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BIODIVERSITY AND CONSERVATION - ORIGINAL ARTICLE

The effect of climate change on populations of the Amazon endemic Xingu Screech Owl (Aves-Strigidae)

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ABSTRACT

Climate change is restructuring ecological dynamics worldwide, with particularly severe impacts in tropical regions, especially forested areas. The Amazon ecosystem is currently undergoing rapid deforestation. The owl family, Strigidae, is especially sensitive to habitat disturbance and may have strong population declines due to environmental change. In this study, the potential effects of climate change were investigated with the recently recognized Xingu Screech-owl (*Megascops stangiae* Dantas, Weckstein, Bates, Oliveira, Catanach & Aleixo 2021) by applying species distribution models (SDMs) to predict how climatically suitable habitat will change over time. The *M. stangiae* is likely to be negatively impacted because of the loss of climatically suitable areas, because it is dependent on preserved forests. The owls' distribution was modeled using occurrence records and bioclimatic variables under the current emissions scenario, as well as two future projections: optimistic and pessimistic. We found that both scenarios predicted a loss of more than half of the area suitable for the owl. Although *M. stangiae* is currently classified as least concern (LC) by the *International Union for Conservation of Nature* Red List (IUCN), our findings indicate that the species may soon require being classified as critically endangered (CR). These results underscore the urgent need to understand the ecological consequences of climate change for Amazonian endemic species and to implement targeted conservation strategies.

KEYWORDS: Xingu screech owl, Amazon Biome, climate change

O efeito das mudanças climáticas nas populações de *Megascops stangiae* (Ave-Strigidae)

RESUMO

As mudanças climáticas possuem significativas consequências na alteração dos padrões ecológicos, especialmente em áreas florestadas. A Amazônia atualmente enfrenta uma forte redução de áreas florestadas devido à grande exploração dos recursos naturais. Entre as aves rapinantes, a família Strigidae pode responder de maneira muito particular a alterações no seu habitat por serem vulneráveis a perturbações no ambiente. Neste trabalho, foi avaliado os efeitos das mudanças climáticas sobre a espécie corujinha-do-xingu *(Megascops stangiae* Dantas, Weckstein, Bates, Oliveira, Catanach & Aleixo 2021), por meio de modelos de distribuição de espécies (MDEs), com o intuito de avaliar ganhos ou perdas de áreas climaticamente adequadas para a espécie. Acredita-se que *M. stangiae* será impactada negativamente pela perda de áreas climaticamente adequadas, por ser uma espécie dependente de florestas preservadas. Os modelos espaciais foram projetados a partir de dados de ocorrência de *M. stangiae* e variáveis climáticas, considerando o atual cenário de emissão de gases e dois cenários futuros (otimista e pessimista). Em ambos os cenários nossos resultados projetaram uma perda de mais da metade de áreas adequadas para ocorrência de *M. stangiae*. Atualmente, *M. stangiae* é considerada como menos preocupante (LC) na Lista Vermelha da União Internacional para Conservação da Natureza (IUCN), contudo, nossos resultados demonstram que em breve a espécie seria classificada como criticamente ameaçada (CR). Assim, para garantir a conservação de *M. stangiae*, é necessário compreender os processos de alterações climáticas e seus impactos na biodiversidade de espécies endêmicas da Amazônia.

PALAVRAS-CHAVE: Corujinha-do-xingu, Amazônia, Mudanças climáticas

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INTRODUCTION

Climate change is driving shifts in ecological patterns, causing important and negative impacts on biodiversity (De Souza et al. 2013). Reports from the Intergovernmental Panel on Climate Change (IPCC 2023) indicate alarming results of these global changes, such as the melting of permafrost and changes in precipitation regimes. These changes caused by climate are exacerbated by deforestation and wildfires (Polade 2014; Jansson and Taş 2014). Tropical regions are among the most severely impacted, with climate projections forecasting temperature increases of up to 4°C and precipitation declines of around 20% by 2100, thereby exposing organisms to unprecedented and changing climatic conditions (Aguirre-Gutiérrez et al. 2025). In addition to climate-related impacts, these regions are also experiencing extensive loss of native vegetation cover due to anthropic activities (Ometto et al. 2022).

In the Amazon ecosystem, for instance, a marked reduction in forest cover is due to the intensive exploitation of natural resources and to land-use activities, including logging, mining, and the expansion of areas for cattle ranching and agriculture (both illegal and legal). These processes are contributing to rising atmospheric CO_2 levels and the disruption of biogeochemical cycles (Tabari 2020). According to the Annual Deforestation Report for Brazil, compiled by MapBiomas, the Amazon lost over 4 million hectares of forest between 2019 and 2023, representing approximately 25% of the total deforested area in the country during that time (RAD 2023). In this context, the loss of forested areas has negative consequences not only by increasing CO_2 emissions, but also by drastically affecting ecological interactions that shape the structure, dynamics, and functioning of ecosystems, ultimately altering habitat availability and species occurrence across the landscape (Román-Palacios and Wiens 2020).

The Amazon is recognized as the most biodiverse region on the planet, containing hundreds of endemic species associated with distinct habitat types throughout the region, to which specific adaptations and ecological specializations from organisms, particularly birds, have developed (Ribas and Aleixo 2019). Among vertebrates, birds are one of the groups most vulnerable to the impacts of climate change due to the many endemic species and those with restricted geographic ranges, which makes them excellent bioindicators in the face of environmental change (Hoffmann et al. 2020). The increasing disturbance of forests, which shapes the spatial patterns and distribution of this group, is closely associated with the decline in the effectiveness of several ecosystem services provided by birds, such as seed dispersal and pollination (Michalski and Peres 2017). Thus, as this group is affected by climate change and additional factors such as deforestation and edge effects, these ecological interactions tend to decline, potentially leading to the collapse of entire forest communities of organisms (Jirinec et al. 2021).

Top avian predators, such as the owls (family Strigidae, order Strigiformes), are increasingly at risk due to the aforementioned issues. These raptors may respond in particularly sensitive ways to habitat alterations because of their complex predator–prey relationships, and consequently they are vulnerable to those disturbances (Ahumada et al. 2023). The Strigidae family has a broad distribution across the entire Neotropical region, with 26 species recorded in Brazil (Favretto 2021; Pacheco et al. 2021). The genus *Megascops* Kaup 1848 is the second most species-rich genus in the family, comprising ~22 species commonly called screech-owls (Gill et al. 2025). The genus includes small to medium-sized species that inhabit a variety of habitats and are endemic to the Americas (Sick 1997).

A prominent species is the recently described Xingu Screech-owl, *Megascops stangiae* Dantas, Weckstein, Bates, Oliveira, Catanach & Aleixo 2021. It was described based on molecular analysis and was previously within the taxon *Megascops watsonii usta* (P.L.Sclater, 1858) (Holt et al. 2020; Dantas et al. 2021). The Xingu screech owl is endemic to the Amazon, restricted to the northern portions of the Tapajós–Xingu and Xingu–Tocantins interfluves (Dantas et al. 2021). Its habitat is *terra-firme* forests, where, like other *Megascops* spp., it preys on a range of invertebrates and small vertebrates (Muñoz and Kattan 2007). This species has a high conservation priority, because its geographical distribution lies within an area of one the most critically impacted regions by land-use change, marked by exceptionally high rates of deforestation (Carvalho et al. 2020).

Considering the intense anthropogenic pressures and ongoing environmental change, this study aims to assess the combined effects of climate change and deforestation on the potential distribution of the *M. stangiae*. Using predictive species distribution modeling under different future scenarios of climate and land cover, we evaluate how these factors may influence the availability of suitable habitat for the species, providing critical insights to support conservation and management efforts in an ecologically high-priority region. We predicted that *M. stangiae* will be negatively impacted by the loss of climatically suitable areas, essentially as it depends on preserved forests, like other species in this family (Mikkola 2020), and this forest is rapidly disappearing.

METHODS

Study area

The study area was chosen to include the distribution of the *M. stangiae* (Dantas et al. 2021), which is restricted to the northern portions of the Tapajós–Xingu and Xingu–Tocantins interfluves (Figure 1). For the purposes of ecological niche modeling, the entire extent of both the Tapajós–Xingu and Xingu–Tocantins interfluves was used, while the species' range as defined by Dantas et al. (2021) was used exclusively to

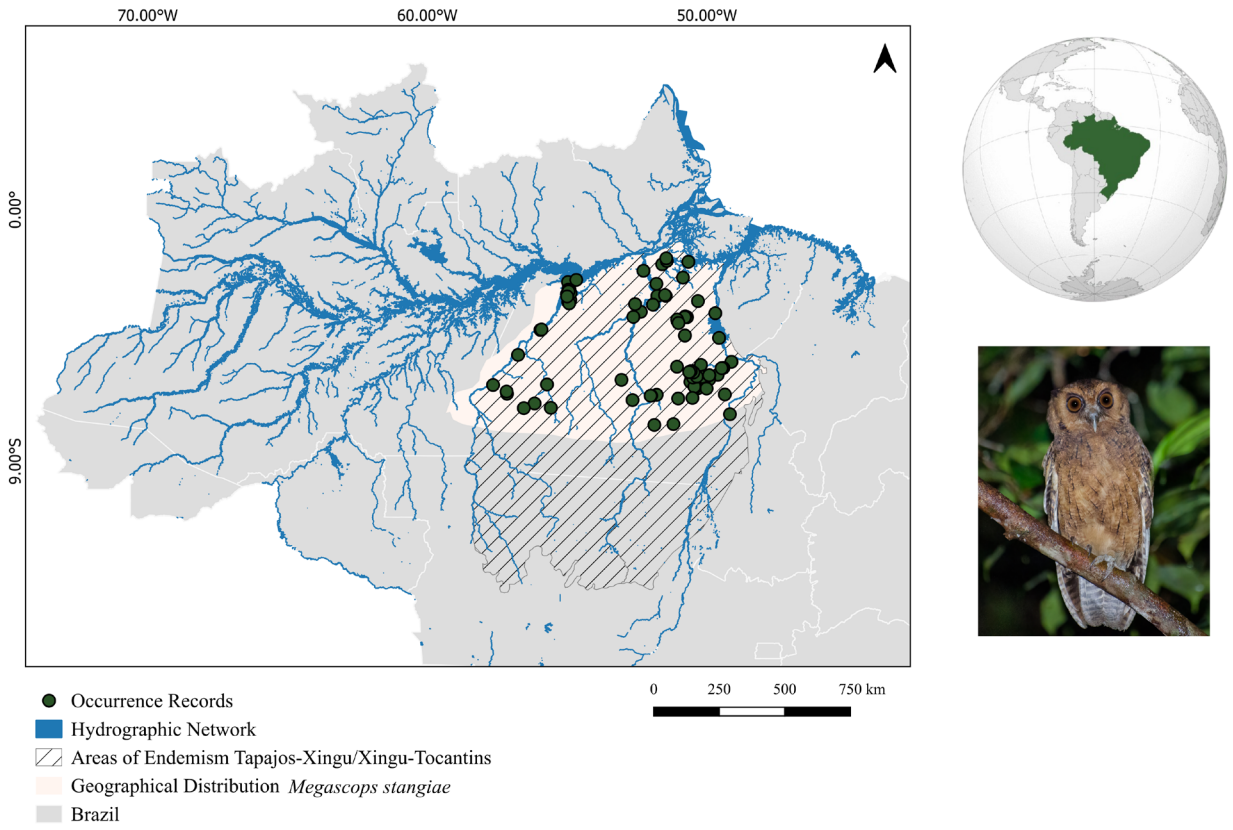


Figure 1. Map of the study area with the known geographic distribution of *M. stangiae* in the Brazilian Amazon (Dantas et al. 2021). The upper right corner provides a broader view of the study area's location in relation to Brazil (in green) and the world. The lower right corner shows an individual *M. stangiae*. Hatched area: Tapajos-Xingu and Xingu-Tocantins interfluve. Photo: Pablo Vieira Cerqueira.

obtain occurrence records and calibrate the species distribution models for *M. stangiae*.

Occurrence records for the species were obtained from multiple sources, including: *eBird* (https://ebird.org/home), *Global Biodiversity Information Facility* (GBIF.org [03 October 2024]. GBIF Occurrence Download https://doi.org/10.15468/dl.xk2tkv), Vertnet (http://vertnet.org/), and the ornithological collection of the Museu Paraense Emílio Goeldi. As this is a recently described species, previously considered part of the *M. watsonii usta* complex, we used the distribution following Dantas et al. (2021), to constrain occurrence records. Data were cleaned by removing obviously inaccurate records and nomenclature was verified. Duplicate records were removed, and we applied a cell-size reduction approach using the *spThin* package (Aiello-Lammens et al. 2015), to reduce spatial autocorrelation and sampling bias. This technique randomly selects a single occurrence within each cell of a grid that has twice the resolution of the environmental variables (Andrade et al. 2020). Considering that this species has a limited distribution, the Tapajós-Xingu and Xingu-Tocantins interfluves were determined as M, as proposed by the BAM diagram of Soberón and Peterson (2005).

Climate data

A total of 19 bioclimatic variables (WorldClim platform, version 2.1; http://www.worldclim.org) were used for the baseline scenario, available at a spatial resolution of 2.5 arcminutes (~5 km) for the boundaries of the Xingu–Tapajós and Xingu–Tocantins areas of endemism. The same 19 bioclimatic variables projected by atmosphere–ocean general circulation models (AOGCMs) were used for the 2041–2060 period. To address model uncertainty, we used a cluster analysis, following Varela et al. (2015). Based on this approach, five AOGCMs were selected: ACCESS-CM2, CMCC-ESM2, HadGEM3-GC31-LL, IPSL-CM6A-LR, and MRI-ESM2-0. Two Shared Socioeconomic Pathways (SSPs) were selected: SSP2-4.5 as the optimistic and SSP5-8.5 as the pessimistic scenario, to evaluate alternative future greenhouse gas emission scenarios.

We used principal component analysis (PCA) to reduce collinearity and limit the dimensionality of the climatic variables, following Gotelli et al. (2016) and De Marco and Nóbrega (2018). For future projections, the coefficients obtained from the PCA performed on baseline climate data were applied to compute the scores for future climate data from each selected

AOGCM, thereby maintaining consistent dimensionality across climate datasets (Sillero and Barbosa 2021).

Modeling and Model Evaluation

Four algorithms were employed to generate the species distribution model for the *M. stangiae*, to reduce different sources of bias: *Maximum Entropy* (MaxEnt) (Phillips et al. 2008), *Support Vector Machine* (SVM) (Tax and Duin 2004), *Random Forest* (RDF) (Breiman 2001), and *Generalized Linear Model* (GLM) (Guisan et al. 2002). MaxEnt uses a presence–background approach, analyzing the relationship between confirmed species occurrence records (presence) and the broader study area (background) (Peterson et al. 2011). In contrast, SVM, RDF, and GLM operate using presence data in combination with absence data from locations where the species is assumed not to occur. Due to the lack of true absence data for the species, pseudo-absences were generated using the environmental restriction method, applying a 1:1 ratio of pseudo-absence to presence points for each taxon analyzed. Due to the lack of true absence data for the species, pseudo-absences were generated using the environmental restriction method, applying a 1:1 ratio of pseudo-absence to presence points for each taxon analyzed. This method allocates pseudo-absences in areas outside the species' climatic niche envelope. Specifically, the environmental envelope is first estimated using the BIOCLIM algorithm based on the environmental conditions associated with occurrence records. Pseudo-absences are then sampled from environmental space beyond this envelope, ensuring that they represent conditions that are environmentally distinct from those associated with known presences while reducing the likelihood of assigning pseudo-absences within potentially suitable areas (Engler et al. 2004).

For data partitioning, we used a random k-fold approach replicated five times (Roberts et al. 2017). Model performance was evaluated using the Sørensen index (Sørensen 1948) and area under the curve (AUC). The Sørensen index (0 – 1) measures the similarity between predictions and observations, and 1 indicates best accuracy (Leroy et al. 2018). AUC (Fielding and Bell 1997) is a threshold-independent performance metric derived from the receiver operating characteristic (ROC) curve, which plots the true positive rate (sensitivity) against the false positive rate (1 – specificity) across all possible thresholds. The AUC is the probability that a randomly selected presence site is more suitable than a randomly selected absence (or background) site. Values range from 0 to 1, where 0.5 indicates performance no better than random, and values closer to 1 indicate better discrimination (Lobo et al. 2008). Consensus models were generated using the *ensemble forecasting* approach (Araújo and New 2007). The ensemble was constructed by averaging the outputs of algorithms whose performance exceeded the overall mean performance across all models, based on the Sørensen Index. This procedure was applied to both the baseline scenario and each of the future scenarios. Final continuous suitability models were converted into binary presence/absence maps using threshold values derived from the Sørensen index. All modeling and evaluation procedures were conducted using the ENMTML package (Andrade et al. 2020), available at https://github.com/andrefaa/ENMTML), in R v4.3.1 (2023).

Spatial extents for the Species Distribution Models

Species distribution models with two distinct spatial extents were used to estimate climatically suitable areas for the occurrence of the *M. stangiae*. The first, the phylogeographic scenario, includes only the region currently known for the species following Dantas et al. (2021), and is conservative based on phylogeographic evidence. The second, the expanded interfluvial scenario, encompasses the entire set of adjacent Amazonian interfluves that are plausibly accessible to the species, given the absence of evident geographic barriers to dispersal. The use of these two scenarios allows for the comparison of spatial patterns of climatic suitability under different assumptions of geographic limitation, contributing to a broader understanding of both the current range boundaries and the species' potential for expansion in response to environmental change.

Overlap of the climatic distribution model with forest remnants

Given that *M. stangiae* is forest-dependent, the climatic models were overlapped with forest cover remnants for both the baseline and future scenarios to produce a distribution model more representative of its actual habitat. Forest remnant data for the present and future and all scenarios were obtained from vegetation cover projections following Chen et al. (2022). These data are derived from a global land projection dataset that incorporates the most recent socioeconomic and climate change scenarios and is compatible with the future climate projections used in this study. For the present analysis, the two forest types associated with the target taxon's distribution were selected: tropical broadleaf evergreen forest and tropical broadleaf deciduous forest.

RESULTS

A total of 103 unique occurrence records were obtained for *M. stangiae*. The performances of both SDMs were satisfactory for both evaluation metrics: the Sørensen index = 0.93, and the AUC = 0.95. The average threshold value obtained was 0.49.

SDMs for the phylogeographic scenario estimated a total suitable area of 415,290 km² under baseline conditions, including the overlap of forest remnants (Figure 2). Under future climate scenarios, *M. stangiae* is projected to lose 67% in the optimistic (SSP2-4.5) and 92% of suitable habitat in the pessimistic (SSP5-8.5) scenario (Table 1). Habitat loss in the phylogeographic scenario was greater than that projected

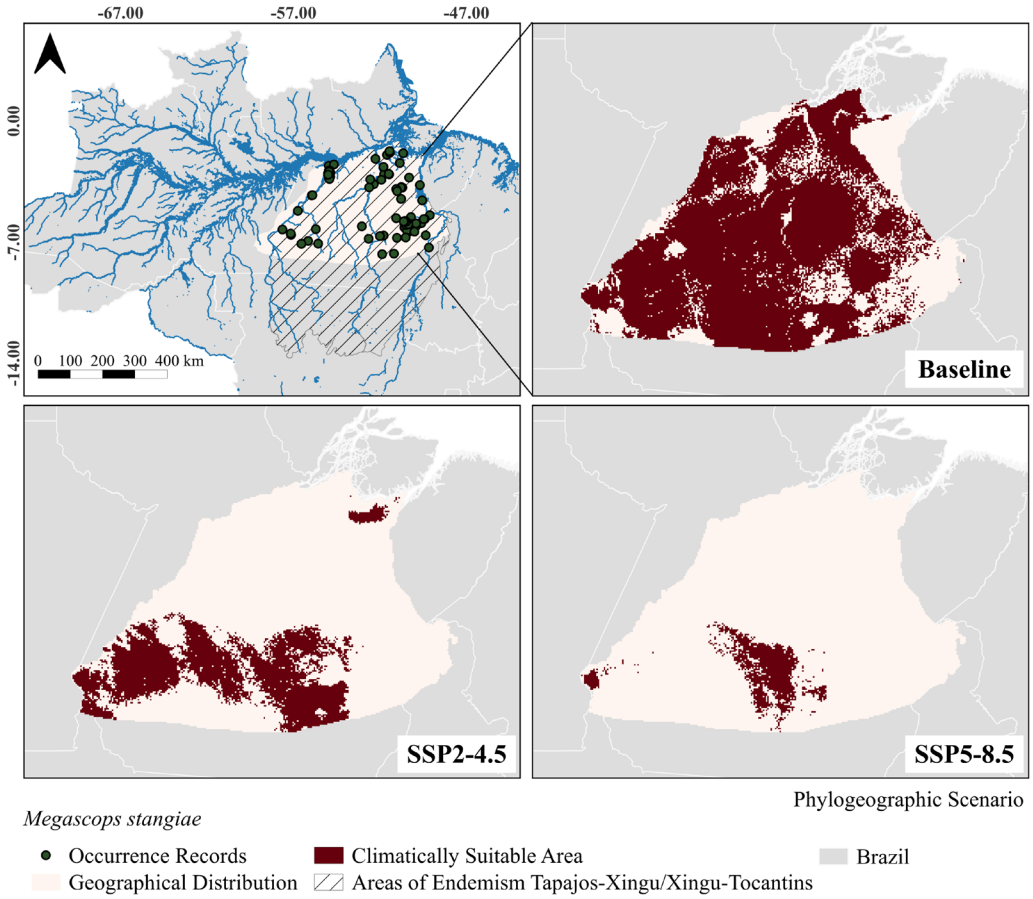


Figure 2. Potential future distribution of *M. stangiae* under the Phylogeographic Scenario, as estimated by SDMs. SSP2-4.5 represents the model under the optimistic future scenario, and SSP5-8.5 represents the model under the pessimistic future scenario (2041-2060). Hatched area: Tapajos-Xingu and Xingu-Tocantins interfluve.

Table 1. Distribution area (in km²) of *M. stangiae* under baseline conditions and future scenarios for the year 2060 (optimistic and pessimistic), with the percentage (%) of area lost.

Modelling Scenarios		Baseline Conditions	Optimistic (SSP2-4.5)	Pessimistic (SSP5-8.5)
Phylogeographic Scenario	Total Area (km²)	415,290	135,438	33,586
	Percentage of loss		67	92
Expanded Interfluvial Scenario	Total Area (km²)	766,536	325,412	171,188
	Percentage of loss		58	78

under the expanded interfluvial scenario. In the expanded interfluvial scenario, the total suitable area was 766,536 km² under baseline conditions, and projected losses of 58% under the optimistic (SSP2-4.5) and 78% under the pessimistic (SSP5-8.5) scenario, resulting in a difference of 351,246 km² between them (Figure 3). Overall, the results indicate that, despite projected gains and stable suitable areas across temporal scenarios, substantial losses of climatically suitable areas are projected in the future (Figure 4).

DISCUSSION

The *M. stangiae* is likely to lose more than half the area of its current distribution before the end of the century due to a combination of climate change and deforestation. Our results are consistent with recent SDM studies that support growing concerns regarding the high extinction risk of bird species, as they suggest that numerous populations of endemic birds are highly susceptible to substantial losses driven by projected increases in climate change impacts (De Moraes et al. 2024, 2025; Ferreira et al. 2024; Da Silva et al. 2025).

Presently, *M. stangiae* is considered least concern (LC) in the International Union for Conservation of Nature (IUCN) Red List (2024). Based on the high likelihood of habitat loss indicated by the projections from our models, *M. stangiae* is predicted to suffer drastic population declines within 30 years (De Moraes et al. 2024). Indeed, our models indicate that climatically suitable areas soon will be largely absent from the species' current range under the phylogeographic scenario, with resilient areas persisting primarily in the southern portion of its distribution only under the expanded interfluvial scenario.

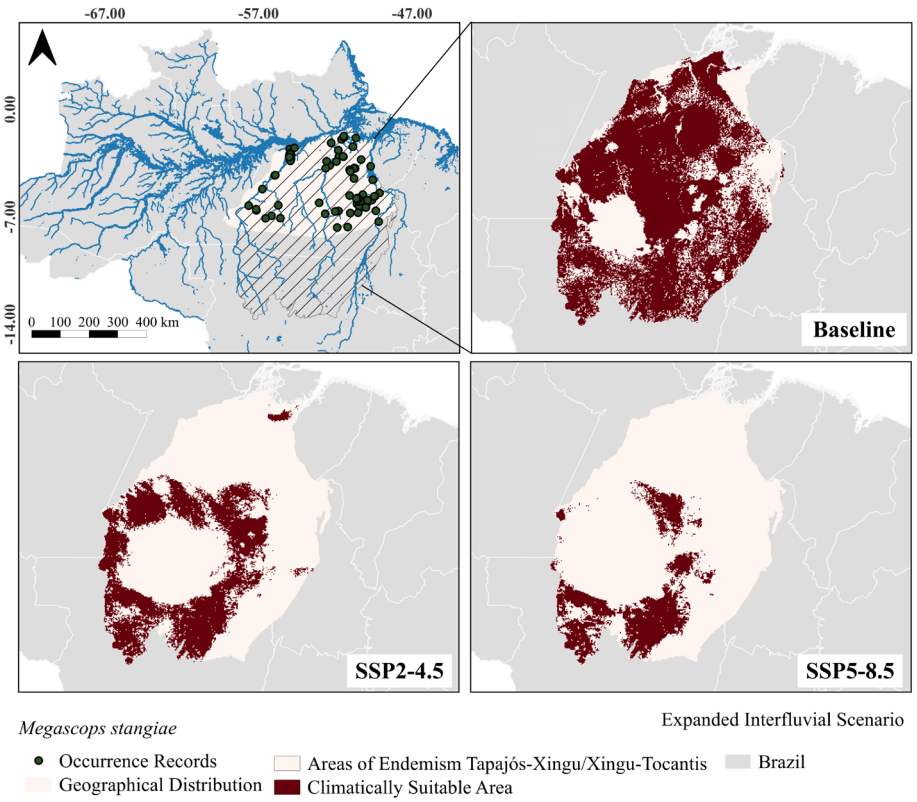


Figure 3. Potential distribution of *M. stangiae* under the Expanded Interfluvial Scenario, as estimated by SDMs. SSP2-4.5 represents the model under the optimistic future scenario, and SSP5-8.5 represents the model under the pessimistic future scenario (2041-2060). Hatched area: Tapajos-Xingu and Xingu-Tocantins interfluve.

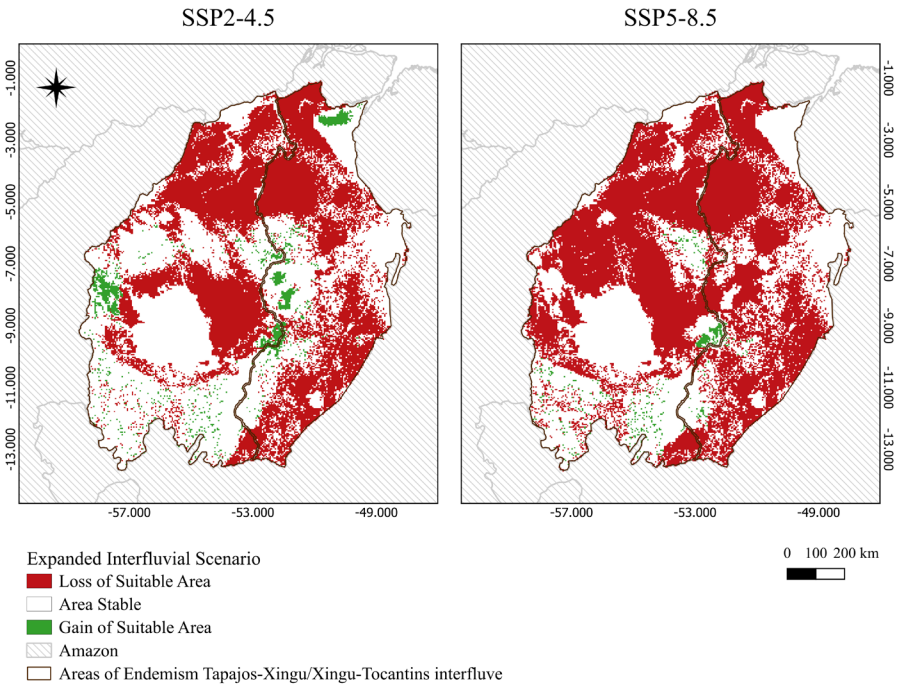


Figure 4. Predicted changes in the climatically suitable area for *M. stangiae* under the Expanded Interfluvial Scenario, estimated using species distribution models (SDMs). Panels show projections for the SSP2-4.5 (optimistic) and SSP5-8.5 (pessimistic) climate scenarios for 2041–2060. Red indicates projected losses of climatically suitable areas, green indicates projected gains, and white represents stable suitable areas. The outlined polygon corresponds to the Tapajós–Xingu/Xingu–Tocantins interfluve, and the hatched background represents the Amazon region.

Thus, if *M. stangiae* is unable to, or does not, disperse into those southern areas, it will be at serious risk of extinction, given the projected loss of up to 92% of suitable habitat under the pessimistic scenario. The fact that the *M. stangiae* occurs in forested areas overlapping interfluves with high levels of deforestation and anthropogenic disturbance further increases its extinction risk, primarily due to forest fragmentation processes, which hinder or prevent the dispersal of forest-dependent organisms across an agricultural matrix (Da Silva et al. 2005). This risk can also be observed in other taxonomic groups, including insects, mammals, and primates (Gomes et al. 2024). Similar patterns can be assessed in other tropical ecosystems across the Neotropical region (Pereira et al. 2024).

Another constraint to the colonization of southern areas by *M. stangiae*, as projected in the expanded interfluvial scenario, is the potential competition with *M. watsonii usta* that occurs precisely in the southern portion of the Tapajós–Xingu and Xingu–Tocantins interfluves (Holt et al. 2020). These two species appear to be geographically segregated, even though no geographic barriers, such as rivers, valleys, or mountains, impede their movements to the other's geographic area (Dantas et al. 2021). Thus, considering that both species occupy the same type of habitat and feed on similar prey, such as small vertebrates and invertebrates (Favretto 2021), their geographic segregation may result from competitive exclusion. Thus, the southward dispersal of *M. stangiae* in search of climatically suitable forest remnants would face an additional challenge of potential ecological competition with *M. watsonii usta*. Thus, the outlook for the future of *M. stangiae* is extremely concerning, with the possibility of drastic population declines that would place the species at high risk of extinction under a critical scenario.

A surprisingly large gap in the modelled distribution of *M. stangieae* appears in the central portion of the Tapajós–Xingu and Xingu–Tocantins interfluves (Figure 3). It may be due to the southern and southwestern regions of the state of Pará having extensive areas of white-sand vegetation types such as *campina*, *campinarana*, alluvial forests, and savannas, as well as ecotonal zones bordering the Cerrado (Da Silva et al. 2021). These various vegetation types differ substantially from the rain forests that are the typical habitat of *M. stangiae* (Favretto, 2021), with different climatic characteristics, and which were likely captured by the models, resulting in the projection of a large area of climatic unsuitability for the species across much of the southern and southwestern regions of the state of Pará. This suggests an additional challenge for the future of *M. stangiae* in any potential process of dispersal and colonization of new areas in the southern portion of its current range. A large proportion of the climatically suitable remnants projected for the future are in a mosaic landscape with open vegetation areas that may act as barriers to the dispersal of forest-dependent species such as the *M. stangiae*, further hindering its ability to colonize new areas south of its current range.

CONCLUSION

In conclusion, *M. stangiae* is unlikely to disperse and colonize the climatically suitable areas projected under the expanded interfluvial scenario. As a result, this owl will most likely remain restricted to its current range, which is likely to face severe losses of suitable habitat. Such a reduction is likely to lead to a dramatic population decline and increasing extinction risk. Thus, the species is likely to be cryptically endangered, in that important projected reductions in the spatial distribution are pending. Understanding this reduction and its causes can inform the development of targeted conservation strategies to mitigate the effects of climate change and deforestation. These findings underscore the urgent need for comprehensive conservation planning, including the creation and expansion of protected areas (PAs) within the Amazon Biome. Furthermore, the implementation of ecological corridors connecting key forest remnants is critical to maintaining habitat continuity for bird species that are particularly vulnerable to population pressures, such as the Xingu screech owl.

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