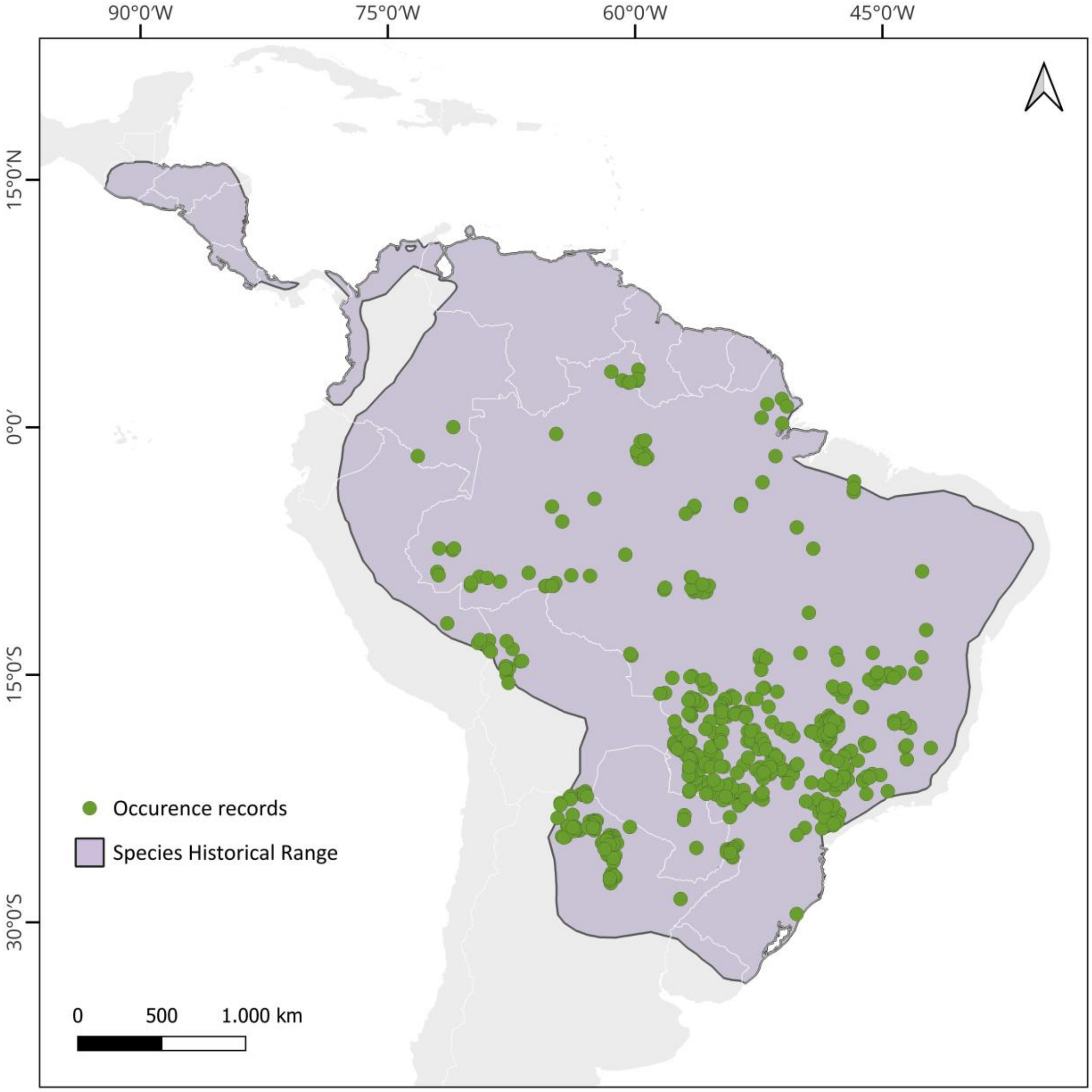

Figure 1 - The study area defined by the IUCN's historical range for *M. tridactyla* and the 485 verified presence records used in the modelling processes.

2.2 Environmental variables

To build the models and generate present and future predictions, we selected a total of 20 environmental variables at a 1 km spatial resolution. Despite the large extent of the study area and the species home range, we opted to work with a high resolution to allow the result models to be integrated in local and regional conservation planning. Land Use and Cover maps were obtained from Li et al. (2017), which divided Land Cover in six categories: water, forests, grassland, farmland, urban and baren. The 19 bioclimatic layers were sourced from WorldClim v. 2.1 (Fick & Hijmans 2017). All variables were cropped and masked to the species' historical range and reprojected to the WGS 84 Coordinate System using the *terra* R package (Hijmans 2025).

To address multicollinearity among bioclimatic variables, we performed a Variance Inflation Factor (VIF) analysis using the *usdm* R package (Naimi et al. 2014), excluding variables with a correlation greater than 0.6. This process resulted in the selection of five bioclimatic variables (Bio 2: Mean Diurnal range; Bio 3: Isothermality; Bio 8: Mean Temperature of Wettest Quarter; Bio 15: Precipitation Seasonality; and Bio 18: Precipitation of Warmest Quarter), along with the Land Cover layer.

2.3 Modelling

2.3.1 Calibration & Evaluation

All modelling steps were performed in R using the *sdm* package (Naimi & Araújo, 2016). To reduce algorithm-specific bias, we fitted four algorithms -*Maxent*, *Random Forest*, *GLM* and *GAM*- each calibrated with presence-only data augmented by randomly generated background points and pseudo-absences following Barbet-Massin et al. (2012) (see Table 1). All algorithms ran with default settings. Occurrence records were partitioned into training (75%) and testing (25%) subsets, and each model was iterated ten times for *GLM*, *GAM,* and *Random Forest,* and 15 times for *Maxent,* following Barbet-Massin et al. 2012. We assessed model performance using the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) plot and the True Skill Statistic (TSS). AUC values range from 0 to 1, with values above 0.7 considered indicative of good model performance (Fielding & Bell 1997, Sillero et al. 2021). TSS values range from -1 to 1, with values above 0.5 indicating that species distribution is non-random (Sillero et al. 2021).

Table 1 - Type and number of pseudo-absences or background points used for each modelling algorithm in predicting the habitat suitability of *M. tridactyla*, following Barbet-Massin et al. (2012).

Algorithm	Absence Type	Numbers of Points
Maxent (Phillips et al. 2006)	Background	10000
Random Forest (Breiman 2001)	Pseudo-absence	487
GAM (Hastie & Tibshirani 1986)	Pseudo-absence	1000
GLM (McCullagh & Nelder 1989)	Pseudo-absence	1000

We assessed variable importance and response curves to evaluate their influence on the models. An ensemble model was created by selecting the best-performing models for each algorithm, maximizing model specificity and sensibility. This resulted in projected habitat suitability maps. To reduce potential outliers arising from algorithm selection and modeling settings, we generated a raster layer with the mean suitability values of the ensemble models using the 'mosaic' function from the *terra* R package following Meireles et al. 2022.

2.3.2 Future Projections

For future predictions, we used Land Cover maps from Li et al. (2017) and bioclimatic variables from the CMCC-ESM2 Global Circulation Model (GCM) (Lovato et al. 2022), which has demonstrated strong performance in modelling processes covering both South and Central America (Ortega et al. 2021). We chose to project habitat suitability to the 2041-2060 period, combining 2041-2060 bioclimatic layers with the 2050 land cover map, and the 2061-2080 period, combining 2061-2080 bioclimatic layers with the 2100 land cover map. To assess the effects of climate and land cover changes under different scenarios, we selected two projection groups: an optimistic and a pessimistic scenario.

In the optimistic scenario, we combined Shared Socioeconomic Pathway (SSP) 245 bioclimatic layers - representing a milder and more realistic trajectory based on current emission rates and global policies - with the A1B land cover projection, which follows a similar trend of moderate environmental change. Under this scenario, global temperature increase is expected to be limited to 2,5 ºC, with a slower rate of natural habitat conversion into human-modified landscapes (Gidden et al. 2019, Li et al. 2017, Riahi et al. 2017).

In the pessimistic scenario, we combined SSP 585 bioclimatic layers - representing a fossil- fuel-driven, highly exploitative future with minimal efforts to reduce emissions - with the A2 land cover projection, which follows a similar pattern of extensive environmental change. Under this scenario, global temperatures could rise by up to 5 ºC, accompanied by a rapid conversion of natural habitats into human-modified landscapes (Gidden et al. 2019, Li et al. 2017, Riahi et al. 2017).

As with the present predictions, we created an ensemble model for each method in both scenarios and generated a mean suitability raster using the *terra* R package. Suitability loss/gain analysis was assessed using QGIS (QGIS Development Team 2009). We calculated the difference between the projected suitability pixel values for each scenario and the current suitability pixel values, resulting in positive values (suitability gain) and negative values (suitability loss). We considered changes in suitability between 0,05 and -0,05 to be poor indicators of change and attributed such values as no change in suitability.

3. RESULTS

3.1 Niche Modelling

The modeling process resulted in a total of 225 models, with an average AUC of 0.83±0.05 and an average TSS of 0.57±0.08, indicating moderate performance and predictive power (Sillero et al. 2021). *Random Forest* performed best, with a mean AUC of 0.87 and mean TSS of 0.65, followed by *maxent* (AUC = 0.80; TSS = 0.57), *gam* (AUC = 0.83; TSS = 0.57) and *glm* (AUC = 0.77; TSS = 0.49).

Of the six variables used, Isothermality (BIO3) was the most influential in predicting suitable habitats for *M. tridactyla*, contributing 30% to the observed patterns, followed by BIO18 (20%), BIO2 (7%), BIO8 (2%). Contrary to expectations, Land Use and Cover contributed only 1% to the model.

Response curves revealed that habitat suitability for the species is higher when: isothermality (BIO3) ranges between 50% and 65%; BIO18 values range between 500mm and

1000mm; BIO15 values increase; and BIO 8 values rise to a turning point (≅ 22ºC) (Fig. 2). In terms of land use, Forest and Grassland categories appear to favor habitat suitability for the species. Conversely, Farmland, Urban and Barren categories are associated with lower suitability values, although these values remain within a satisfactory range, between 0,4 and 0,6 (Fig 2F).

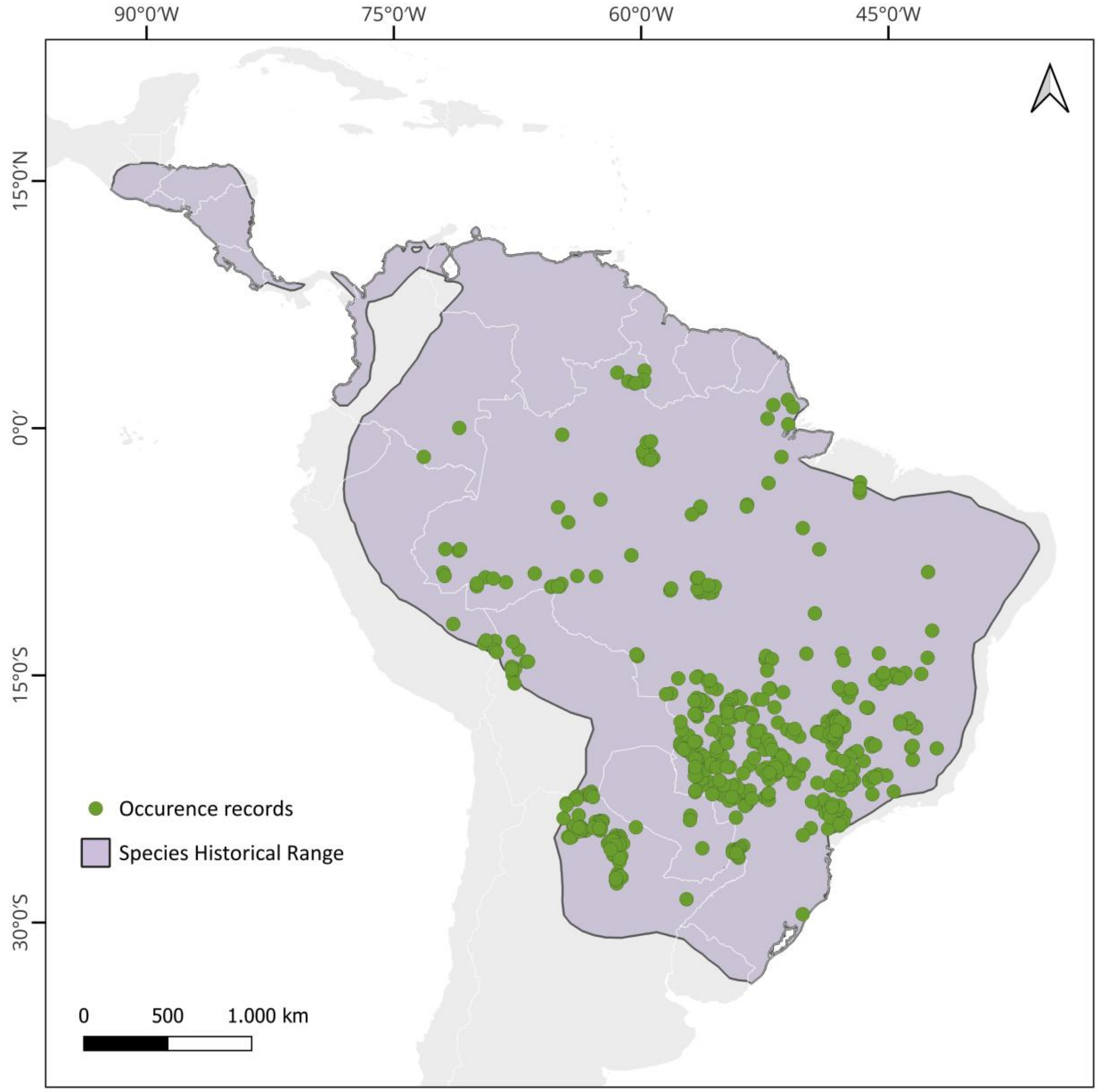

Figure 2 – Mean response curves for the variables included in the habitat suitability model for *M. tridactyla*.

3.2 Current and Future Predictions

The current prediction showed that most of the species' geographical range (59%) is covered by areas with low suitability values (0 to 0.25) (Fig. 3). Areas with medium (0.25 to 0.50) and high suitability (> 0.5) represented 25% and 16% of the study area, respectively. Our model showed capacity for predicting medium and high suitability in areas where excluded records in the filtering process were placed, especially in Central America (Fig. 3).

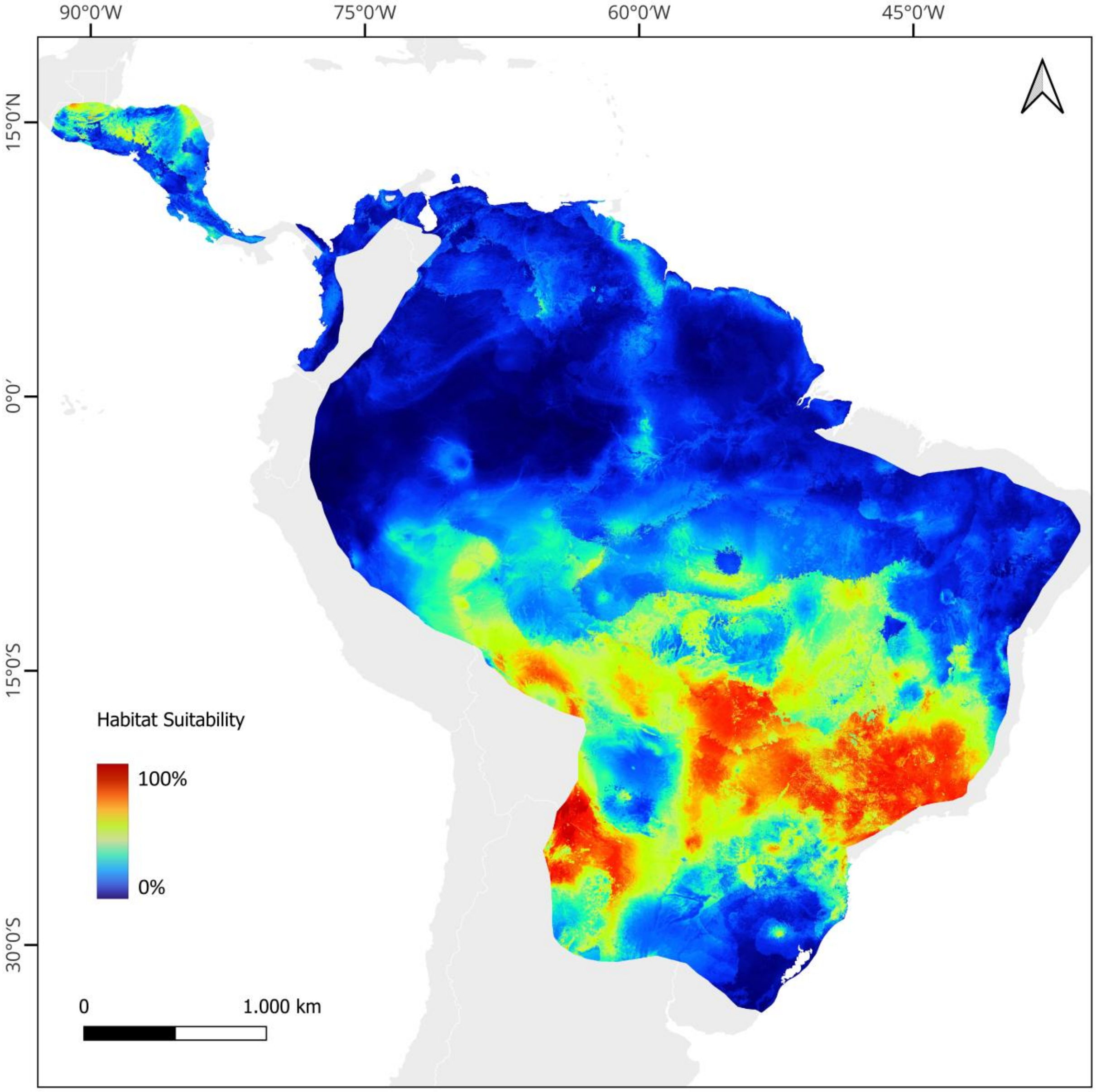

Figure 3 - Current habitat suitability map for *M. tridactyla.*

Future predictions varied according to the scenarios and time span (Fig. 4). In the optimistic scenario (ssp245 emission scenario), habitat suitability for *M. tridactyla* will show no change in 47% of the area, while suitability will increase in 37% and decrease in 16% of the area by 2041-2060, with only slight shifts in the distribution of suitable and unsuitable areas (Fig. 4A). Although an initial increase is projected, by 2061-2080 the species' suitability will decrease greatly when compared to the current levels, with a loss of suitability in 31% of its range and a gain in only 18% (Fig. 5). Additionally, by 2061-2080 suitable areas will become more concentrated in the eastern part of the study area, along the Atlantic Forest (Fig. 4B).

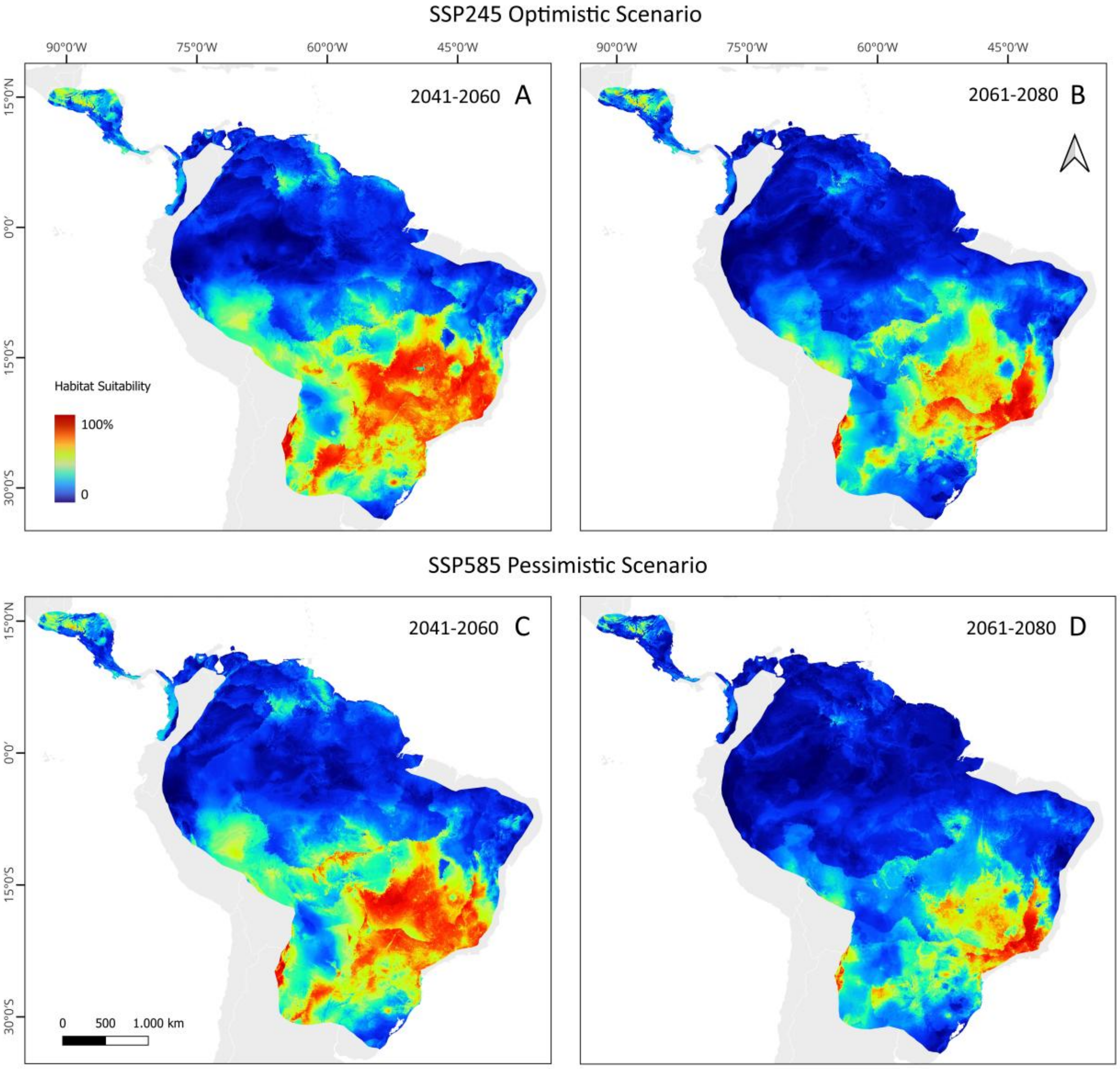

Figure 4 - Projected habitat suitability for *M. tridactyla* in 2041-2060 and 2061-2080. Maps A and B show future suitability for the optimistic scenario (SSP245), while C and D show future suitability for the pessimistic scenario (SSP585).

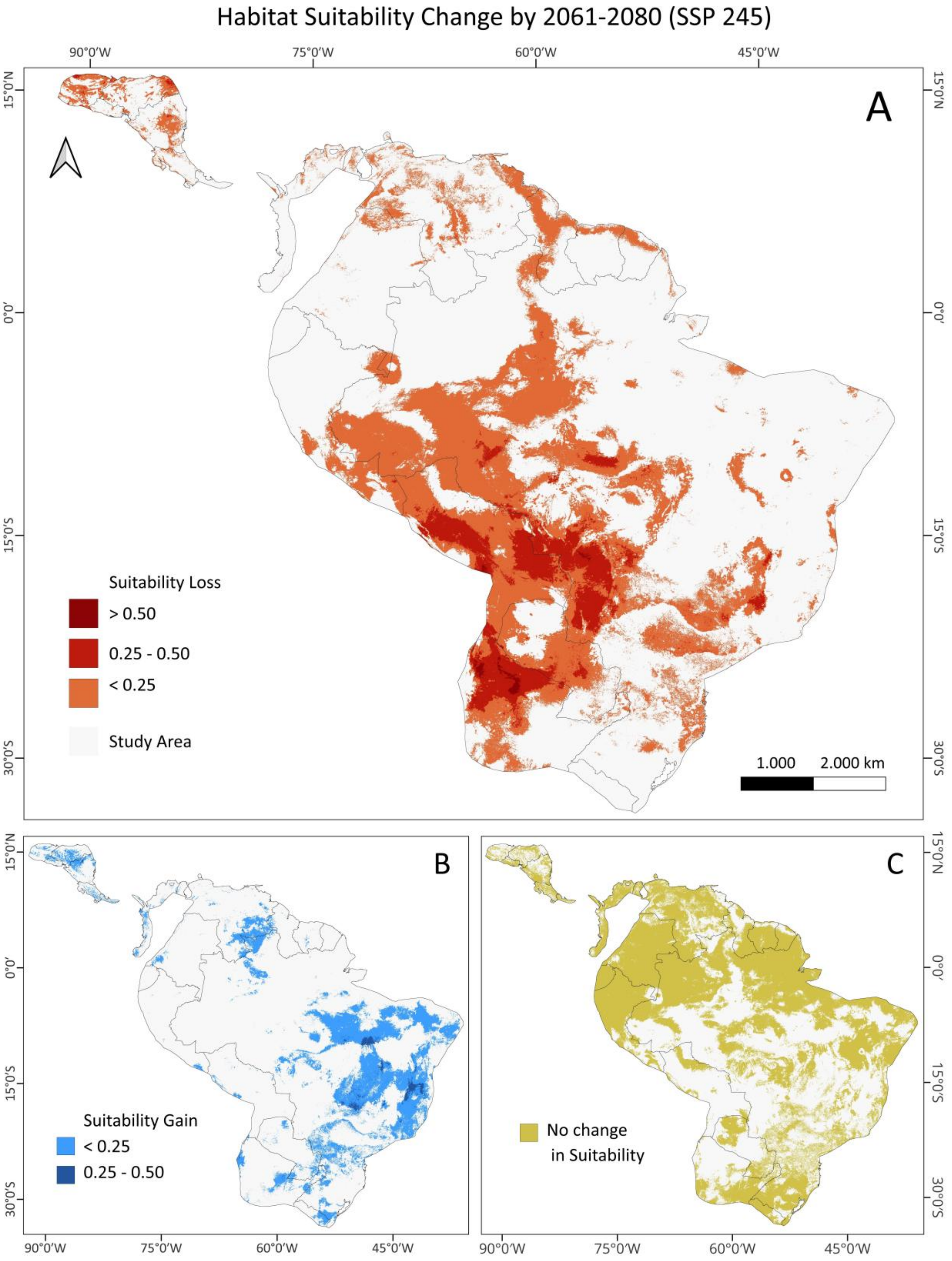

Figure 5 – Project change in habitat suitability for *M. tridactyla* by 2061-2080 in the ssp245 optimistic scenario. Map A shows predicted loss in suitability; Map B shows predicted gain in suitability and Map C shows areas where suitability levels will not change.

In the pessimistic scenario (ssp585 emission scenario), habitats follow a similar pattern but with a more pronounced global decline in suitability (Fig. 4C and 4D). By 2041-2060, suitability will increase in 36% and decrease in 19% in the species' range, indicating a stronger negative impact on habitat quality. Notably, by 2080, the decline in suitability will be even more severe, with suitability decreasing in 41% of the area and increase in only 11% (Fig. 6).

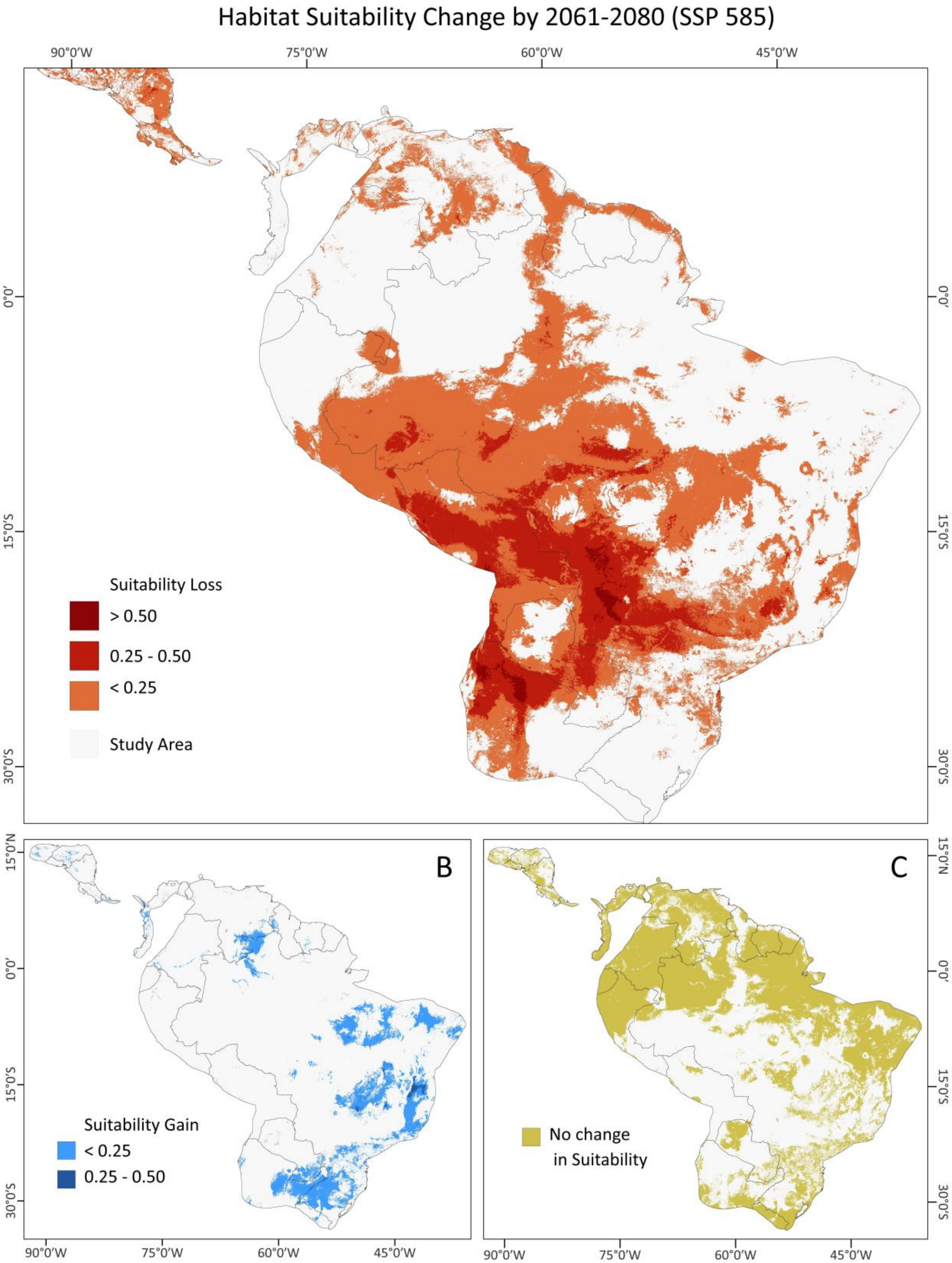

Figure 6 – Project change in habitat suitability for *M. tridactyla* by 2061-2080 in the ssp585 pessimistic scenario. Map A shows predicted loss in suitability; Map B shows predicted gain in suitability and Map C shows areas where suitability levels will not change.

4. DISCUSSION

Our results indicate that climate plays a crucial role in determining habitat suitability for *M. tridactyla*. Due to its low metabolism, individuals may struggle to occupy landscapes without favorable climatic conditions, particularly regarding temperature and precipitation (McNab 1984). The high relative importance of Isothermality (Bio2) and its optimal range (50% - 65%) reafirms that the species thrives in environments with moderate temperature variation within a month compared to yearly fluctuations, while extreme variations – either too low or too high - reduce habitat suitability. Additionally, the species benefits from precipitation levels between 500mm and 1000mm in the warmest quarter (Bio18), suggesting that temporary drops in temperature and increased humidity caused by rainfall may help individuals cope with daytime heat stress.

On the other hand, land use and cover had little influence on habitat suitability for *M. tridactyla*. In some cases, the species can use agriculture fields, timber plantations, and livestock farming areas for foraging, resting, and dispersal (Kreutz et al. 2012, Miranda 2004, Shaw et al. 1987). While these modified landscapes may offer food sources and low energy dispersal routes, their proximity to human activities also expose individuals to threats, including roadkills, poaching, and increased mortality from domestic dogs (Quiroga et al. 2016, Miranda et al. 2014). Additionally, individuals might suffer from pesticide poisoning in agricultural and timber plantation areas (Braga et al. 2014). Although land use and cover contributes less to the model than bioclimatic variables, the highest suitability values were associated with forests and grasslands, reinforcing the importance of preserved habitats for maintaining healthy *M. tridactyla* populations (Diniz & Brito 2015).

Current predictions indicate that areas with medium (from 0,25 to 0,5) and high suitability values (> 0.5) are primarily concentrated in tropical savannahs. The Brazilian Cerrado harbors sites with large giant anteaters populations, with some protected areas reaching population densities of up to 0.2 individuals/km² (Miranda et al. 2006). Similarly, the Argentinian portion of the Gran Chaco, another high-suitability area, has recorded dense populations in certain locations (Quiroga et al. 2016). However, both biomes are experiencing rapid habitat conversion due to expanding agricultural activities, leading to increased habitat loss and fragmentation (Braga 2010, Baxendali & Buzai 2009). Without direct intervention, ongoing human activities may reduce their ability to sustain viable *M. tridactyla* populations.

Our expectations regarding the future of habitat suitability for the species were only partially validated. We initially anticipated a steady decline in suitability across both scenarios in 2041-2060 and 2061-2080. However, our results revealed an unexpected pattern: by 2041-2060, habitat suitability is projected to increase in more areas than it will decrease across the species' historical distribution. While this might suggest that climate change could initially have some positive effects, this short-term gain is followed by a sharp decline in suitability levels by 2061- 2080. In the pessimistic SSP 585 scenario, the decline is even more severe. In the medium term, this temporary increase in suitability could create a false perception that the species is not being affected by climate change, potentially reducing conservation efforts at a time when proactive measures are crucial to safeguarding populations that will face serious challenges in the future.

By 2061-2080, in addition to the widespread decline in habitat suitability, medium and high suitability areas will become concentrated in the eastern portion of the species' distribution range, further compromising its conservation status. In this novel suitability scenario, the most suitable habitats will be located primarily in the Atlantic Forest - the most densely populated biome in Brazil (IBF 2020) - as well as in the ecotone between this biome and the Brazilian Cerrado, a region heavily impacted by agriculture, livestock farming, and mining activities. If the species avoid human-dominated landscapes and remain in lower-suitability areas, it may suffer from reduced resource availability, leading to declines in both individual fitness and overall population viability. On the other hand, if individuals tend to occupy the more suitable areas, they may face an even stronger challenge.

When human activities disrupt the environmental cues that species use to assess habitat quality, individuals may be lured into areas where they cannot thrive, diminishing both individual and population fitness. This pattern, defined as an ecological trap (Hale & Swearer 2016, Schlaepfer et al. 2002,), has been documented in some species (Buderman et al. 2020, Northrup et al. 2012). Although climate serves as one such cue for *M. tridactyla,* it is only one of many factors guiding site selection (Bertassoni & Ribeiro 2019). If, by 2061-2080, individuals disperse toward climatically optimal zones, they will likely face intensified conflicts with human activities, such as habitat destruction, road mortality, poaching, and pesticide exposure. Whether the species persists in suboptimal habitats or shifts its range, its future remains increasingly precarious.

Such scenarios could drive *M. tridactyla* toward extinction, undermining its ecological role and associated ecosystem services. For example, a single giant anteater can consume up to 35,000 ants and termites daily (Moeller 1990); widespread declines would allow populations of cellulose- feeding insects- such as *Coptotermes* and *Syntermes*- to explode, accelerating wood degradation and destabilizing vegetation in the medium to long term. Moreover, outbreaks of pest species like *Acromyrmex* and *Syntermes* can devastate economically important crops, inflicting strong losses on agricultural systems (Zarbin et al. 2009).

Although previous studies have evaluated the impact of climate change on *M. tridactyla,* none have integrated future land use and cover dynamics. For example, Zimbres et al. (2012) forecast a pattern of suitability loss that differ from ours, and Roberto (2017) used species-distribution models on contemporary Brazilian records to show that the Cerrado and the Amazon biomes are currently the most suitable. These contrasting outcomes illustrate that ecological-niche models are highly sensitive to input data and parameter choices and therefore must be interpreted with caution (Zurell & Engler 2019).

Although our models moderate performance, some data-related gaps warrant attention. During filtering, many occurrence records from Colombia's open savannahs- where the species is known to occur – were excluded, likely leading to underestimation of habitat suitability in that region. However, Colombian populations of *M. tridactyla* are declining sharply due to human pressures and are listed as Vulnerable nationally (MADS 2014), which may indeed reduce the viability of habitats we may have underestimated. This underscores that ecological niche models necessarily simplify reality, and their inherent limitations can yield inaccurate suitability predictions (Zurell & Engler 2019). Consequently, conservation planning must integrate our model outputs with regional and local variables that could either bolster or compromise the species' persistence (Ferraz et al. 2012).

Furthermore, exploring additional dimensions of species' ecological niche may be essential to fully understand where the species can persist now and in the future. Our findings advance this understanding by shedding light on critical ecological requirements, providing valuable insights for future research, conservation strategies, and policy decisions. Ultimately, this study underscores the urgent need to evaluate how giant anteaters - and other important ecological species - will respond to a rapidly changing world shaped by land use and cover change and climate change, challenges that even human societies find difficult to overcome.

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