International Journal of Primatology
https://doi.org/10.1007/s10764-024-00481-z

Check for updates

Ecological Forecasting for Night Monkeys in the *Aotus lemurinus* Complex: Climate-driven Threats to Habitat Suitability

Julián Arango-Lozano[1] · Felipe Andrés Toro-Cardona[2] · Juan Sebastián O. Montilla[3] · Héctor E. Ramírez-Chaves[4]

Received: 5 November 2024 / Accepted: 23 December 2024

Abstract
Climate change poses threats to global biodiversity, particularly in groups such as American primates, which are restricted to forested ecosystems. Assessing species-specific and habitat vulnerabilities is crucial to understand how climate change impacts this group. We investigated the impact of climate change and habitat vulnerability for the three species of night monkeys in the *Aotus lemurinus* complex (*A. grisemembra, A. lemurinus*, and *A. zonalis*), a group of American primates which is highly vulnerable to environmental disturbance. Using ecological niche modeling, we projected how different climate scenarios could alter the distribution of the three species, and calculated a vulnerability transformation index for quantifying susceptibility of natural habitats to conversion into anthropogenic land covers. Our findings reveal that the currently most favourable habitats for all species will reduce, with *A. griseimembra* experiencing the greatest declines, particularly in lowland areas. *A. lemurinus* shows relatively smaller habitat losses overall, with the greatest reduction in Ecuador. *A. zonalis* is the least-affected species, but still faces some level of risk. The results emphasize the need for detailed ecological assessments in biogeographically important regions, particularly areas projected to maintain habitat stability under future climate scenarios. Targeted research should focus on identifying species-specific responses to habitat changes in order to refine conservation strategies for night monkeys. These findings provide actionable insights for prioritizing highland

OPEN DATA

Badge earned for open practices: Open Data. Experiment materials and data are available in the repository at https://data.mendeley.com/datasets/tc59dyztsy/1 and https://osf.io/tns8x/.

Handling Editor: Joanna M. Setchell

Extended author information available on the last page of the article

Published online: 04 February 2025

forest restoration, implementing mitigation measures for habitat loss driven by human activities and climate change, and enhancing monitoring in underexplored regions.

Keywords Conservation · Ecological niche modeling · Fragmentation · Primates · Vulnerability

Introduction

Climate change and landscape modifications are key topics in ecological and biodiversity conservation (Fischer & Lindenmayer, 2007; Galindo-Cruz et al., 2024; Hagerman et al., 2010; Ramirez-Villegas et al., 2014). These threats impact biodiversity at different levels (e.g., population connectivity, trophic dynamics, genetic and functional diversity), generating changes in distribution across different spatial scales, representing a high risk especially for endemic species (Rani et al., 2020; Sattar et al., 2021). The loss of intact or relatively undisturbed natural vegetation such as primary forests may pose a more immediate threat than climate change. For example, in America, Brazil and Colombia experienced decreases in primary forest cover of 36% and 49% respectively, between 2022 and 2023, while total tropical primary forest loss in 2023 reached 3.7 million hectares (Global Forest Review, 2024). American forests are listed among the vulnerable ecosystems facing high risks of habitat loss under future climate change scenarios (Feeley et al., 2012, 2013; Rojas-Soto et al., 2012; Prieto et al., 2016). These changes require a focus on threatened groups and the development of ecosystem-based strategies to mitigate and adapt to the increasing impacts of climate change (da Silva et al., 2022; Korstjens & Hillyer, 2016; Ruhl, 2008).

Ecological niche modeling (ENM) offers a robust approach to assessing the broader impacts of climate change on different species as primates associated to forested ecosystems (Cavalcante et al., 2020; Sales et al., 2020). ENMs allow researchers to characterize ecological and bioclimatic niches by using environmental variables and occurrence data (Moreno-Contreras et al., 2020; Ramirez-Villegas et al., 2014; Shanee et al., 2015; Warren & Seifert, 2011). This approach enables the identification of suitable geographical areas under different projected spatiotemporal scenarios, making it possible to predict potential habitat changes and to assess species vulnerability to climate and habitat transformation (Alvarado-Serrano & Knowles, 2014; Ramirez-Villegas et al., 2014; Mota-Vargas & Rojas-Soto, 2016; Sales et al., 2020). These methodologies have proven particularly effective in guiding conservation strategies by identifying priority areas for conservation and management under climate change scenarios (Estrada et al., 2017; Li et al., 2018; Moreno-Contreras et al., 2020; Sales et al., 2020).

American primates are highly sensitive to climate change and forest loss, as changing temperatures and precipitation regimes may affect migration patterns, reproductive behaviors, and the delicate balance of their populations (Korstjens & Hillyer, 2016; Carvalho et al., 2019; Bernard & Marshal, 2020; Campos et al., 2020; Upadhyay, 2020). Moreover, primates face crucial environmental challenges, as some species inhabit tropical forests threatened by deforestation, habitat degradation, and loss of ecological functionality (Edwards et al., 2014; Giam, 2017). Consequently, American primates are currently experiencing population declines, with over 40% of the taxa assessed as threatened by the International Union for Conservation of Nature (IUCN; Estrada et al., 2012, 2017; Fernandez et al., 2022; Korstjens & Hillyer, 2016; Ryland et al., 1997). The hypothesis that the distribution of American primates could shift to higher elevations under future climate scenarios adds another layer of complexity to their conservation (Forero-Medina et al., 2010; Iturralde-Pólit et al., 2017; Li et al., 2018; Arias-González et al., 2021, 2023). While these higher-elevation forests may serve as potential refuges, they are themselves vulnerable to environmental changes and may not fully replicate the conditions of lowland habitats (Forero-Medina et al., 2010; Iturralde-Pólit et al., 2017; Sales et al., 2020).

The *Aotus lemurinus* complex includes three closely related species of night monkey: *Aotus griseimembra, A. lemurinus*, and *A. zonalis*. These species are characterized by gray, dense, woolly fur, relatively small heads with large, striking, red eyes with white–cream surrounded fur (Fernandez-Duque et al., 2023; Fig. 1). The three species are restricted to the Americas, encompassing Colombia, Ecuador, Panamá, and Venezuela (Defler, 2003; Montilla et al., 2021; Shanee et al., 2023b; Svensson et al., 2010). IUCN categorizes *A. griseimembra* and *A. lemurinus* as Vulnerable (VU), and *A. zonalis* as Near threatened (NT) (Link et al., 2021a, 2021b; Méndez-Carvajal & Link, 2021). Threats include illegal trafficking and trade, hunting, habitat degradation, and the transformation of forests to agricultural matrices (Henao-Díaz et al., 2020; Montilla et al., 2021; Shanee, 2023).

The current distribution of the *A. lemurinus* complex may be limited by fragmentation, as suggested for other primates (e.g., *Alouatta palliata* in Mexico, *A. seniculus* and *Cebus albifrons* in Colombia, and *Brachytheles* in Brazil, among others (Tabarelli et al., 2004; Benchimol & Peres, 2014). As for other American primates, their dispersal capacity may be influenced and altered by future variable weather regimes (Carvalho et al., 2019; Bernard & Marshal, 2020), potentially limiting range extensions due to physiological constraints (Korstjens & Hillyer, 2016; Sales et al., 2020).

Fig. 1 Faces of the *Aotus lemurinus* species complex. **a** *A. griseimembra* from Puerto Parra, Medium Magdalena River basin, February 2024 (photograph by Jose Julio), **b** *A. lemurinus* from Pijao, Quindío, Central Andes of Colombia, March 2019 (photograph by Sebastian Montilla), **c** *A. zonalis* from Turbo, Antioquia, Biogeographic Chocó region, May 2024 (photograph by Ruben Torres).

Given the current habitat loss, fragmentation, and the compounded effects of climate change, the distribution of the three night-monkey species in the *Aotus lemurinus* complex faces a risk of contraction in the near future. In this study, we used ENMs to evaluate the relative impacts of climate change and habitat vulnerability on the current and projected distribution of the complex, identify areas of high conservation priority, and provide actionable insights into the effective management and preservation of these primates' habitats.

Methods

Occurrence Data and Accessible Areas

We obtained species occurrence records for the three species from the Global Biodiversity Information Facility (GBIF) and established the distribution patterns for each species based on studies that describe the species ranges (Defler, 2003; Henao-Díaz et al., 2020; Mantilla-Meluk & Ortega, 2011; Montilla et al., 2021; Shanee et al., 2023b). Based on these studies, we selected records from elevations below 1000 m in the Caribbean region and the Magdalena River basin of Colombia for *A. griseimembra*, from elevations above 1000 m in the Andes of Colombia, Ecuador, and Venezuela for *A. lemurinus*, and from the Chocó–Darién Moist Forests at elevations below 1500 m for *A. zonalis*. We then cleaned the occurrence data for each species within the *A. lemurinus* complex by removing sites in areas outside the ranges defined by previous studies and duplicate records (Cobos et al., 2018).

In total, we used 265 occurrences from elevations between 0 and 990 m in Colombia to model the ecological niche of *A. griseimembra*, 213 occurrences from elevations between 1000 and 3000 m for *A. lemurinus* (corresponding to Andean locations in Colombia, Ecuador, and Venezuela), and 80 localities from elevations between 0 and 780 m for *A. zonalis* in Colombia and Panama. We created the accessible areas (M sensu Soberon & Peterson, 2005) for each species, by selecting and adjusting ecoregions to the occurrences (Dinerstein et al., 2017), using the online version of ArcGis (Esri, 2024; Fig. 2). M refers to the potential geographical space where a species can occur, which is determined by both environmental factors and geographic boundaries, such as ecoregions, these areas act as a spatial mask for cropping bioclimatic variables (Rojas-Soto et al., 2024; Soberon & Peterson, 2005).

Environmental Variables

To characterize the climatic niche of the three species and obtain their potential distributions, we used bioclimatic variables (1970–2000 timeframe) from the WorldClim v2.1 database (Fick & Hijmans, 2017) at a 30 arc-second resolution (~ 1 km^2). From the 19 available bioclimatic variables, we excluded bio 8 (mean temperature of wettest quarter), bio 9 (mean temperature of driest quarter), bio 18 (precipitation of warmest quarter), and bio 19 (precipitation of coldest quarter;

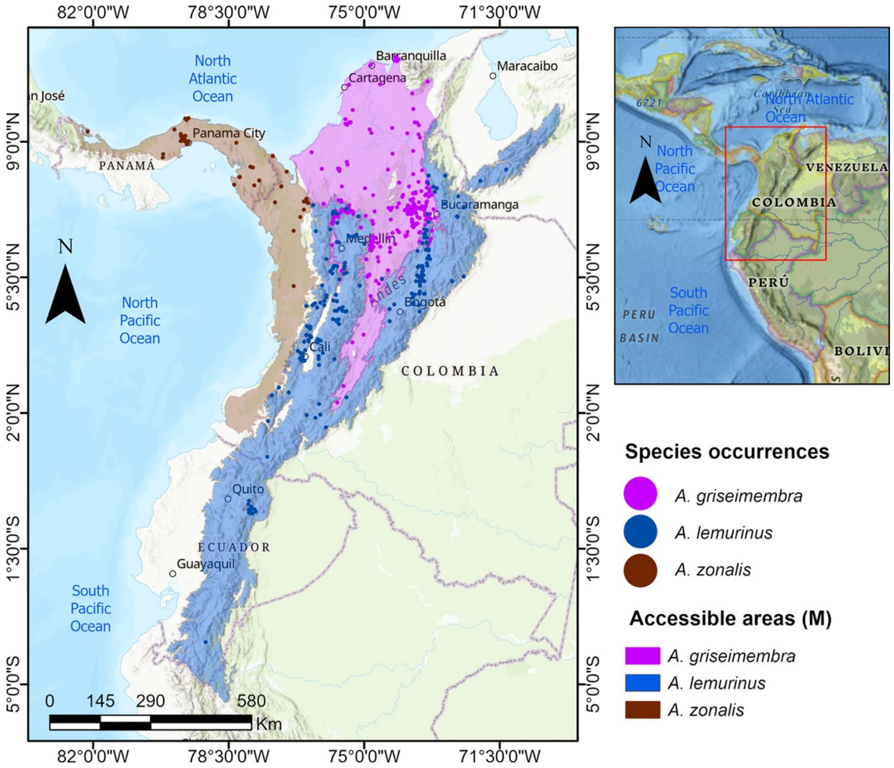

Fig. 2 Description of records and extension of accessible areas (*M*) for three night-monkey (*Aotus*) species, based on ecological niche modeling conducted between May 2023 and July 2024. The accessible areas represent the potential geographic range where the species can occur.

Table 1 in supplementary material). We excluded these variables because they present atypical values, which can negatively affect model performance (Booth, 2022; Escobar et al., 2014). We masked the remaining 15 variables and cropped them to the extent of the accessible area for each species. Then, we performed a correlation test using the masked environmental variables and identified pairs of variables with correlation coefficients greater than 0.8 or less than −0.8 (Díaz-Vallejo et al., 2024). While we retained one variable from each pair for general analyses, we also created alternative sets of variables for niche modeling to account for the potential biological relevance of some highly correlated variables (Cobos et al., 2018; Echeverry-Cárdenas et al., 2021; Table 2 in supplementary material).

Ecological Niche Modeling

For each species, we selected 80% of the occurrences randomly for model training, and used the remaining 20% for model validation. This ensures the model is trained to recognize spatial similarities between occurrence records and environmental variables while reserving a subset of data for independent validation (Arango-Lozano et al., 2023; Cobos et al., 2019). We identified the best model by testing different parameter combinations using the Maxent algorithm (Phillips et al., 2006) and the kuenm package in R (Cobos et al., 2019). We excluded "hinge" and "threshold" features to reduce response function complexity (Elith et al., 2011) and tested different complexities (Warren & Seifert, 2011) by changing the values of the regularization multiplier from 0.1 to 1 in intervals of 0.1 and then 2, 3, 4, and 5. We selected the best models based on the evaluation metrics in kuenm (AUC ratio, omission rate, and AIC) and projected onto the accessible areas for the species under future shared socioeconomic pathways (ssp) with the least variation (conservative approach) in climate conditions (ssp126, ssp245) and the greatest variation (greater modification) in climate conditions (ssp585) for the years 2041–2060.

We compared the results of five global circulation models (GCMs): HadGEM3-GC31-LL (GCM1), IPSL-CM6A-LR (GCM2), ACCESS-CM2 (GCM3), EC-Earth3-Veg (GCM4), and UKESM1-0-LL (GCM5). Each GCM simulates climate dynamics using different datasets, including land cover, oceanic circulation, and atmospheric processes (Padhiary et al., 2020; Yu et al., 2014). Using a variety of GCMs enhances model robustness, enabling us to assess areas of agreement and divergence for a broader perspective on future climate variability (Padhiary et al., 2020; Reshmidevi et al., 2018).

HadGEM3-GC31-LL: Focuses on ocean–atmosphere interactions, providing detailed simulations of sea surface temperatures and atmospheric circulation patterns. IPSL-CM6A-LR emphasizes the role of cloud processes and their interactions with aerosols, crucial for understanding radiative forcing and climate sensitivity. ACCESS-CM2 shows representations of Southern Hemisphere climate processes, including the Australian monsoon and ocean–atmosphere coupling. EC-Earth3-Veg integrates dynamic vegetation models to assess feedback mechanisms between the biosphere and atmosphere, enhancing predictions related to land-use changes and carbon cycling. UKESM1-0-LL builds upon the HadGEM3-GC31-LL framework by incorporating comprehensive land-use feedback, including the effects of agriculture and deforestation on climate systems. (García-Franco et al., 2020; Reshmidevi et al., 2018).

To obtain the potential distribution under present and future climate-change scenarios, we reclassified the output of selected models into presence/absence maps using the 10-percentile training presence threshold. This approach, where the lowest 10% of training occurrence records (based on the predicted suitability values) are excluded, helps to account for potential errors or uncertainties in occurrence data while identifying areas with a higher likelihood of suitable conditions for the species. We refer to pixels with a probability of species occurrence = 1 as “currently most favourable conditions” in this study.

Climate Change and Habitat Loss

We evaluated the current and future potential distribution of the three night monkeys using pixel counts. First, we calculated the percentage of pixels gained, lost, and stability (with no changes in distribution) in each scenario (ssp and GCM) relative to the current distribution. Then, we obtained a consensus of potential distribution for each species under each ssp scenario, considering agreement among predicted pixels in at least four of the five GCMs as the consensus potential distribution. We then used these consensus maps to evaluate potential habitat loss in future scenarios. To achieve this, we superimposed the current and consensus future ranges (assembled from areas in four or more GCMs) with a "vulnerability of land cover to anthropogenic change raster" (Esri, 2024). This layer shows areas where natural vegetation such as forest could be converted to agriculture and urban lands by 2050, based on the model's predictions of human-induced land-cover changes (available data in https://livingatlas.arcgis.com/landcover-2050/). We used a transformation index of the vulnerability data which ranges from zero to one, where high values indicate a high susceptibility to natural cover transformation. We classified the raster values into three vulnerability categories: low (0–0.3), moderate (0.3–0.7), and high (0.7–1). For each species´ potential distribution in current and future scenarios (consensus model), we obtained the proportion of their distribution on each vulnerability category using a raster product operation in ArcGIS.

Results

Ecological Niche Modeling

We evaluated 210 niche models for *Aotus griseimembra* and 290 for *A. zonalis*. For both species, only one model parametrization met the model selection criteria. For *A. lemurinus*, we evaluated 210 candidate models, of which eight models met kuenm evaluation criteria. For this species, we selected the model with the lowest omission rate (Table 3 in supplementary material). The currently most favourable conditions span 48,602 pixels for *A. griseimmebra*, 214,359 pixels for *A. lemurinus*, and 48,602 pixels for *A. zonalis*.

Climate Change and Habitat Loss

A. griseimembra was the most affected by climate change, especially under the ssp585 scenario, where losses exceed 70% across all distribution models (Fig. 3). For *A. lemurinus*, the loss was greater in GCM4, with stability declining more in the ssp245 and ssp585 scenarios than ssp126. *A. zonalis* showed the least loss of distribution area and the most stable range, particularly under ssp126 (Fig. 3).

We observed major changes in the areas occupied by *A. griseimembra* in all future scenarios, particularly in low-elevation habitats (< 700 m a.s.l), which will lose the conditions needed to support the species in the Caribbean region of Colombia. The currently most favourable conditions for *A. griseimembra* may potentially extend to sub-Andean forests at elevations over 1000 m, where it could find suitable habitats alongside *A. lemurinus* (Fig. 4).

A. lemurinus is projected to experience the smallest reduction in areas with the most favourable conditions under future scenarios when compared to its current suitable habitat, which is primarily located in mid- and highlands above 1000 m. This

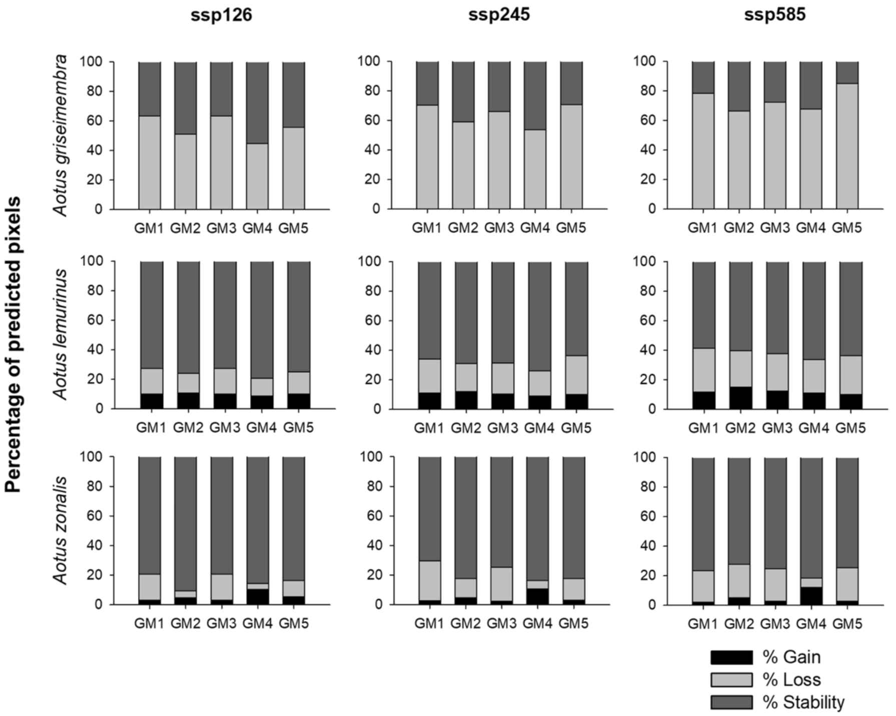

Fig. 3 Percentage of gain, loss, and stability in predicted pixels (potential distribution) for three species of night monkeys in the *Aotus lemurinus* complex under current and future scenarios. We conducted the study between May 2022 and July 2024. GM1: HadGEM3-GC31-LL; GM2: IPSL-CM6A-LR; GM3: ACCESS-CM2; GM4: EC-Earth3-Veg; GM5: UKESM1-0-LL. Scenarios include ssp126, ssp245, and ssp585, representing different greenhouse gas concentration trajectories.

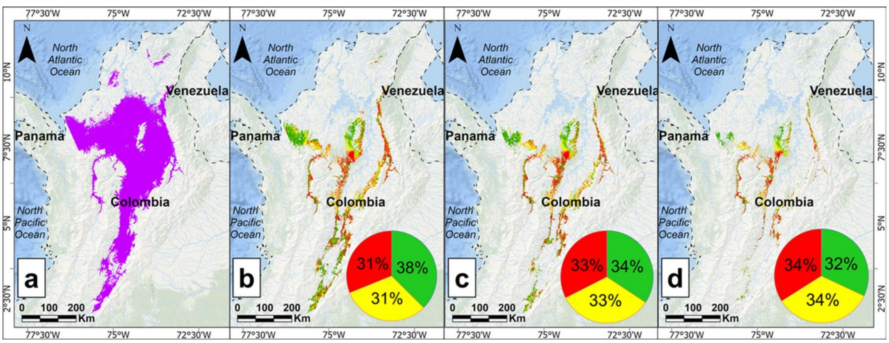

Fig. 4 Potential distribution (consensus model) for *Aotus griseimembra* under different climate change scenarios: **a** current conditions, **b** consensus distribution model in ssp126, **c** consensus distribution model in ssp245, **d** consensus distribution model in ssp585. Models were generated using ecological niche modeling (MaxEnt), based on species occurrence records and bioclimatic variables. Color pixels indicate vulnerability to change categories values: *green* = low, *yellow* = mid, *red* = high. Scenarios include ssp126, ssp245, and ssp585, representing different greenhouse gas concentration trajectories.

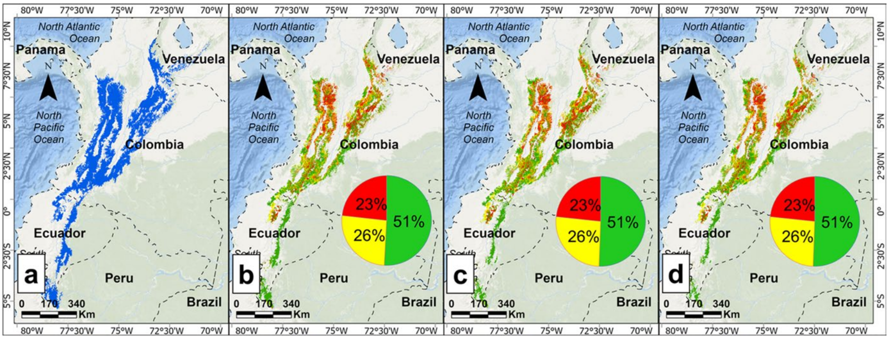

Fig. 5 Potential distribution (consensus model) for *Aotus lemurinus* under different scenarios: **a** current conditions, **b** consensus distribution model in ssp126, **c** consensus distribution model in ssp245, **d** consensus distribution model in ssp585. Models were generated using ecological niche modeling (MaxEnt), based on species occurrence records and bioclimatic variables. Color pixels indicate vulnerability to change categories values: *green* = low, *yellow* = mid, *red* = high. Scenarios include ssp126, ssp245, and ssp585, representing different greenhouse gas concentration trajectories.

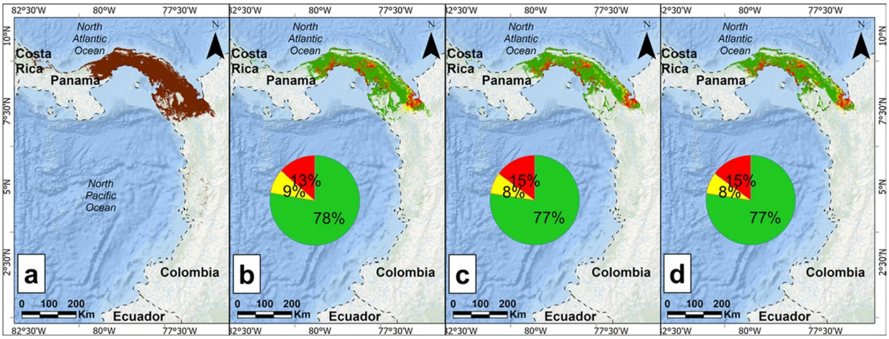

Fig. 6 Potential distribution (consensus model) for *Aotus zonalis* under different scenarios: **a** current conditions, **b** consensus distribution model in ssp126, **c** consensus distribution model in ssp245, **d** consensus distribution model in ssp585. Models were generated using ecological niche modeling (MaxEnt), based on species occurrence records and bioclimatic variables. Color pixels indicate vulnerability to change categories values: *green* = low, *yellow* = mid, *red* = high. Scenarios include ssp126, ssp245, and ssp585, representing different greenhouse gas concentration trajectories.

is where the displacement of potential distribution for this species is most evident. The greatest risk for *A. lemurinus* lies in the ssp585 scenario, particularly affecting populations in the southernmost regions near Ecuador, where the loss of habitat was greatest (Fig. 5). Furthermore, new suitable areas are limited to regions with moderate to high vulnerability to environmental change.

For *A. zonalis*, the most geographically restricted species of the complex, trends in reduction of the distribution area were smaller than for *A. griseimembra*, but greater than those for *A. lemurinus*. However, the areas maintained in future scenarios are predominantly (> 70%) in habitats with low vulnerability to change (Fig. 6).

Discussion

Our study shows a reduction in suitable habitats for all three *Aotus* species under future climate scenarios, with *A. griseimembra* experiencing the greatest decline, particularly in lowland areas of the Caribbean region. *A. lemurinus* is less affected but still shows potential habitat losses in regions close to Ecuador under the ssp585 scenario, which represents a high-emissions pathway characterized by rapid economic growth, heavy reliance on fossil fuels, and limited implementation of climate policies (Upadhyay, 2020; Yu et al., 2014). Although new suitable habitats may emerge in higher elevations of the Andes, these areas face high vulnerability to transformation to modified land uses (Ramirez-Villegas et al., 2014; Maiti, 2016; Fadrique et al., 2018; Tovar et al., 2022; Global Forest Review, 2024).

This pattern of habitat reduction is not unique to *Aotus* species. Other primates, including those of the genera *Ateles*, *Alouatta*, *Cebus*, *Mico*, *Saguinus*, and *Saimiri*, also face similar habitat reductions under climate scenarios due to their reliance on forested areas (Iturralde-Pólit et al., 2017; Carvahlo et al., 2019; da Silva et al., 2022). Comparative studies of these primates reveal a broader vulnerability pattern among arboreal species with specialized ecological niches, further emphasizing the risks posed by climate change (Estrada et al., 2017; Carvahlo et al., 2019; Sales et al., 2020).

Our models show contrasting responses within the *Aotus lemurinus* species complex under future climate scenarios, offering insights into their vulnerability. *A. zonalis*, the most geographically restricted species, shows the potential to maintain some of its habitat at lower to middle elevations, However, these areas are not immune to climate impacts. In contrast, *A. griseimembra* and *A. lemurinus* face more substantial habitat reduction, particularly in southern regions near Ecuador and the threatened dry forests of Colombia (Miles et al., 2006), It is aligned with research on other primates, such as *Ateles marginatus*, *A. paniscus*, *Alouatta palliata*, *Cebus aequatorialis*, which also show habitat losses concentrated in lowland forest ecosystems due to climate and land-use changes (Cavalcante et al., 2024; Shanee et al., 2023a).

While new suitable habitats may emerge at higher elevations for *A. griseimembra*, these areas are identified as highly vulnerable to environmental change, posing crucial conservation challenges (Estrada et al., 2017; Sales et al., 2020). This mirrors patterns observed in *Saguinus leucopus*, *S. oedipus*, *Plecturocebus ornatus*, and *P. caquetensis*, where high elevations offer refuge but are increasingly at risk due to climate warming and limited space (Arias-González et al., 2021, 2023).

The Andean cordilleras harbor diverse forest habitats that are undergoing changes in temperature and decreasing precipitation, potentially causing higher elevation forests to resemble those found at lower elevations (Báez et al., 2022; Fadrique et al., 2018; Feeley et al., 2013; Peters et al., 2013). Although future scenarios show suitable areas for both *A. griseimembra* and *A. lemurinus*, overlaying the current distribution of each species onto a vulnerability to change layer across America suggests that potential suitable conditions may be even more limited than anticipated. Specifically, over 30% of areas are classified as being highly vulnerable to change in general records for the year 2050. This assessment considers the possible loss of natural habitats to agricultural and/or urban mixed coverages in the future, which is one of the most common threats to American primates (Estrada et al., 201; Gonçalves et al., 2021; Magioli et al., 2021; Galán-Acedo et al., 2024).

The designation of high vulnerability to change areas does not necessarily imply that conservation efforts will prevent the transformation of natural habitats (as primary forests) to anthropogenic zones; rather, these areas are critical because they are where imminent transformation is most likely (Global Forest Review, 2024). This raises a key question of whether conservation strategies should focus solely on high vulnerability areas (Arias-González et al., 2021, 2023; Carvalho et al., 2019; Cavalcante et al., 2020), or whether they should also consider areas with lower or moderate vulnerability. This dilemma underscores the current lack of clear protocols for prioritizing conservation efforts in the face of inevitable environmental change (Bernard & Marshall, 2020; Carvalho et al., 2019; da Silva et al., 2022; Sales et al., 2020). We suggest that focusing on moderate vulnerability areas ("yellow zones") could be a particularly effective strategy. These areas are less likely to undergo rapid change than high vulnerability ("red zones"), yet they are still critical for maintaining habitat connectivity and supporting primate populations (Carvalho et al., 2019; Fernandez et al., 2022; Shanee, 2023). In addition, monitoring land use and changes over the coming years will be crucial to verify trends in vulnerability and ensure alignment with conservation priorities (Carvalho et al., 2019; Gonçalves et al., 2021; Maiti, 2016; Rani et al., 2020; Rojas-Soto et al., 2012).

The most geographically restricted species in our study, *A. zonalis* shows minor overall reductions, with future scenarios indicating a greater proportion of areas with low vulnerability to environmental change. Our findings do not suggest a potential shift in this primate distribution from lowland to highland regions, but further research is needed to confirm these trends and ensure accurate future habitat projections. We recommend increased conservation efforts focused on the protection and restoration of forests, enhanced monitoring and data collection in underexplored regions, and the implementation of strategies to mitigate habitat loss due to agricultural expansion, logging, and climate change. Additionally, a comprehensive understanding of the genetic diversity and resilience of isolated populations will be crucial for developing effective conservation plans to safeguard these vulnerable species amid ongoing environmental changes.

While our models provide valuable insights into the potential impacts of climate change on the *Aotus lemurinus* complex, ENMs assume equilibrium between species and their environment, which can oversimplify species–environment relationships, especially under rapidly changing climatic conditions (Zhang et al., 2019). This static approach does not account for dynamic or stochastic processes, such as extreme climate events, which recent research highlights as major drivers of biodiversity loss and population decline (Kiribou et al., 2024). For instance, severe droughts, heatwaves, or other extreme events could disproportionately affect primate populations by exacerbating habitat loss, reducing food availability, or increasing physiological stress (Kiribou et al., 2024; Zhang et al., 2019). While our models predict shifts in suitable habitats, they do not capture these short-term but potentially catastrophic events. Incorporating such dynamics in future models, possibly by integrating data on extreme events and their ecological impacts, would improve the robustness of predictions and provide a more comprehensive assessment of species vulnerability.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10764-024-00481-z.

Acknowledgements We thank the Universidad de Caldas, Programa de Maestría en Ciencias Biológicas, for their support in constructing the methodology and initial drafts of this manuscript. We extend our gratitude to Karime Angarita Corzo and Andrew John Connolly for their valuable assistance with article formatting and English language editing respectively. We are deeply appreciative of the reviewers and editors for their constructive comments, which greatly enhanced the quality of the manuscript.

This study received no specific grant from any funding agency, commercial, or not-for-profit sectors. We declare no conflicts of interest related to this research.

Author Contributions All co-authors conceived and designed the study, performed data analyses, and wrote the manuscript.

Funding Open Access funding provided by Colombia Consortium.

Data Availability The supplementary materials include three (3) tables describing the use of bioclimatic variables and the resulted selected ecological niche models, annexed to this manuscript. Additionally, raster files for current and projected future species distributions, are available in the Mendeley Data repository at: doi:https://doi.org/10.17632/tc59dyztsy.1 (https://data.mendeley.com/datasets/tc59dyztsy/1); and OSF https://osf.io/tns8x/

Ethical Statement This research did not involve the manipulation of primates; all data was gathered from literature and global and regional databases.

Inclusion and Diversity Statement The author list includes contributors from the location where the research was conducted, who participated in study conceptualization, study design, data collection, analysis, and/or interpretation of the findings.

References

Alvarado-Serrano, D. F., & Knowles, L. L. (2014). Ecological niche models in phylogeographic studies: applications, advances and precautions. *Molecular Ecology Resources, 14*(2), 233–248. https://doi.org/10.1111/1755-0998.12184

Arango-Lozano, J., Patiño-Siro, D., & Toro-Cardona, F. (2023). Reaching new environments through illegal trade: Evidence of a widely traded turtle in Colombia. *Aquatic Ecology, 57*(2), 471–480. https://doi.org/10.1007/s10452-023-10023-z

Arias-González, C., González-Maya, J. F., Gonzalez Zamorano, P., & Ortega Rubio, A. (2021). Climate refugia for two Colombian endemic tamarin primates are critically under-protected. *Mammalian Biology, 101*(5), 531–543. https://doi.org/10.1016/j.jnc.2023.126345

Arias-González, C., González-Maya, J. F., García-Villalba, J., Blázquez, M. C., Lizárraga, J. A. A., Castro, S. C. D., & Rubio, A. O. (2023). The identification and conservation of climate refugia for two Colombian endemic titi (*Plecturocebus*) monkeys. *Journal for Nature Conservation, 72*, 126345. https://doi.org/10.1016/j.jnc.2023.126345

Báez, S., Fadrique, B., Feeley, K., & Homeier, J. (2022). Changes in tree functional composition across topographic gradients and through time in a tropical montane forest. *PLoS ONE, 17*(4), e0263508. https://doi.org/10.1371/journal.pone.0263508

Benchimol, M., & Peres, C. A. (2014). Predicting primate local extinctions within "real-world" forest fragments: A pan-neotropical analysis. *American Journal of Primatology, 76*(3), 289–302. https://doi.org/10.1002/ajp.22233

Bernard, A. B., & Marshall, A. J. (2020). Assessing the state of knowledge of contemporary climate change and primates. *Evolutionary Anthropology: Issues, News, and Reviews, 29*(6), 317–331. https://doi.org/10.1002/evan.21874

Booth, T. H. (2022). Checking bioclimatic variables that combine temperature and precipitation data before their use in species distribution models. *Austral Ecology, 47*(7), 1506–1514. https://doi.org/10.1111/aec.13234

Campos, F. A., Kalbitzer, U., Melin, A. D., Hogan, J. D., Cheves, S. E., Murillo-Chacon, E., & Fedigan, L. M. (2020). Differential impact of severe drought on infant mortality in two sympatric Neotropical primates. *Royal Society Open Science, 7*(4), 200302. https://doi.org/10.1098/rsos.200302

Carvalho, J. S., Graham, B., Rebelo, H., Bocksberger, G., Meyer, C. F., Wich, S., & Kühl, H. S. (2019). A global risk assessment of primates under climate and land use/cover scenarios. *Global Change Biology, 25*(9), 3163–3178. https://doi.org/10.1111/gcb.14671

Cavalcante, T., de Souza Jesus, A., Rabelo, R. M., Messias, M. R., Valsecchi, J., Ferraz, D., & Barnett, A. A. (2020). Niche overlap between two sympatric frugivorous Neotropical primates: Improving ecological niche models using closely-related taxa. *Biodiversity and Conservation, 29*(8), 2749–2763. https://doi.org/10.1007/s10531-020-01997-5

Cavalcante, T., Barnett, A. A., & Van doninck, J., & Tuomisto, H. (2024). Modelling 21st century refugia and impact of climate change on Amazonia's largest primates. *Ecography, 2024*(e06988), 1–13. https://doi.org/10.1111/ecog.06988

Cobos, M. E., Jiménez, L., Nuñez-Penichet, C., Romero-Alvarez, D. & Simões, M. (2018). Sample data and training modules for cleaning biodiversity information. *Biodiversity Informatics, 13*, 49–50. https://doi.org/10.17161/bi.v13i0.7600

Cobos, M. E., Peterson, A. T., Barve, N., & Osorio-Olvera, L. (2019). kuenm: An R package for detailed development of ecological niche models using Maxent. *PeerJ, 7*, e6281.

da Silva, L. B., Oliveira, G. L., Frederico, R. G., Loyola, R., Zacarias, D., Ribeiro, B. R., & Mendes-Oliveira, A. C. (2022). How future climate change and deforestation can drastically affect the species of monkeys endemic to the eastern Amazon, and priorities for conservation. *Biodiversity and Conservation, 31*(3), 971–988. https://doi.org/10.1007/s10531-022-02373-1

Defler, T. R. (2003). *Primates de Colombia. Serie de Guías Tropicales de Campo, no. 4*. Conservación Internacional Colombia.

Díaz-Vallejo, M., Peña-Peniche, A., Mota-Vargas, C., Piña-Torres, J., Valencia-Rodríguez, D., Rangel-Rivera, C. E., ... & Rojas-Soto, O. (2024). Analyses of the variable selection using correlation methods: An approach to the importance of statistical inferences in the modelling process. *Ecological Modelling*, *498*, 110893.

Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N. D., Wikramanayake, E., & Saleem, M. (2017). An ecoregion-based approach to protecting half the terrestrial realm. *BioScience, 67*(6), 534–545.

Echeverry-Cárdenas, E., López-Castañeda, C., Carvajal-Castro, J. D., & Aguirre-Obando, O. A. (2021). Potential geographic distribution of the tiger mosquito *Aedes albopictus* (Skuse, 1894) (Diptera: Culicidae) in current and future conditions for Colombia. *PLoS Neglected Tropical Diseases, 15*(5), e0008212. https://doi.org/10.1371/journal.pntd.0008212

Edwards, D. P., Tobias, J. A., Sheil, D., Meijaard, E., & Laurance, W. F. (2014). Maintaining ecosystem function and services in logged tropical forests. *Trends in Ecology & Evolution, 29*(9), 511–520. https://doi.org/10.1016/j.tree.2014.07.003

Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt forecologists. *Diversity and distributions, 17*(1), 43–57. https://doi.org/10.1111/j.1472-4642.2010.00725.x

Escobar, L. E., Lira-Noriega, A., Medina-Vogel, G., & Peterson, A. T. (2014). Potential for spread of the white-nose fungus (*Pseudogymnoascus destructans*) in the Americas: Use of Maxent and NicheA to assure strict model transference. *Geospatial Health, 9*(1), 221–229.

Estrada, A., Raboy, B. E., & Oliveira, L. C. (2012). Agroecosystems and primate conservation in the tropics: A review. *American Journal of Primatology, 74*(8), 696–711. https://doi.org/10.1002/ajp.22033

Estrada, A., Garber, P. A., Rylands, A. B., Roos, C., Fernandez-Duque, E., Di Fiore, A., Nekaris, K. A., Nijman, V., Heymann, E. W., Lambert, J. E., Rovero, F., Barelli, C., Setchell, J. M., Gillespie, T. R., Mittermeier, R. A., Arregoitia, L. V., de Guinea, M., Gouveia, S., Dobrovolski, R., … Li, B. (2017). Impending extinction crisis of the world's primates: Why primates matter. *Science Advances, 3*, e1600946.

Fadrique, B., Báez, S., Duque, Á., Malizia, A., Blundo, C., Carilla, J., Osinaga-Acosta, O., Malizia, L., Silman, M., Farfán-Ríos, W., Malhi, Y., Young, K. R., Cuesta, F. C., Homeier, J., Peralvo, M., Pinto, E., Jadan, O., Aguirre, N., Aguirre, Z., & Feeley, K. J. (2018). Widespread but heterogeneous responses of Andean forests to climate change. *Nature, 564*, 207–212. https://doi.org/10.1038/s41586-018-0715-9

Feeley, K. J., Rehm, E. M., & Machovina, B. (2012). Perspective: The responses of tropical forest species to global climate change: Acclimate, adapt, migrate, or go extinct? *Frontiers of Biogeography, 4*, 69–84.

Feeley, K. J., Hurtado, J., Saatchi, S., Silman, M. R., & Clark, D. B. (2013). Compositional shifts in Costa Rican forests due to climate-driven species migrations. *Global Change Biology, 19*, 3472–3480. https://doi.org/10.1111/gcb.12300

Fernandez, D., Kerhoas, D., Dempsey, A., Billany, J., McCabe, G., & Argirova, E. (2022). The current status of the world's primates: Mapping threats to understand priorities for primate conservation. *International Journal of Primatology, 43*(1), 15–39. https://doi.org/10.1007/s10764-021-00242-2

Fernandez-Duque, E., Juárez, C. P., & Defler, T. R. (2023). Morphology, systematics, and taxonomy of owl monkeys. In E. Fernandez-Duque (Ed.), *Biology, adaptive radiation, and behavioral ecology of the only nocturnal primate in the Americas* (pp. 3–23). Springer International Publishing.

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1km spatial resolution climate surfaces for global land areas. *International Journal of Climatology, 37*(12), 4302–4315. https://doi.org/10.1002/joc.5086

Fischer, J., & Lindenmayer, D. B. (2007). Landscape modification and habitat fragmentation: A synthesis. *Global Ecology and Biogeography, 16*(3), 265–280. https://doi.org/10.1111/j.1466-8238.2007.00287.x

Forero-Medina, G., Joppa, L., & Pimm, S. L. (2010). Constraints to species' elevational range shifts as climate changes. *Conservation Biology., 25*, 163–171. https://doi.org/10.1111/j.1523-1739.2010.01572.x

Esri (2024). ArcGIS [online]. Environmental Systems Research Institute, Redlands.

Galán-Acedo, C., Hass, G. P., Klain, V., Bencke, P., & Bicca-Marques, J. C. (2024). Urban matrices threaten patch occurrence of howler monkeys in anthropogenic landscapes. *Land, 13*(4), 514. https://doi.org/10.3390/land13040514

García-Franco, J. L., Gray, L. J., & Osprey, S. (2020). The American monsoon system in HadGEM3 and UKESM1. *Weather and Climate Dynamics, 1*(2), 349–371. https://doi.org/10.5194/wcd-1-349-2020

Giam, X. (2017). Global biodiversity loss from tropical deforestation. *Proceedings of the National Academy of Sciences, 114*(23), 5775–5777. https://doi.org/10.3390/land13040514

Galindo-Cruz, A., Sahagún-Sánchez, F. J., López-Barrera, F., & Rojas-Soto, O. (2024). Recent changes in tropical-dry-forest connectivity within the Balsas Basin Biogeographic Province: Potential effects on endemic-bird distributions. *Nature Conservation, 55*, 177–199. https://doi.org/10.3897/natureconservation.55.120594

Gonçalves, F., Sales, L. P., Galetti, M., & Pires, M. M. (2021). Combined impacts of climate and land use change and the future restructuring of Neotropical bat biodiversity. *Perspectives in Ecology and Conservation, 19*(4), 454–463. https://doi.org/10.1016/j.pecon.2021.07.005

Global Forest Review (2024). Tropical forest loss drops steeply in Brazil and Colombia, but high rates persist overall. Global Forest Review, updated April 4, 2024. World Resources Institute. Available online at https://research.wri.org/gfr/latest-analysis-deforestation-trends

Hagerman, S., Dowlatabadi, H., Satterfield, T., & McDaniels, T. (2010). Expert views on biodiversity conservation in an era of climate change. *Global Environmental Change, 20*(1), 192–207. https://doi.org/10.1016/j.gloenvcha.2009.10.005

Henao-Díaz, F., Stevenson, P., Carretero-Pinzón, X., Castillo-Ayala, C., Pacheco, J., Defer, T., GarcíaVillalba, J., Caro, D., Link, A., Moreno, M., Palacios, E., Duque, N., Soto-Calderón, I., Soto, L., Velásquez-Tibata, J., Olaya-Rodríguez, M., Noguera-Urbano, E., Valencia, L. (2020). *Atlas de la biodiversidad de Colombia. Primates*. Instituto de Investigación de Recursos Biológicos Alexander von Humboldt.

Iturralde-Pólit, P., Dangles, O., Burneo, S. F., & Meynard, C. N. (2017). The effects of climate change on a mega-diverse country: Predicted shifts in mammalian species richness and turnover in continental Ecuador. *Biotropica, 49*(6), 821–831. https://doi.org/10.1111/btp.12467

Kiribou, R., Tehoda, P., Chukwu, O., Bempah, G., Kuehl, H. S., Ferreira, J., ... & Heinicke, S. (2024). Exposure of African ape sites to climate change impacts. *PLOS Climate*, *3*(2), e0000345. https://doi.org/10.1371/journal.pclm.0000345

Korstjens, A. H., & Hillyer, A. P. (2016). Primates and climate change: A review of current knowledge. In A. W. Serge & J. M. Andrew (Eds.), *An introduction to primate conservation* (pp. 175–192). Oxford University Press.

Li, J., Li, D., Xue, Y., Wu, B., He, X., & Liu, F. (2018). Identifying potential refugia and corridors under climate change: A case study of endangered Sichuan golden monkey (*Rhinopithecus roxellana*) in Qinling Mountains. *China. American Journal of Primatology, 80*(11), e22929. https://doi.org/10.1002/ajp.22929

Link, A., de la Torre, S. & Moscoso, P. (2021). *Aotus lemurinus*. The IUCN Red List of Threatened Species 2021: e.T1808A17922601. https://doi.org/10.2305/IUCN.UK.2021-1.RLTS.T1808A17922601. Accessed on 04 September 2023.

Link, A., Urbani, B. & Mittermeier, R. A. (2021). *Aotus griseimembra* (amended version of 2019 assessment). The IUCN Red List of Threatened Species 2021: e.T1807A190452803. https://doi.org/10.2305/IUCN.UK.2021-1.RLTS.T1807A190452803. Accessed on 30 August 2023.

Magioli, M., de Barros, K. M. P. M., Chiarello, A. G., Galetti, M., Setz, E. Z. F., Paglia, A. P., Abrego, N., Riberiro, M. C., & Ovaskainen, O. (2021). Land-use changes lead to functional loss of terrestrial mammals in a Neotropical rainforest. *Perspectives in Ecology and Conservation, 19*(2), 161–170. https://doi.org/10.1016/j.pecon.2021.02.006

Maiti, P. (2016). Global climate change and its effects on biodiversity. *Biodivers J, 7*(3), 311–318.

Mantilla-Meluk, H., & Ortega, A. M. J. (2011). Revisiting the taxonomic status and ecological partitioning of night monkeys genus *Aotus* in western Colombia, with notes on *Aotus zonalis* Goldman, 1914. *Revista Biodiversidad Neotropical, 1*(1), 28–37.

Méndez-Carvajal, P. G. & Link, A. (2021). *Aotus zonalis*. The IUCN Red List of Threatened Species 2021: e.T39953A17922442. https://doi.org/10.2305/IUCN.UK.2021-1.RLTS.T39953A17922442.en. Accessed on 04 September 2023.

Miles, L., Newton, A. C., DeFries, R. S., Ravilious, C., May, I., Blyth, S., Kapos, V., & Gordon, J. E. (2006). A global overview of the conservation status of tropical dry forests. *Journal of Biogeography, 33*(3), 491–505. https://doi.org/10.1111/j.1365-2699.2005.01424.x

Montilla, S. O., Mopán-Chilito, A. M., Murcia, L. N. S., Triana, J. D. M., Ruiz, O. M. C., Montoya-Cepeda, J., & Link, A. (2021). Activity patterns, diet and home range of night monkeys (*Aotus griseimembra* and *Aotus lemurinus*) in tropical lowland and mountain forests of central Colombia. *International Journal of Primatology, 42*, 130–153. https://doi.org/10.1007/s10764-020-00192-1

Mota-Vargas, C., & Rojas-Soto, O. R. (2016). Taxonomy and ecological niche modeling: Implications for the conservation of wood partridges (genus *Dendrortyx*). *Journal for Nature Conservation, 29*, 1–13. https://doi.org/10.1016/j.jnc.2015.10.003

Moreno-Contreras, I., Sánchez-González, L. A., Arizmendi, M. D. C., Prieto-Torres, D. A., & Navarro-Sigüenza, A. G. (2020). Climatic niche evolution in the *Arremon brunneinucha* complex (Aves: Passerellidae) in a Mesoamerican landscape. *Evolutionary Biology, 47*(2), 123–132. https://doi.org/10.1007/s11692-020-09498-7

Padhiary, J., Patra, K. C., Dash, S. S., & Uday Kumar, A. (2020). Climate change impact assessment on hydrological fluxes based on ensemble GCM outputs: A case study in eastern Indian River Basin. *Journal of Water and Climate Change, 11*(4), 1676–1694. https://doi.org/10.2166/wcc.2019.080

Peters, T., Drobnik, T., Meyer, H., Rankl, M., Richter, M., Rollenbeck, R., Thies, B. & Bendix, J. (2013). Environmental changes affecting the Andes of Ecuador. In J. Bendix, E. Beck, A. Braüning, F. Makeschin, R. Mosandl, S. Scheu (Eds.), *Ecosystem services, biodiversity and environmental change in a tropical mountain ecosystem of South Ecuador* (pp. 20–34). Springer. https://doi.org/10.1007/978-3-642-38137-9_2

Phillips, S. J., Dudík, M. & Schapire, R. E. (2006). A maximum entropy approach to species distribution modeling. In: *Proceedings of the 21st International Conference on Machine Learning* (pp. 655–662). ACM Press. https://doi.org/10.1016/j.ecolmodel.2005.03.026

Prieto-Torres, D. A., Navarro-Sigüenza, A. G., Santiago-Alarcon, D., & Rojas-Soto, O. R. (2016). Response of the endangered tropical dry forests to climate change and the role of Mexican Protected Areas for their conservation. *Global Change Biology, 22*(1), 364–379.

Rani, G., Kaur, J., Kumar, A. & Yogalakshmi, K. N. (2020). Ecosystem health and dynamics: an indicator of global climate change. In P. Singh, R. Singh, & V. Srivastava (Eds.), *Contemporary*

Environmental Issues and Challenges in Era of Climate Change (pp. 1–32). Springer. https://doi.org/10.1007/978-981-32-9595-7_1

Ramirez-Villegas, J., Cuesta, F., Devenish, C., Peralvo, M., Jarvis, A., & Arnillas, C. A. (2014). Using species distributions models for designing conservation strategies of Tropical Andean biodiversity under climate change. *Journal for Nature Conservation, 22*(5), 391–404. https://doi.org/10.1016/j.jnc.2014.03.007

Reshmidevi, T. V., Kumar, D. N., Mehrotra, R., & Sharma, A. (2018). Estimation of the climate change impact on a catchment water balance using an ensemble of GCMs. *Journal of Hydrology, 556*, 1192–1204. https://doi.org/10.1016/j.jhydrol.2017.02.016

Rojas-Soto, O. R., Sosa, V., & Ornelas, J. F. (2012). Forecasting cloud forest in eastern and southern Mexico: Conservation insights under future climate change scenarios. *Biodiversity and Conservation, 21*, 2671–2690. https://doi.org/10.1007/s10531-012-0327-x

Rojas-Soto, O., Forero-Rodríguez, J. S., Galindo-Cruz, A., Mota-Vargas, C., Parra-Henao, K. D., Peña-Peniche, A., ... & Trinidad-Domínguez, C. D. (2024). Calibration areas in ecological niche and species distribution modelling: Unravelling approaches and concepts. *Journal of Biogeography*, *51*(8), 1416–1428. https://doi.org/10.1111/jbi.14834

Ruhl, J. B. (2008). Climate change and the endangered species act: Building bridges to the no-analog future. *Boston University Law Review, 88*(1), 1–62.

Ryland, A. B., Mittermeier, R. A., & Rodriguez-Luna, E. (1997). Conservation of neotropical primates: Threatened species and an analysis of prima the diversity by country and region. *Folia Primatologica, 68*(3–5), 134–160. https://doi.org/10.1159/000157243

Sales, L., Ribeiro, B. R., Chapman, C. A., & Loyola, R. (2020). Multiple dimensions of climate change on the distribution of Amazon primates. *Perspectives in Ecology and Conservation, 18*(2), 83–90. https://doi.org/10.1016/j.pecon.2020.03.001

Sattar, Q., Maqbool, M. E., Ehsan, R., Akhtar, S., Sattar, Q., Maqbool, M. E. & Akhtar, S. (2021). Review on climate change and its effect on wildlife and ecosystem. *Open Journal of Environmental Biology*, *6*(1), 8–14. https://doi.org/10.17352/ojeb.000021

Shanee, S., Allgas, N., Shanee, N. & Campbell, N. (2015). Distribution survey, ecological niche modelling and conservation assessment of the Peruvian night monkey: *Aotus miconax* Thomas, 1927 (Mammalia: Primates: Aotidae) in north-eastern Peru, with notes on the distributions of *Aotus spp*. Gray, 1870. *Journal of Threatened Taxa*, *7*(3), 6947–6964. https://doi.org/10.11609/JoTT.o4184.6947-64

Shanee, S. (2023). Threats and conservation of owl monkeys (*Aotus spp*.) In E. Fernandez-Duque (Ed.), *Biology, adaptive radiation, and behavioral ecology of the only nocturnal primate in the Americas* (pp. 649–671). Springer International Publishing. https://doi.org/10.1007/978-3-031-13555-2_22

Shanee, S., Fernández-Hidalgo, L., Allgas, N., Vero, V., Bello-Santa Cruz, R., Bowler, M., ... & Mendoza, A. P. (2023). Threat analysis of forest fragmentation and degradation for Peruvian primates. *Diversity*, 15(2), 276. https://doi.org/10.3390/d15020276

Shanee, S., Tirira, D. G., Aquino, R., Carretero-Pinzón, X., Link, A., Maldonado, A. M., & Fernandez-Duque, E. (2023). Geographic distribution of owl monkeys. In E. Fernandez-Duque (Ed.), *Owl monkeys: biology, adaptive radiation, and behavioral ecology of the only nocturnal primate in the Americas* (pp. 25–62). Springer International Publishing. https://doi.org/10.1007/978-3-031-13555-2_2

Soberon, J., & Peterson, A. T. (2005). Interpretation of models of fundamental ecological niches and species' distributional areas. *Biodiversity Informatics, 2*(2005), 1–10.

Svensson, M. S., Samudio, R., Bearder, S. K., & Nekaris, K. A. I. (2010). Density estimates of Panamanian owl monkeys (*Aotus zonalis*) in three habitat types. *American Journal of Primatology, 72*(2), 187–192. https://doi.org/10.1002/ajp.20758

Tabarelli, M., Cardoso da Silva, J. M., & Gascon, C. (2004). Forest fragmentation, synergisms and the impoverishment of neotropical forests. *Biodiversity & Conservation, 13*, 1419–1425. https://doi.org/10.1023/B:BIOC.0000019398.36045.1b

Tovar, C., Carril, A. F., Gutiérrez, A. G., Ahrends, A., Fita, L., Zaninelli, P., ... & Hollingsworth, P. M. (2022). Understanding climate change impacts on biome and plant distributions in the Andes: Challenges and opportunities. *Journal of Biogeography*, *49*(8), 1420–1442. https://doi.org/10.1111/jbi.14389

Upadhyay, R. K. (2020). Markers for global climate change and its impact on social, biological and ecological systems: A review. *American Journal of Climate Change, 9*(03), 159. https://doi.org/10.4236/ajcc.2020.93012

Warren, D. L., & Seifert, S. N. (2011). Ecological niche modeling in Maxent: The importance of model complexity and the performance of model selection criteria. *Ecological Applications, 21*(2), 335–342. https://doi.org/10.1890/10-1171.1

Yu, M., Wang, G., Parr, D., & Ahmed, K. F. (2014). Future changes of the terrestrial ecosystem based on a dynamic vegetation model driven with RCP8. 5 climate projections from 19 GCMs. *Climatic Change, 127*, 257–271. https://doi.org/10.1007/s10584-014-1249-2

Zhang, L., Ameca, E. I., Cowlishaw, G., Pettorelli, N., Foden, W., & Mace, G. M. (2019). Global assessment of primate vulnerability to extreme climatic events. *Nature Climate Change, 9*(7), 554–561. https://doi.org/10.1038/s41558-019-0508-7

Authors and Affiliations

Julián Arango-Lozano[1] · Felipe Andrés Toro-Cardona[2] · Juan Sebastián O. Montilla[3] · Héctor E. Ramírez-Chaves[4]

✉ Felipe Andrés Toro-Cardona
tc.felipe28@gmail.com

Julián Arango-Lozano
arangolozanoj1@gmail.com

1 Maestría en Ciencias Biológicas, Universidad de Caldas, Manizales, Colombia

2 Grupo de Ecología y Evolución de Vertebrados, Instituto de Biología, Universidad de Antioquia, Medellín, Colombia

3 Laboratorio de Ecología de Bosques Tropicales y Primatología, Universidad de los Andes, Bogotá, D.C, Colombia

4 Departamento de Ciencias Biológicas and Centro de Museos, Museo de Historia Natural, Universidad de Caldas, Calle 65 No 26-10, 170004 Manizales, Caldas, Colombia