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Silvestre

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THE MINERS OF SOUTH AMERICA: an ecological approach to the genus
Geositta

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**THE MINERS OF SOUTH AMERICA: an ecological approach to the genus
*Geositta***

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RICARDO CAMARGOS DE MEIRELES

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RESUMO

O gênero *Geositta* é um grupo de aves terrestres pertencentes à família Scleruridae e distribuído por toda a América do Sul. Composto por onze espécies, habitam ambientes abertos e áridos, como campos, áreas arbustivas, rochosas e desérticas, além de compartilharem comportamentos semelhantes, como uma dieta majoritariamente insetívora e serem escavadoras. Das onze espécies pertencentes ao gênero, *Geositta poeciloptera* é atualmente a mais estudada e também a única ameaçada de extinção. Considerando todo o conhecimento acerca da espécie, pretendemos neste estudo responder às perguntas que surgiram ao longo de sete anos de trabalho em campo. Nossas principais questões foram: (1) Quais os efeitos da precipitação e da arquitetura do ninho na sobrevivência do ninho de *G. poeciloptera*? (2) Como será o efeito das mudanças climáticas na distribuição futura de *G. poeciloptera* frente a diferentes políticas de emissão de gases de efeito estufa? (3) Por compartilharem preferências de habitat semelhantes, qual será o efeito das mudanças climáticas e da altitude na distribuição das sete espécies não migrantes distribuídas nos trópicos? Com base em 86 ninhos monitorados e com medidas de arquitetura aferidas na região dos Campos do Alto Rio Grande, calculamos o sucesso aparente e modelamos as taxas diárias de sobrevivência do ninho (TSD). O sucesso geral aparente do ninho foi de 58% e as estimativas baseadas em TSDs foram de ~45%. Fase do ninho, área de entrada da cavidade, altura do ninho e tendência temporal linear foram os principais fatores que influenciaram as DSRs. Para as perguntas 2 e 3 utilizamos registros de ocorrência de diferentes fontes além dos coletados em campo e recorremos à modelagem de nicho ecológico utilizando diferentes algoritmos. Para previsões futuras, usamos dois Modelos Gerais de Circulação e diferentes cenários políticos de emissão de gases de efeito estufa. Para *G. poeciloptera* encontramos um futuro não muito otimista, com uma diminuição considerável das áreas climaticamente adequadas para a espécie. Já para as outras espécies não migrantes, encontramos padrões diferentes de áreas climaticamente adequadas para espécies de limites de ocorrência em elevações mais baixas e as de elevações mais altas, o que parece ser devido ao zoneamento vegetacional e elevacional das encostas andinas, que proporcionam maior umidade em áreas de altitude intermediária. Nossos resultados nos permitem compreender melhor a

ecologia desta família de aves ainda pouco estudada, além de contribuir nas estratégias de conservação dessas espécies.

Palavras-chave: Andes, Brasil, aves neotropicais, *Geositta*, modelagem de nicho ecológico, sobrevivência de ninho.

ABSTRACT

The genus *Geositta* is a group of terrestrial birds belonging to the family Scleruridae and distributed throughout South America. Composed of eleven species, they inhabit open and arid environments, such as grasslands, shrubby, rocky and desert areas, in addition to sharing similar behaviors, such as a mostly insectivorous diet and being excavators. Of the eleven species belonging to the genus, *Geositta poeciloptera* is currently the most studied and also the only one threatened with extinction. Considering all the knowledge about the species, in this study we intend to answer the questions that occasionally arose over seven years of fieldwork. Our main questions were: (1) What are the effects of precipitation and nest architecture on *G. poeciloptera* nest survival? (2) How will climate change affect the future distribution of *G. poeciloptera* in the face of different greenhouse gas emission policies? (3) As they share similar habitat preferences, what will be the effect of climate change and altitude on the distribution of the seven non-migrating species distributed in the tropics? Based on 86 monitored nests and architectural measurements taken in the Upper Rio Grande Grasslands region, we calculated apparent success and modeled daily nest survival rates (DSR). Apparent overall nest success was 58% and estimates based on DSRs were ~45%. Nest phase, cavity entrance area, nest height and linear temporal trend were the main factors that influenced DSRs. For questions 2 and 3 we used occurrence records from different sources in addition to those collected in the fieldwork and resorted to ecological niche modeling using different algorithms. For future predictions, we use two General Circulation Models and different greenhouse gas emission policy scenarios. For *G. poeciloptera*, we found a not very optimistic future, with a considerable decrease in areas climatically suitable for the species. As for the non-migrating species, we found different patterns of climatically suitable areas for lowland species and highland species, which seems to be due to the vegetational and elevational zonation of the Andean slopes, which provide greater humidity in these areas of intermediate elevation. Our results allow us to better understand the ecology of this few studied bird family, in addition to contributing to the conservation strategies of these species.

Keywords: Andes, Brazil, neotropical birds, *Geositta*, ecological niche modeling, nest survival.

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INTRODUÇÃO GERAL

Ambientes abertos, tais como os campos, são um dos ecossistemas mais dinâmicos da terra, pois sofrem de forma mais intensa perturbações periódicas naturais ou antrópicas no tempo e no espaço, como supressão do fogo, mudanças no uso da terra e mudanças climáticas (Vickery *et al.* 2000, Gibson & Newman 2019). Além disso, os campos naturais são encontrados em todo mundo e são muito importantes fornecendo bens e serviços para humanidade como estoque de água em aquíferos, armazenamento de carbono no solo, além de possuir grande biodiversidade (Gibson & Newman 2019).

Dentre os grupos animais encontrados em áreas abertas, as aves campestres, especialmente as obrigatórias, são um dos grupos mais sensíveis a alterações nos seus habitats e, conseqüentemente, mais ameaçadas de extinção (Vickery *et al.* 1999). Esta sensibilidade muito se deve ao fato das diferentes preferências de habitat de cada espécie, como por exemplo a preferência de altura e densidade da vegetação (Vickery *et al.* 2000, Lopes & Peixoto 2018), dificultando a elaboração de estratégias de conservação para cada uma (Vickery *et al.* 2000). Ademais, nos últimos anos, poucos estudos foram direcionados à conservação dessas espécies (Stotz *et al.* 1996; Azpiroz *et al.* 2012).

A família Scleruridae é composta por dezoito espécies de aves distribuídas na América do Sul e encontradas em áreas florestais (gênero *Sclerurus*) ou áreas abertas (gênero *Geositta*) (Remsen 2020). Semi-terricolas e escavadoras, estas espécies constroem seus próprios ninhos em cavidades no solo, geralmente em barrancos ou encostas íngremes (Sick 1997, Machado *et al.* 2017, Gómez 2019, Remsen 2020) ou podem também ocupar cavidades já previamente construídas por outros animais, como tatus e pica-paus (Fjeldså & Krabbe 1990, Sick 1997, Remsen 2003, Silva e Silva, 2005, Ridgely & Tudor 2009, Machado *et al.* 2017).

Membros do gênero *Geositta*, composto por onze espécies, habitam ambientes abertos e áridos como os campos limpos, áreas arbustivas, rochosas além de áreas desérticas (Fjeldså & Krabbe 1990, Sick 1997, Ribeiro *et al.* 2017, Remsen 2020, IUCN 2022, Machado *et al.* 2017). Apesar de dez espécies estarem classificadas como “Pouco Preocupante (LC)”, quatro dessas estão com população em declínio

(IUCN 2022), sendo a perda de habitat por conversão em áreas agricultáveis e também pecuária os principais motivos da diminuição de suas populações (Remsen 2020). Apenas *Geositta poeciloptera* se encontra atualmente classificada como “Vulnerável (VU)” no Brasil (MMA 2022) e também globalmente (Birdlife International 2022, IUCN 2022).

Popularmente conhecida como Andarilho, Bate-bunda e Abana-cauda (Figura 1) dependendo da região, esta é uma ave campestre encontrada majoritariamente nos campos naturais do Cerrado Brasileiro, no entanto, existem registros históricos para fora dos limites do país (mas ainda nos limites do Cerrado), como Bolívia e Paraguai (Sick 1997, del Casitillo *et al.* 2005, Herzog *et al.* 2016). Dentre os fatores citados acima que estão levando sua população ao declínio, as mudanças climáticas também são um forte indício de ameaça à espécie (Marini *et al.* 2009). Além disso, poucas unidades de conservação abrigam a espécie (ICMBio 2011) comprometendo ainda mais sua conservação.



Figura 1 – *Geositta poeciloptera* em seu habitat natural com solo exposto e vegetação rala. Foto: Ricardo Mendes

Devido ao seu grau de ameaça, sua distribuição restrita e pontual e suas características comportamentais únicas, a espécie despertou grande interesse de estudo do grupo liderado por pesquisadores das Universidades Federais de Viçosa

(UFV) e Minas Gerais (UFMG), tendo grande parte de sua história natural e biologia reprodutiva descritas (veja Machado *et al.* 2017, Lopes & Peixoto 2018, Meireles *et al.* 2018, Lopes *et al.* 2021, Lopes *et al. in press*).

Abaixo, resumimos o que se sabe da espécie até o momento:

- 1) Machado *et al.* (2017), durante três anos de estudo, descreveram muito do que se sabe atualmente sobre a história natural da espécie como material utilizado para a construção dos ninhos, arquitetura dos ninhos, tamanho médio da ninhada (3), tamanho médio e descrição dos ovos, período de incubação (~17,5 dias) e período de ninhego (~15,5 dias), período reprodutivo, além de detalhar comportamentos parentais.
- 2) Lopes & Peixoto (2018), focaram no uso do habitat de diversas aves campestres ameaçadas, descrevendo com mais detalhes características da cavidade utilizada para nidificação de *G. poeciloptera*, além de detalhar as características de habitat da espécie, como altura e adensamento da vegetação preferencial para sua ocorrência.
- 3) Meireles *et al.* (2018), identificaram quais atributos do solo direcionam a escolha dos locais de nidificação da espécie e identificaram uma preferência por locais com pouca estrutura do solo, facilitando a escavação das cavidades ninho. Estes solos possuem alta presença de silte e pouca presença de argila, características do horizonte C, solo pouco exposto naturalmente, o que pode ser um dos determinantes da distribuição pontual da espécie no Cerrado brasileiro.
- 4) Lopes *et al.* (2021), investigaram as variações sazonais e intersexuais nos níveis de testosterona plasmático da espécie. Foram encontrados níveis mais altos em machos, associado ao comportamento de agressividade, e territorialidade apenas durante o período reprodutivo.
- 5) Lopes *et al. (in press)* após sete anos de estudo com indivíduos identificados com anilhas coloridas e dados secundários, investigaram a ecologia de movimento da espécie, que, até então possuía informações contraditórias (veja Bates *et al.* 1992, Parker & Willis 1997, Remsen 2003, Silva e Silva 2005, Peixoto 2014, Machado *et al.* 2017, Lopes & Peixoto 2018, Remsen & Sharpe 2020). Foi identificado que a espécie é residente, porém sua detectabilidade está ligada ao seu comportamento territorial restrito ao

período reprodutivo, época em que displays de voo são realizados para atração de parceiros e/ou defesa de território.

Com base no grande conhecimento acerca da ecologia e história natural de *G. poeciloptera* descritos, pretendemos neste estudo responder às perguntas que surgiram a partir do desenvolvimento das pesquisas elencadas acima. No primeiro capítulo, procuramos compreender se a precipitação e quais características de arquitetura do ninho são responsáveis por garantir a sobrevivência da espécie. No segundo capítulo, utilizando modelagem de nicho ecológico, investigamos os efeitos das mudanças climáticas no presente e futuro frente a diferentes políticas de emissões de gases de efeito estufa sobre a distribuição da espécie, além de identificar áreas prioritárias para sua conservação. No terceiro capítulo, assim como no segundo, utilizamos a modelagem de nicho ecológico para compreender se os efeitos das mudanças climáticas sobre sete espécies residentes do gênero serão semelhantes, considerando serem espécies que compartilham comportamentos e preferências de habitat similares, mas que se distribuem por diferentes altitudes na América do Sul. Esperamos com isso contribuir para um aumento no conhecimento e conservação de todo o gênero *Geositta*, pertencente a uma família de aves ainda muito pouco estudada (Remsen 2020), além de contribuir no entendimento da dinâmica climática de ambientes áridos e semiáridos.

Chapter I: Nest survival of the threatened Campo Miner *Geositta poecilopectera*: a tropical cavity-nesting grassland bird

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RESUMO

A sobrevivência do ninho é um passo fundamental na biologia reprodutiva das aves e é essencial para a compreensão das estratégias utilizadas para melhorar as chances de sucesso do ninho. Aqui estudamos os principais fatores que impulsionam o sucesso de nidificação do Andarilho *Geositta poecilopectera* (Scleruridae), uma ave neotropical campestre e ameaçada de extinção que nidifica em cavidades no solo. Calculamos o sucesso aparente e modelamos as taxas diárias de sobrevivência do ninho (DSR) com base em 86 ninhos monitorados para investigar os efeitos das covariáveis relacionadas ao ninho na sua sobrevivência. Na modelagem DSR, analisamos os efeitos da fase reprodutiva (períodos de incubação e ninhegos), épocas reprodutivas (anos), tendências temporais (lineares e quadráticas) precipitação diária e covariáveis individuais do ninho (altura, distância do topo da cavidade ao topo do barranco, profundidade da cavidade e área de entrada da cavidade). O sucesso geral aparente do ninho foi de 58% e as estimativas baseadas em DSRs foram de ~45%. Fase do ninho, área de entrada da cavidade, altura do ninho e tendência temporal linear foram os principais fatores que influenciaram as DSRs. A sobrevivência durante a incubação foi menor (~54%) do que durante o período de ninhego (~83%), e ambas as fases apresentaram valores maiores no início da estação reprodutiva. A predação foi o principal fator de falha do ninho (23,3%, N = 20), seguido pelo abandono do ninho (10,5%, N = 9) e usurpação do ninho (7%, N = 6). Nossos resultados nos permitem entender e conservar melhor esta espécie ameaçada e também lançar luz sobre a ecologia reprodutiva de toda uma família endêmica da região Neotropical.

Palavras-chave: Brasil, Cerrado, aves campestres, atributos relacionados ao ninho, sucesso reprodutivo.

ABSTRACT

Nest survival is a key step in the reproductive biology of birds and is essential for understanding the strategies used to improve the chances of nest success. Here we studied the main factors driving nesting success of the Campo Miner *Geositta poeciloptera* (Scleruridae), a threatened Neotropical grassland bird that nests in cavities, usually along steep soil banks. We calculated the apparent success and modeled daily nest survival rates (DSR) based on 86 nests monitored to investigate the effects of nest-related covariates on the nest survival. In the DSR modeling, we looked at the effects of reproductive phase (incubation and nestling periods), breeding seasons (years), temporal-trends (linear and quadratic) rainfall, and nest's individual covariates (height, distance from the top of the cavity to the top of the bank, cavity depth and cavity entrance area). The overall apparent nest success was 58% and estimates based on DSRs were ~45%. Nest phase, cavity entrance area, nest height, and a linear time trend were the main factors influencing DSRs. The survival during incubation was lower (~54%) than during the nestling period (~83%), and both phases showed higher values in the beginning of the breeding season. Predation was the main driver of nest failure (23.3%, $N = 20$), followed by nest abandonment (10.5%, $N = 9$) and nest usurpation (7%, $N = 6$). Our results allow us to better understand and conserve this threatened species and also shed light in the reproductive ecology of a whole family endemic to the Neotropics.

Keywords: Brazil, Cerrado, grassland birds, nest-related attributes, reproductive success.

1. INTRODUCTION

The study of nest survival in birds can reveal the strategies they use to maximize breeding success, as well as the causes of nest failure thus advancing our understanding of life-history evolution. Nest architecture is one of the most important factors that can influence nest survival in birds, as it is related to the degree of protection against predators and inclement weather, two important sources of nest failure (Collias & Collias 1984, Hansell 2000). Nests within cavities are usually less vulnerable to predation than open nests, since the cavity itself makes the nest inconspicuous to predators, and because the size of the cavity entrance may prevent access of larger predators to the nest content (Martin & Li 1992, Paclik *et al.* 2009). Furthermore, the cavity may also buffer olfactive and auditory cues that otherwise could reveal the nest location. Such clues are usually more intense after hatching, with the smell and sound of begging nestlings, as well as an increase in adult activity at the nest site, by attracting predators' attention, result in larger rates of nest failure during the nestling period (Skutch 1949, 1985).

Cavities are usually well protected against adverse weather, which could reduce nest survival, including cold, heat, storms, hail, and even snow (Collias & Collias 1984, Ke & Lu 2009, Coombs *et al.* 2010). Weather can also have indirect impacts on nest survival, since ectothermic predators, such as lizards and snakes (well-known nest predators - Skutch 1985, Fry 2001, Woodall 2001), regulate their activity levels and metabolic rates with increasing or decreasing in temperature and precipitation (Bennett 1990, Eskew & Todd 2017). The study of cavity-nesting has an additional importance, as some species are keystone excavators in the community, contributing to the nesting of several other species whose reproduction relies on pre-existing cavities (Bednarz *et al.* 2004, Aitken & Martin 2007). Despite that, the study of cavity-nesting birds, especially in the tropics, remains largely neglected, probably because their nests are inconspicuous and difficult to find and/or to monitor.

In this paper, we investigated which environmental and nest-related factors influence nest survival of the Campo Miner *Geositta poeciloptera*, a threatened tropical grassland bird that excavates galleries in steep soil banks within which it nests. We hypothesized that nest architecture and rainfall pattern can influence nest survival in Campo Miners, and predicted that: 1) nest architectural features that are known to deter

predators from accessing its content, such as greater height in relation to the ground level, greater distance to the top of the steep soil bank, greater cavity depth, and smaller cavity entrance will have a positive effect on nest survival; 2) nest survival rates will be higher during periods of higher rainfall because ectothermic predators will be less active. Finally, we discuss the implications of our findings for the development of conservation and management strategies for this threatened species.

2. METHODS

2.1. Study area

We conducted the fieldwork in the municipality of São João del-Rei, a countryside area covering 6.900 ha (centered at 21°10'20.93"S, 44°10'56.46"W) during the breeding season (Fig.1). In 2014 and 2015 the fieldwork was conducted from early August to late January, and in 2016 and 2019, it was conducted from early August to late December. The study area is in the Upper Rio Grande Grasslands, a large (~1.2 million ha) mountainous region (~900-1600 m a.s.l) in the southern part of the state of Minas Gerais, southeastern Brazil. Local climate type is Cwb according to the Köppen Climate Classification System, which means a humid subtropical climate with dry winter and wet temperate summer (Álvares *et al.* 2013). Mean annual precipitation is ~1500 mm, mean temperature is 14.3°C during winter and 17.0°C during summer (Sá Júnior *et al.* 2012). The study area is in the ecotone between the Cerrado and the Atlantic Forest (IBGE 2004), with natural open grasslands as the main vegetation type, with semi-deciduous forests along creeks and lower areas (Azevedo 1962). The grassland sites studied are subject to frequent fires and extensive cattle breeding, presenting a short and sparse grass cover. For clarity, we made a short movie of the study area that better describes the habitat and the type of nest cavity built by the species (<https://youtu.be/EM6SRlyiHVA>).

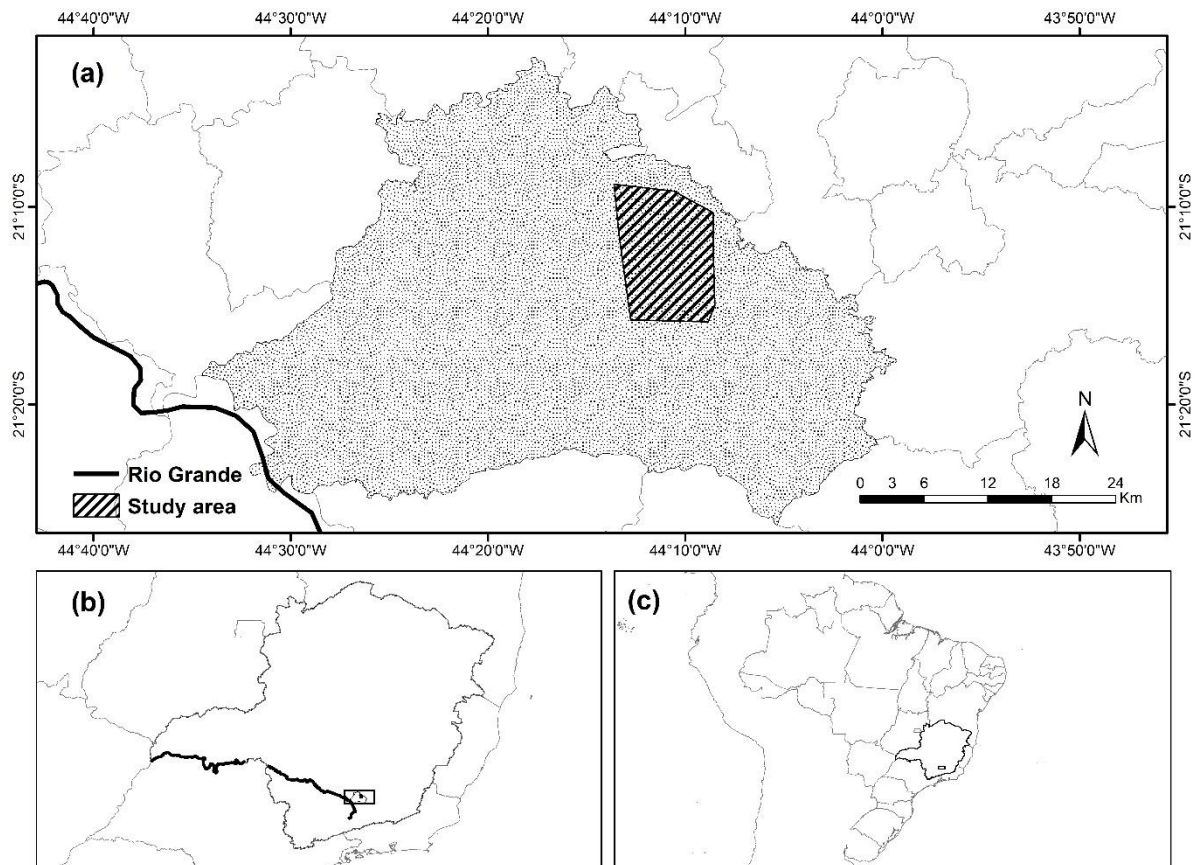


Figure 1. Study area in the Upper Rio Grande Grasslands region, municipality of São João del-Rei (a), Minas Gerais (b), Brazil (c).

2.2. Study species

The Campo Miner is a rare and patchily distributed ground dwelling passerine that is endemic to patches of pure grasslands within the Cerrado savannas (Ridgely & Tudor 2009, Lopes et al. 2010, Machado et al. 2017), one of the world's biodiversity hotspots (Myers *et al.* 2000). The Campo Miner is threatened by a rampant loss of its habitat as well as by climate changes (Marini et al. 2009a), being Endangered in Brazil (CEMAVE 2018) and globally Vulnerable (Birdlife International 2020). The species, which is poorly protected in conservation units (Marini *et al.* 2009b), was recently included in the National Action Plan for the Conservation of Endangered Species in the Cerrado (ICMBio 2021a).

Members of this species build their nests within cavities they excavate in the soil. Until quite recently, little was known about the breeding biology of the Campo Miner

until our research group started to study it (Machado *et al.* 2017, Meireles *et al.* 2018, Lopes *et al.* 2021). This is a socially monogamous species that exhibits bi-parental care and has a mean clutch size of 3 eggs, with an incubation period of ~17.5 days and a nestling period of ~15.5 days (Machado *et al.* 2017, Meireles *et al.* 2018). It is territorial during the breeding season, which lasts for about 5 months (August to December) (Machado *et al.* 2017, Lopes *et al.* 2021). This multiple-brooding species usually build a new cavity for each breeding attempt, and may use cavities excavated by other species, such as armadillo and woodpeckers (Machado *et al.* 2017).

2.3. Data collection

We searched for nests by: 1) inspecting all kinds of features that could harbor nest-cavities (*e.g.*, ravines, gullies, termite mounds); 2) observing behavioral cues (*e.g.*, following adults until observing them excavating the nest cavities or carrying nest material or food for nestlings) and; 3) systematically inspecting the steep soil banks along the roads cuts, because the species often nests in them (Machado *et al.* 2017). All nests located were georeferenced with a GPS device and monitored until found to be inactive.

Four nest-cavity features were measured with a measuring tape for all nests monitored: 1) distance from the base of the steep soil bank to the cavity entrance hole (hereafter nest height, for simplicity); 2) distance from the top of the cavity to the top of the steep soil bank; 3) cavity depth and; 4) height and width of the cavity entrance hole (which allowed us to calculate the cavity entrance area). The cavity entrance area was estimated using the ellipse area formula: $area = \pi \times r1 \times r2$, where $r1$ and $r2$ are the radii of the height and width of the entrance hole, respectively. All measurements were standardized and performed by the authors RCM and TLSSM after the nesting attempt ended, avoiding interference in the reproduction of the species.

We also collected information about the total daily rainfall for the four breeding seasons, through the meteorological database of the automatic station of the National Institute of Meteorology (INMET 2021), located in the city of São João del-Rei.

2.4. Nest monitoring

We monitored the nests with an inspection camera (burrowscope) at intervals of two to four days from the date they were found until they were inactive. To avoid much disturbance, which might cause nest abandonment, all inspections were carried out when the adult bird was not inside the nest. At each inspection, we recorded the nest content (number of eggs and/or nestlings) and its status: 1) unchanged (still with eggs or nestlings); 2) depredated; 3) abandoned; and 4) successful (Marini *et al.* 2010). We considered as successful the nests in which at least one nestling fledged, depredated when nest contents disappeared and abandoned those in which incubation or nestling care ceased without any obvious reasons (five or more days of observation without noticing the presence of parents) and the dead contents remained in the nest.

2.5. Data analysis

We estimated nest survival of the species using two methods. First, we calculated the apparent success (the simple percentage of successful nests considering the total found), which allowed comparisons with other studies that did not use a more robust method of analysis. Second, we estimated nest survival by daily survival rates (DSR), using likelihood-based modeling inferences in program MARK 9.x (White & Burnham 1999, Rotella *et al.* 2004). This analysis allows a wide variety of competing mathematical models to be assessed via likelihood-based information-theoretic approach (Burnham & Anderson 2002, Dinsmore & Dinsmore 2007). Thus, the daily survival rates of nests can be modelled as functions of specific covariates related to the nests, groups and/or time (see Rotella *et al.* 2004, Dinsmore & Dinsmore 2007). We ranked the final set of candidate models based on the Akaike Information Criterion corrected for small sample sizes (AICc, the best those with $\Delta AICc \leq 2$). We also considered the model and variable weights to infer the importance of covariates (following Burnham & Anderson, 2002).

In the modeling, we evaluated the effect of group covariates represented by reproductive phase (*i.e.*, incubation and nestling periods) and years of study. The idea was to test differences in the DSR between phases, and among years (2014, 2015, 2016, and 2019). In addition, considering the entire duration of each breeding season, we tested temporal-trends variation on DSR (linear and quadratic) and constant trend (null). In the cases of linear (T) and quadratic (TT) trends, we consider that the

conditions of the reproductive cycle may vary throughout the season, indicating the respective trends of increasing or decreasing DSR throughout the seasons. The constant model, on the other hand, assumes that the DSR is constant throughout the reproductive season and is therefore similar to Mayfield's (1961) method. We also tested the influence of the rainfall (rain) along the breeding season, represented by the accumulated daily precipitation for the period sampled in each year. Finally, we tested nest's individual covariates (height, distance from the top of the cavity to the top of the steep soil bank, cavity depth, and cavity entrance area) to evaluate the importance of the nest architecture on DSR.

Our initial global model predicted DSR under additive effects of the covariates nest-phase, years, temporal quadratic trend along the season (TT), and nest architecture variables (Phase+Year+TT+Height+DistTop+Depth+Area). Based on this structure, we built a set of simpler models using all possible combinations approach by restricting the covariates and substituting the quadratic trend "TT" by linear trend "T", and the covariate "year" by "rain" to test which of all factors were the most important for survival. We did not build nonsensical models with both time structure (*e.g.*, year) and time-varying covariate (*e.g.*, rainfall) to avoid overparameterization (following White & Burnham 1999).

As a measure of relative importance of each covariate, we used the AICc weights (w_i) of the models in the final set to estimate the variable weights (cumulative weight of all models including a particular covariate). Covariates that presented weights above 50% were considered to be quite explanatory. We also used the model averaging approach to accommodate uncertainty in the parameter estimates and presented the final set of models without those with uninformative parameters (following Arnold 2010). To calculate the cumulative nest success probability during each phase of the nesting cycle (incubation and nestling), we used the expression DSR^t , where t represents the mean number of days for incubation (17) and nestling (15) periods. We calculated the entire nest success by the product of the estimates of incubation and nestling periods.

3. RESULTS

We monitored a total of 86 nests, 26 of which were found in 2014, 25 in 2015, 19 in

2016, and 16 in 2019. The first active nest was found on August 18th and the last nest became inactive on December 27th. Thus, we considered 132 days the duration of the breeding season monitored. Among the nest measurements, the distance from the cavity to the top of the bank was the one with the greatest variation and the cavity depth the one with the least variation (Table 1).

Table 1. Architectural measures of 86 nests of the Campo Miner *Geositta poeciloptera* found in the Upper Rio Grande Grasslands, southeastern Brazil.

Measures	Mean	SD	Min	Max
Cavity height (cm)	74.1	33.8	25.0	198.0
Distance from the cavity to the top of the bank (cm)	55.6	52.1	6.0	300.0
Cavity depth (cm)	43.3	9.2	29.5	73.0
Cavity entrance area (cm ²)	62.0	28.3	23.0	197.8

Mean = Average measures of the nests found; SD = Standard Deviation; Min = Minimum Value; Max = Maximum Value.

3.1. Nest survival

Overall apparent nest success was 58%, and varied more among years (35.5-78.9%) than nest success estimates calculated from DSRs (45.1% overall, range 45.0-45.2%; Table 2). Nest survival during incubation was lower (~54%) than during nestling period (~83%), and in both phases we observed higher values in the beginning of the breeding season (Table 2).

Table 2. Summary of estimates of daily survival rates for the different phases (incubation and nestling) and for the four years of monitoring nests of *Geositta poecilopectera* in southeastern Brazil.

Year	Incubation			Nestling			Total breeding			
	Mean DSR	SE	DSR Range*	Nest Survival Based on DSR	Mean DSR	SE	DSR Range*	Nest Survival Based on DSR	Nest Survival Based on DSR	Apparent Nest Survival
2014	0.964	0.012	0.989-0.904	0.543	0.987	0.006	0.996-0.965	0.829	0.450	0.577
2015	0.964	0.012	0.989-0.904	0.542	0.987	0.006	0.996-0.965	0.829	0.450	0.560
2016	0.964	0.012	0.989-0.905	0.544	0.987	0.006	0.996-0.965	0.830	0.451	0.789
2019	0.964	0.012	0.989-0.904	0.542	0.987	0.006	0.996-0.965	0.829	0.449	0.375
All	0.964			0.543	0.987			0.829	0.450	0.580

*variation from the beginning to the end of the breeding season

The modeling based on all possible combinations of the covariates resulted in 288 models, this set was reduced to 26 models by exclusion of those noninformative parameters. The most parsimonious model included nest phase, nest height, cavity entrance area, and the linear temporal trend (Table 3). The next two models showed some uncertainty ($\Delta AICc < 2$) and differed from the first by the absence of nest height in the second model and the replacement of the linear trend by the quadratic trend in the third model (Table 3).

Table 3. Model selection results of nest survival for 86 nests of the Campo Miner *Geositta poeciloptera* monitored in the Upper Rio Grande Grasslands, southeastern Brazil.

Model	AICc	$\Delta AICc$	w_i	K	Deviance
Phase+Height+Area+T	304.666	0	0.281	5	294.632
Phase+Area+T	305.111	0.444	0.225	4	297.088
Phase+Height+Area+TT	306.332	1.665	0.122	6	294.284
Phase+Area+TT	306.697	2.030	0.102	5	296.662
Phase+DistTop+Area+T	307.118	2.451	0.082	5	297.083
Phase+Area+Depth+T	307.119	2.452	0.082	5	297.085
Phase+DistTop+Area+Depth+T	309.128	4.462	0.030	6	297.080
Phase+Area	310.447	5.781	0.015	3	304.434
Height+Area+T	311.385	6.718	0.009	4	303.362
Area+T	311.591	6.924	0.008	3	305.577
Phase+Area+Depth	312.453	7.786	0.005	4	304.430
Phase+T	312.512	7.8455	0.005	3	306.498
Height+Area+TT	312.725	8.059	0.005	5	302.691
Area+TT	312.931	8.264	0.004	4	304.907
Phase+Year	313.554	8.888	0.003	5	303.520
Area+Depth+T	313.600	8.933	0.003	4	305.577

Model	AICc	ΔAICc	<i>w_i</i>	K	Deviance
				1	
Phase+Year+DistTop+Height+Area+Depth+TT*	313.620	8.953	0.003	1	291.467
Phase	313.983	9.316	0.002	2	309.976
DistTop+Height+Area	314.634	9.968	0.001	4	306.611
Area	315.027	10.361	0.001	2	311.021
Area+Depth	317.034	12.367	0	3	311.020
Year	317.616	12.949	0	4	309.593
DistTop+Height	318.336	13.669	0	3	312.322
T	318.642	13.975	0	2	314.635
(.)	318.795	14.128	0	1	316.792
Rain	320.798	16.131	0	2	316.791

AICc = Akaike Information Criteria corrected for small sample sizes; *w_i* = Akaike weight; K = number of parameters included in each model; * global model; (.) = null model; (T) = linear temporal trend; (TT) = quadratic temporal trend; Year = breeding season years; Phase = incubation and nestling period; Height = nest height; Area = cavity entrance area; Depth = cavity depth; DistTop = distance from the cavity to the top of the steep soil bank; Rain = Rainfall.

Considering the full set of models, the modeling showed as important covariates (variable weights > 50%) the cavity entrance area, nest phase, linear temporal trend, and nest height (Table 4).

Table 4. Covariables weights for 288 models of nest survival of the Campo Miner *Geositta poeciloptera* monitored in the Upper Rio Grande Grasslands, southeastern Brazil.

Covariables	Covariables Weights
Area (cavity entrance area)	0.956
Phase (incubation and nestling period)	0.949
T (linear temporal trend)	0.648
Height (nest height)	0.565
DistTop (distance from the cavity to the top of the steep soil bank)	0.328
TT (quadratic temporal trend)	0.289
Depth (cavity depth)	0.275
Rain (rainfall)	0.241
Year (breeding season years)	0.133

The cavity entrance area negatively affected the DSRs and this covariate was present in the first 11 best models. It was the strongest covariate analyzed based in the variable weights (Table 4). The negative β factor of this covariate did not include the zero in the confidence interval in no model, showing the consistency of the direction of this influence (in the first model $\beta_{\text{Area}} = -0.02 \pm 0.01 \text{ SE}$, 95%CI = -0.04 to -0.01). This indicates that the greater the opening of the cavity, the lower the chance of nest survival (Fig. 2). As an example of this influence, we estimated the DSRs in the incubation based on model averaging of the models considering the lower and higher values of cavity entrance area. For the 22.96 cm² entrance the DSR was 0.9960 ± 0.0025 , and for the 197.82 cm² entrance the DSR was $0.8109 \pm 0.1237 \text{ SE}$. These estimates result respectively in approximately 94% and 3% of nest success during incubation for each cavity entrance area.

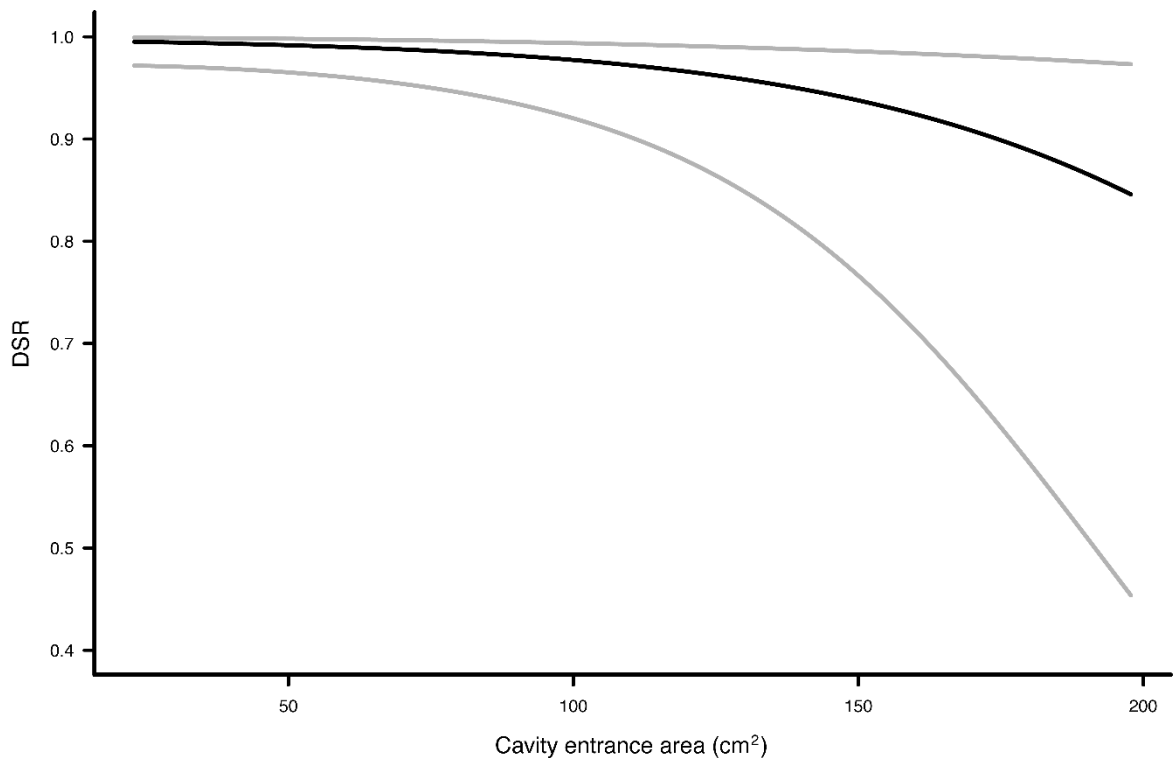


Figure 2. Daily survival rates (DSR) for nests of the Campo Miner *Geositta poeciloptera* in relation to the cavity entrance area. Values estimated for 86 nests monitored in the Upper Rio Grande Grasslands, southeastern Brazil. Gray lines indicate the 95% confidence intervals

The modeling of the nest phase covariate resulted in a consistent lower DSRs for the incubation period in all models where it was included (Table 2). The negative influence of the incubation was clear and present in the first eight models (in the best mode the $\beta_{\text{Phase}} = -1.15 \pm 0.42SE$, 95%CI = -1.99 to -0.31). In addition, the modeling supported a decreasing DSR throughout the breeding season following a linear trend in the first two models and a quadratic trend in the next two. This shows some uncertainty about the pattern of this tendency, but not the direction, because the negative β factor did not include the zero in the confidence interval ($\beta_T = -0.02 \pm 0.007SE$, 95%CI = -0.033 to -0.007). The final estimates based on the model averaging show this tendency of DSR in a shape of a decreasing curve (Fig. 3). On the other hand, the nest height positively influenced the DSR ($\beta_{\text{Height}} = 0.008 \pm 0.005SE$, 95%CI = -0.002 to 0.019), that is, the higher the cavity, the greater

the chance of survival (Fig. 4). But, in this case the direction of influence presented some uncertainty because of the zero within the 95%CI of the respective β factor. Finally, the covariates distance from the cavity to the top of the soil bank, cavity depth, daily rainfall, and breeding season years showed low influence in the DSR based on the data collected.

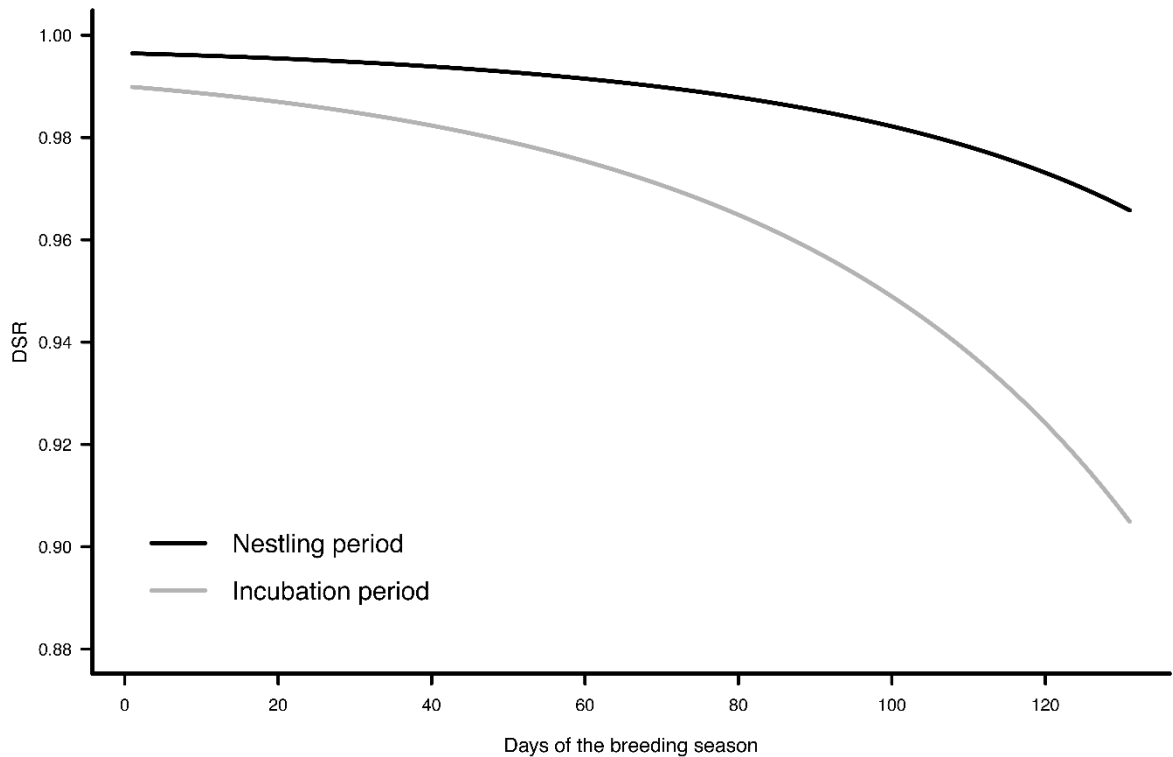


Figure 3. Daily survival rates (DSR) for nest phase (incubation period and nestling period) in linear time trend model for nests of the Campo Miner *Geositta poecliptera* in relation to the days of the breeding season (95% confidence intervals). Values estimated for 86 nests monitored in the Upper Rio Grande Grasslands, southeastern Brazil.

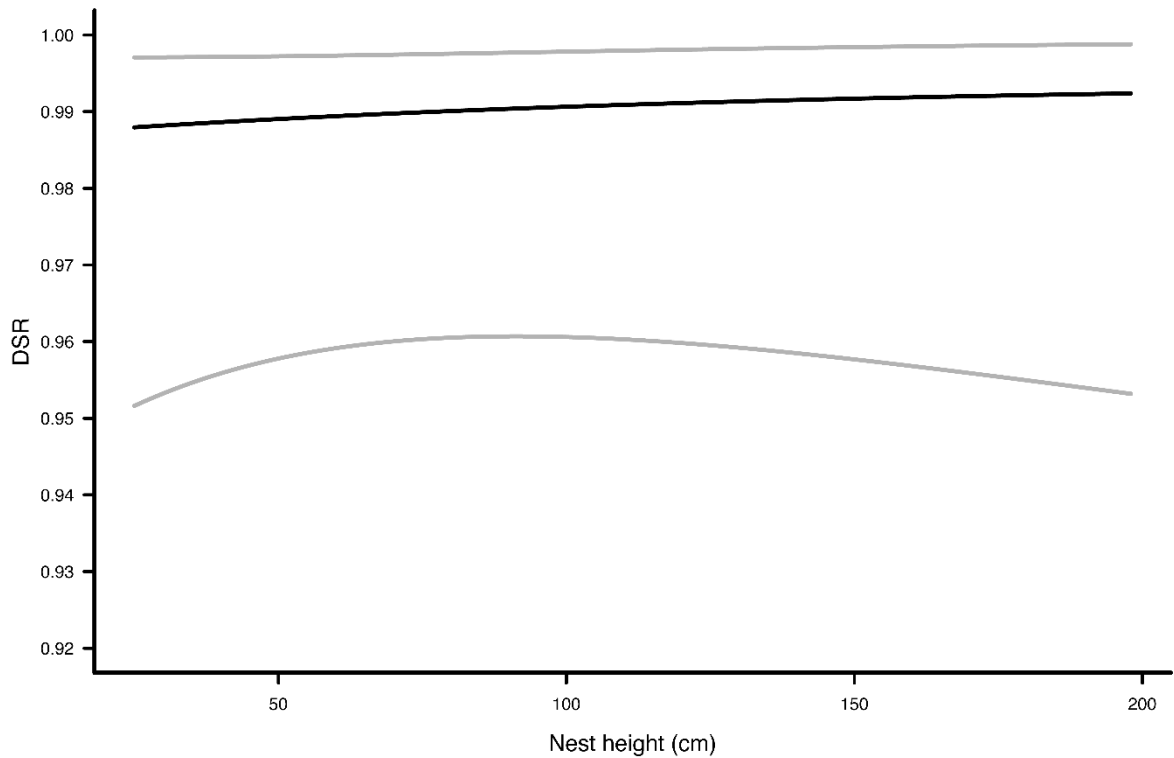


Figure 4. Daily survival rates (DSR) for nests of the Campo Miner *Geositta poeciloptera* in relation to the nest height. Values estimated for 86 nests monitored in the Upper Rio Grande Grasslands, southeastern Brazil. Gray lines indicate the 95% confidence intervals.

Predation was the main cause of nest loss ($N = 20$ of the 86 nests monitored were predated), however, we were not able to determine which species were preying on the nests. In two occasions, we observed an unidentified rodent (probably *Calomys* sp.) within abandoned nest cavities. We also observed once a False Coral Snake *Oxyrhopus rhombifer* (Dipsadidae) inside a cavity under construction. The second most common cause of nest failure was abandonment ($N = 9$), followed by cavity usurpation by swallows ($N = 6$). The Tawny-headed Swallow *Alopochelidon fucata* and the Southern Rough-winged Swallow *Stelgidopteryx ruficollis* were the two swallow species that usurped nest cavities. Even though nest cavity usurpation was uncommon after egg laying, it seems to be a common event during nest excavation, with at least 16 cavities usurped by swallows during the four breeding seasons studied. Finally, nestlings of a single nest were found dead due to an unknown reason.

4. DISCUSSION

The Campo Miner exhibited a comparatively high reproductive success for a grassland bird (58% by apparent success and 45% by DSR) what seems to be related with the general architecture of the nest, which provide a better protection for eggs and nestlings. This can be observed when comparing the reproductive success of Campo Miner with other studies of tropical grassland passerines that build open nests, where the apparent success does not exceed 42% and the success by DSR 35% (e.g., Chiarani & Fontana 2015, Gressler & Marini 2015, Repenning & Fontana 2016, Mwangi *et al.* 2018).

A study with the congeneric Coastal Miner *Geositta peruviana* also found a high reproductive success (76.2% by apparent success, $N = 32$ of 42 monitored nests), which was attributed to the type of nest built by the species - a cavity in the ground with an average depth of 259.9 cm (Gómez 2019). The fact that the Campo Miner and the Coastal Miner usually build a new cavity for each reproductive attempt (Machado *et al.* 2017, Gómez 2019) may also be responsible for its high reproductive success, since cavity reuse can provide clues to nest predators (Otterbeck *et al.* 2019).

The cavity entrance area was an important factor influencing nest survival in Campo Miner, and the smaller the area, the greater the probability of nest success, what is likely due to a smaller probability of suffering predation or nest usurpation. Robertson & Rendell (1990) showed that, when comparing artificial nests with natural nests, the smaller the entrance of the nest boxes, the greater the nest success, and the greater the entrance of the natural nests, the greater the access of nesting usurpers. Cockle *et al.* (2015) also showed that nests of small birds (≤ 130 g) are more likely to survive in cavities with smaller entrances.

Many studies on the reproductive success in birds point to predation as the main cause of nest loss, both for open-nesters and cavity-nesters (Ricklefs 1969, Li & Martin 1991, Miller 2002, Seixas & Mourão 2002, Cockle *et al.* 2015), but the reason why the daily survival rate is higher in the nestling phase than in the egg phase is unclear. Despite the Skutch hypothesis (1949, 1985) predicts that nest predation increases with activity in the nests, this hypothesis was not supported by our empirical data, which found higher predation rates during the incubation period. A possible explanation is because many nest predators are nocturnal, and increased or decreased adult activity

does not interfere with predation rates (Roper & Goldstein, 1997).

Regarding the two species (rodent and snake) identified in cavities dug by the Campo Miner, it was not possible to claim that these species preyed on eggs or nestlings. Members of *Calomys* have a predominantly herbivorous diet, also consuming some arthropods (Dellafiore & Polop 1994, Castellarini *et al.* 1998). In a controlled experiment conducted in captivity, Marini & Melo (1998) offered quail eggs to six individuals of *Calomys callosus*, that did not attempt to eat the eggs. In a similar way, there are no records of eggs or birds in the diet of the snake *O. rhombifer* (Gaiarsa *et al.* 2013), that was possibly using the cavity as shelter, once the animal remained there for five days. It was not possible to verify the fate of the birds that were building the cavity occupied by the snake.

Gómez (2019) reported that nests of the Burrowing Owl *Athene cunicularia* were frequently observed close to Coastal Miner nests, having even reported episodes of nest predation by the owls. Despite being a common species in the study area and also having several nests close to nests of the Campo Miner, it was not possible to verify any predation event by the owl. The fact that the Coastal Miner builds nests in cavities in the ground can be a facilitator for the owl to have access to the nest, once it excavates the cavity until reaching the incubator chamber (Gómez, 2019).

Just as nest reuse can provide clues to an eventual predator (Otterberck *et al.* 2019), the long period of construction (~19 days), laying (~3 days), incubation (~17.5) and parental care (~15.5) for the Campo Miner (Machado *et al.* 2017) can be a factor for predators to recognize nesting sites, thus increasing predation rates over time, leading to decreased reproductive success over the season.

The height from the base of the steep soil bank to the cavity entrance followed the predicted pattern, with higher nests more likely to survive than lower nests. This is a well-known pattern, because higher nests are more difficult to access by terrestrial predators (Nilsson 1984, Rendell & Robertson 1989, Robertson & Rendell 1990, Li & Martin 1991, Cockle *et al.* 2015).

Nest-cavity usurpation by other species is a well-known cause of breeding failure among cavity-nesting birds (Lindell 1996, Hansell 2000), as shown by the high number of nests under construction ($N = 16$) and also active nests ($N = 6$) that were usurped by competing bird species. Swallows are well-known usurpers of passerine nests (Sick 1997, Botero-Delgadillo *et al.* 2015), and the Blue-and-white Swallow (*Pygochelidon cyanoleuca*) has already been reported to seize the nest-cavity of the

Common Miner (*Geositta cunicularia*) in Argentina (Pereira 1937). Usurpation of nest-cavities is a common strategy adopted by species that are unable to excavate their own cavities and, therefore, need to find readily available shelter and nesting sites (Lindell 1996).

5. CONCLUSION

This, together with our previous studies of the species (Machado *et al.* 2017, Meireles *et al.* 2018, Lopes *et al.* 2021), makes the Campo Miner the best studied species of Scleruridae, a family whose none of its 18 members has been fully studied until quite recently (Remsen 2020), representing an important advance in our understanding of the life history of a whole bird family endemic to the Neotropics.

The life history data presented here can be used to develop conservation and management plans for this threatened species. Even though nest survival rates recorded for the Campo Miner were high compared to other tropical grassland passerines, our study points to some management strategies that can be adopted if the breeding success proves to be low somewhere. These strategies include the excavation of artificial cavities along the soil banks to support secondary cavity-nesting species. This management strategy might reduce the risk of cavity usurpation by swallows, indirectly benefiting the Campo Miner, because the species usually excavate the nest-cavities themselves (Machado *et al.* 2017). Additionally, as this is a demanding species in terms of nesting sites (Meireles *et al.* 2018), the opening of new steep soil banks can benefit the Campo Miner in grassland areas where nesting sites are scarce or unavailable.

REFERENCES

- Aitken, K. E. H. & Martin, K. (2007). The importance of excavators in hole-nesting communities: availability and use of natural tree holes in old mixed forests of western Canada. *Journal of Ornithology* 148, 425–434.
- Alvares, C. A., Stape, J. L., Sentelhas, P. C., de Moraes Gonçalves, J. L. & G. Sparovek. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* 22, 711–728.
- Arnold, T. W. (2010). Uninformative parameters and model selection using Akaike's Information Criterion. *Journal of Wildlife Management* 74, 1175–1178.
- Azevedo, L. G. (1962). Tipos de vegetação do Sul de Minas e Campos da Mantiqueira (Brasil). *Anais da Academia Brasileira de Ciências* 34, 225–234.
- Bednarz, J. C., Ripper, D. & Radley, P. M. (2004). Emerging concepts and research directions in the study of cavity-nesting birds: keystone ecological process. *The Condor* 106, 1–4.
- Bennett, A. F. (1990). Thermal dependence of locomotor capacity. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* 259, R253–R258.
- BirdLife International (2020). Species factsheet: *Geositta poecilopectera*. <http://datazone.birdlife.org/species/factsheet/campo-miner-geositta-poecilopectera>. Accessed 13.03.2020.
- Botero-Delgado, E., Poblete, Y. & Vásquez, R. A. (2015). Nestling mortality as a consequence of interspecific competition between secondary cavity nesters in the sub-Antarctic forests of Chile. *The Wilson Journal of Ornithology* 127, 131–134.
- Burnham, K. P. & Anderson, D. R. (2002). *Model selection and multimodel inference: a practical information-theoretic approach*. Springer-Verlag, New York, NY.

- Castellarini, F., Agnelli, H. L. & Polop, J. J. (1998). Study on the diet and feeding preferences of *Calomys venustus* (Rodentia, Muridae). *Mastozoología Neotropical* 51, 5–11.
- CEMAVE (2018). *Geositta poecilopectera* (Wied, 1830). Pp. 408-410. in Instituto Chico Mendes de Conservação da Biodiversidade, eds. Livro Vermelho da Fauna Brasileira Ameaçada de Extinção, vol. 3, Aves. ICMBio, Brasília, BR.
- Chiarani, E. & Fontana, C. S. (2015). Breeding biology of the Lesser Grass-finch (*Emberizoides ypiranganus*) in southern Brazilian upland grasslands. *The Wilson Journal of Ornithology* 127, 441–456.
- Cockle, K. L., Bodrati, A., Lammertink, M. & Martin, K. (2015). Cavity characteristics, but not habitat, influence nest survival of cavity-nesting birds along a gradient of human impact in the subtropical Atlantic Forest. *Biological Conservation* 184, 193–200.
- Collias, N. E. & Collias, E. C. (1984). Nest building and bird behavior. Princeton Legacy Library, New Jersey, NJ.
- Coombs, A.B., Bowman, J. & Garroway C.J. (2010). Thermal properties of tree cavities during winter in a northern hardwood forest. *The journal of Wildlife Management* 74, 1875–1881.
- Dellafiore, C. M. & Polop, J. J. (1994). Feeding habits of *Calomys musculinus* in the crop fields and its borders. *Mastozoología Neotropical* 1, 45–50.
- Dinsmore, S. J. & Dinsmore, J. J. (2007). Modeling avian nest survival in program MARK. *Studies in Avian Biology* 34, 73–83.
- Eskew, E. A. & Todd, B. D. (2017). Too cold, too wet, too bright, or just right? Environmental predictors of snake movement and activity. *Copeia* 104, 584–591.
- Fry, C.H. (2001). Family Meropidae (Bee-eaters). Pp. 286–341. in J. del Hoyo, A. Elliott & J. Sargatal (Eds). *Handbook of the birds of the World*, vol. 6, Mousebirds to Hornbills. Barcelona, Spain, Lynx Edicions.

- Gaiarsa, M. P., Alencar, L. R. V. & Martins, M. (2013). Natural history of Pseudoboine snakes. *Papéis Avulsos de Zoologia* 53, 261–283.
- Gómez, L. (2019). Biología reproductiva de *Geositta peruviana* (Passeriformes: Furnariidae) en la zona reservada Lomas de Ancón, Lima-Perú. Thesis to opt for the Professional Title of Biologist with a mention in Zoology. Universidad Nacional Mayor de San Marcos, Lima, Peru.
- Gressler, D. T. & Marini, M. Â. (2015). Striped-tailed Yellow-finch nesting success in abandoned mining pits from central Brazilian Cerrado. *Brazilian Journal of Biology* 75, 191–197.
- Hansell, M. (2000). Bird nests and construction behavior. Cambridge University Press, Cambridge, UK.
- IBGE. (2004). Mapa de Vegetação do Brasil, Escala 1:5.000.000. Instituto Brasileiro de Geografia e Estatística, Brasília.
- ICMBio. (2021). Sumário executivo do plano de ação nacional para a conservação de aves do cerrado e pantanal. <https://www.icmbio.gov.br/portal/faunabrasileira/plano-de-acao-nacional-lista/3618-plano-de-acao-nacional-para-a-conservacao-das-aves-do-cerrado-e-pantanal>. Accessed 10.01.2021.
- INMET. (2021). Instituto Nacional de Meteorologia. <https://portal.inmet.gov.br/>. Accessed 15.02.2021.
- Ke, D. & Lu, X. (2009). Burrow use by Tibetan Ground Tits *Pseudopodoces humilis*: coping with life at high altitudes. *The Ibis* 151, 321–331.
- Li, P. & Martin, T. E. (1991). Nest-site selection and nesting success of cavity-nesting birds in high elevation forest drainages. *The Auk* 108, 405–418.
- Lindell, C. (1996). Patterns of nest usurpation: when should species converge on nest niches? *The Condor* 98, 464–473.
- Lopes, L. E., Malacco, G. B., Alteff, E. F., Vasconcelos, M. F., Hoffmann, D. & Silveira,

- L. F. (2010). Range extensions and conservation of some threatened or little-known Brazilian grassland birds. *Bird Conservation International* 20, 84–94.
- Lopes, L. E., Teixeira, J. P. G., Meireles, R. C., Bastos, D. S. S., Oliveira, L. L. & Solar, R. (2021). High seasonal variation of plasma testosterone levels for a tropical grassland bird resembles patterns of temperate birds. *Physiological and Biochemical Zoology* 94, 143–151.
- Machado, T. L. S. S., Lombardi, V. T., Meireles, R. C., Teixeira, J. P. G., Solar, R. & Lopes, L. E. (2017). Breeding biology of the threatened Campo Miner (*Geositta poeciloptera* (Aves: Scleruridae), a Neotropical grassland specialist. *Journal of Natural History* 51, 1–13.
- Marini, M. Â. & Melo, C. (1998). Predators of quail eggs, and the evidence of the remains: implications for nest predation studies. *The Condor* 100, 395–399.
- Marini, M. Â., Barbet-Massin, M., Lopes, L.E. & Jiguet, F. (2009a). Predicted climate-driven bird distribution changes and forecasted conservation conflicts in a Neotropical savanna. *Conservation Biology* 23, 1558–1567.
- Marini, M. Â., Barbet-Massin, M., Lopes, L. E. & Jiguet, F. (2009b). Major current and future gaps of Brazilian reserves to protect Neotropical savanna birds. *Biological Conservation* 142, 3039–3050.
- Marini, M. Â., Duca, C. & Manica, L. T. (2010). Técnicas de pesquisa em biologia reprodutiva de aves. Pp 295–312 in S. Von Matter, F. C. Straube, I. Accordi, V. Piacentini, & J. F. Cândido-Jr (Eds). *Ornitologia e Conservação: Ciência Aplicada, Técnicas de Pesquisa e Levantamento* (pp. 295-312). Technical Books, Rio de Janeiro, BR.
- Martin, T. E. & Li, P. (1992). Life history traits of open- vs. cavity-nesting birds. *Ecology* 73, 579–592.
- Meireles, R. C., Teixeira, J. P. G., Solar, R., Vasconcelos, B. N. F., Fernandes, R. B. A. & Lopes, L. E. (2018). Soil attributes drive nest-site selection by the Campo Miner *Geositta poeciloptera*. *PLoS ONE* 13, e0192185.

- Miller, K. E. (2002). Nesting success of Great Crested Flycatcher in nest boxes and in tree cavities: are nest boxes safer from nest predation? *The Wilson Bulletin* 114, 179–185.
- Moors, P. J. (1983). Predation by mustelids and rodents on the eggs and chicks of native and introduced birds in Kowhai Bush, New Zealand. *The Ibis* 125, 137–154.
- Mwangi, J., Ndithia, H. K., Kentie, R., Muchai, M. & Tieleman, B. I. (2018). Nest survival in year-round breeding tropical Red-capped Larks *Calandrella cinerea* increases with higher nest abundance but decreases with higher invertebrate availability and rainfall. *Journal of Avian Biology* 49, e01645.
- Myers, N., Mittermeier, R. A., Mittermeier, C. G., Fonseca, G. A. B. & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature* 403, 853–858.
- Nilsson, S. G. (1984). The evolution of nest-site selection among hole-nesting birds: The importance of nest predation and competition. *Ornis Scandinavica* 15, 167–175.
- Otterbeck, A., Selås, V., Tøttrup Nielsen, J. T., Roualet, E. & Lindén, A. (2019). The paradox of nest reuse: early breeding benefits reproduction, but nest reuse increases nest predation risk. *Oecologia* 190, 559–568.
- Paclik, M., Misik, J. & Weidinger, K. (2009). Nest predation and nest defence in European and North American woodpeckers: a review. *Annales Zoologici Fennici* 46, 361–379.
- Pereira, J. A. (1937). *Miscelánea ornitológica*. *Hornero* 6, 437-449.
- Remsen, J. V. Jr. (2020). Ovenbirds. In *Handbook of the Birds of the World Alive*. In J. del Hoyo, A. Elliott, J. Sargatal, D.A Christie, & de E. Juana (Eds.). Lynx Edicions, Barcelona. <https://www.hbw.com/node/52289>. Accessed 13.03.2020.
- Rendell, W. B. & Robertson, R. J. (1989). Nest-site characteristics, reproductive success and cavity availability for Tree Swallows breeding in natural cavities. *The Condor* 91, 875–885.

- Repenning, M. & Fontana, C. S. (2016). Breeding biology of the Tropeiro Seedeater. *The Auk: Ornithological Advances* 133, 484–496.
- Ricklefs, R. E. (1969). An analysis of nesting mortality in birds. *Smithsonian Contributions to Zoology* 9, 1–48.
- Ridgely, R. S. & Tudor, G. (2009). *Field guide to the songbirds of South America: The Passerines*. University of Texas Press, Austin, TX.
- Robertson, R. J. & Rendell, W. B. (1990). A comparison of the breeding ecology of a secondary cavity nesting bird, the Tree Swallow (*Tachycineta bicolor*), in nest boxes and natural cavities. *Canadian Journal of Zoology* 68, 1046–1052.
- Roper, J. J. & Goldstein, R. R. (1997). A test of the Skutch hypothesis: does activity at nests increase nest predation rates? *Journal of Avian Biology* 28, 111–116.
- Rotella, J. J., Dinsmore, S. J. & Shaffer, T. L. (2004). Modeling nest survival data: a comparison of recently developed methods that can be implemented in Mark and SAS. *Animal Biodiversity and Conservation* 27, 187–205.
- Sá Júnior A, Carvalho, L. G., Silva, F. F. & Alves, M. C. (2012). Application of the Köppen classification for climatic zoning in the state of Minas Gerais, Brazil. *Theoretical Applied Climatology*. 108, 1–7.
- Seixas, G. H. F. & Mourão G. M. (2002). Nesting success and hatching survival of the Blue-fronted Amazon (*Amazona aestiva*) in the Pantanal of Mato Grosso do Sul, Brazil. *Journal of Field Ornithology* 73, 399–409.
- Sick, H. (1997). *Ornitologia brasileira: uma introdução*. Nova Fronteira, Rio de Janeiro, BR.
- Skutch, A. F. (1949). Do tropical birds rear as many young as they can nourish? *The Ibis* 91,430–455.
- Skutch, A. F. (1985). Clutch size, nesting success, and predation on nests of neotropical birds, reviewed. *Ornithological Monographs* 36, 575–594.

- Teunissen, W., Schekkerman, H., Willems, F. & Majoor, F. (2008). Identifying predators of eggs and chicks of Lapwing *Vanellus vanellus* and Godwit *Limosa limosa* in the Netherlands and the importance of predation on wader reproductive. *The Ibis* 150, 74–85.
- White, G. C. & Burnham, K. P. (1999). Program MARK: survival estimation from populations of marked animals. *Bird Study* 46, 120–138.
- Woodall, P.F. (2001). Family Alcedinidae (Kingfishers). in J. del Hoyo, A. Elliott & J. Sargatal (Eds). *Handbook of the birds of the World*, vol. 6, Mousebirds to Hornbills. (pp. 130–249). Barcelona, Spain, Lynx Edicions.

Supplementary material

Data used to generate results for Meireles *et al.* 2021. Nest survival of the threatened Campo Miner *Geositta poecilopectera*: a tropical cavity-nesting grassland bird. *Austral Ecology*

Here we include all the data used in this chapter.

1) Monitored nests data.

Incubation (ID) 2014	date.First Found	date.Last Present	date.Last Checked	Fate	Distance to the cavity from the top (cm)	Cavity Height (cm)	Cavity Area (cm ²)	Cavity Depth (cm)
N1	14	31	31	0	9	89	46.91	33
N2	16	33	33	0	30	60	84.78	51.5
N3	19	33	33	0	8.5	51	38.27	40
N4	19	28	29	1	185	119	59.66	53.5
N5	36	44	44	0	64	90	98.91	63.5
N6	43	60	60	0	10	39	27.48	35
N7	43	47	51	1	185	119	59.66	53.5
N8	43	46	47	1	113	47	32.97	34
N9	45	51	51	0	18	34	51.03	40.5
N10	45	47	48	1	57	46	70.65	43.5
N11	45	48	51	1	26.5	37	63.39	33.5
N12	46	58	58	0	47	41	69.08	29.5
N13	43	60	61	1	26	87	55.93	60
N14	53	70	70	0	89	58	90.08	40
N17	60	75	75	0	37	86	28.06	35.5
N18	71	88	88	0	20	39	56.52	38.5
N19	79	94	94	0	49	94	67.12	30

N20	81	98	98	0	202	134	38.27	38.5
N21	82	99	99	0	61	43	30.62	30
N22	83	100	100	0	16	87	35.72	48
N23	85	102	102	0	26	87	55.93	60
N24	106	113	114	1	51.5	53	22.96	46
N25	113	130	131	1	24	30	35.33	35
N26	114	131	132	1	57	98	25.51	40
Nestlings (ID) 2014	date.First Found	date.Last Present	date.Last Checked	Fate	Distance to the cavity from the top (cm)	Cavity Height (cm)	Cavity Area (cm²)	Cavity Depth (cm)
N1	32	47	47	0	9	89	46.91	33
N2	34	48	48	0	30	60	84.78	51.5
N3	34	47	47	0	8.5	51	38.27	40
N5	45	59	59	0	64	90	98.91	63.5
N6	61	76	76	0	10	39	27.48	35
N9	52	68	68	0	18	34	51.03	40.5
N12	59	74	74	0	47	41	69.08	29.5
N14	71	85	85	0	89	58	90.08	40
N15	53	54	54	0	40.5	78	23.55	38
N16	56	69	69	0	15	25	86.35	34.5
N17	76	91	91	0	37	86	28.06	35.5
N18	89	93	94	1	20	39	56.52	38.5
N19	95	110	110	0	49	94	67.12	30
N20	100	115	115	0	202	134	38.27	38.5
N21	100	103	104	1	61	43	30.62	30
N22	101	116	117	0	16	87	35.72	48
N23	103	115	115	0	26	87	55.93	60
Incubation (ID) 2015	date.First Found	date.Last Present	date.Last Checked	Fate	Distance to the cavity from the top (cm)	Cavity Height (cm)	Cavity Area (cm²)	Cavity Depth (cm)
N1	1	8	8	0	19.5	26	69.08	42
N2	1	14	14	0	23	119	94.2	42

N3	2	9	9	0	57.5	86	84.78	49
N4	18	29	35	1	78	30.5	62.8	58
N7	20	29	35	1	9	31	122.46	61
N8	29	34	34	0	61.5	87	62.8	40
N9	29	38	38	0	23	73	37.68	42
N10	29	44	44	0	38	75	50.24	39
N11	29	46	47	1	63	85	70.65	30
N12	32	35	39	1	50	98	94.98	39
N13	35	52	52	0	38	47	43.96	48
N14	38	45	49	1	36	44	77.71	40
N15	42	59	59	0	65	54	62.8	42
N16	42	59	60	1	58	45	77.71	33
N18	52	69	71	1	54	87	131.88	65
N20	65	69	72	1	14	89	56.52	38
N21	65	66	66	0	21	73	77.71	59
N22	65	74	74	0	46	99	56.52	52
N23	80	90	93	1	300	157	94.2	37
N24	85	102	102	0	36	68	47.1	34
N25	86	103	103	0	46	124	77.72	41
Nestlings (ID) 2015	date.First Found	date.Last Present	date.Last Checked	Fate	Distance to the cavity from the top (cm)	Cavity Height (cm)	Cavity Area (cm2)	Cavity Depth (cm)
N1	9	20	20	0	19.5	26	69.08	42
N2	15	29	29	0	23	119	94.2	42
N3	10	20	20	0	57.5	86	84.78	49
N5	30	38	38	0	65	64	62.8	40
N6	20	22	23	1	31	42	197.82	73
N8	35	45	45	0	61.5	87	62.8	40
N9	39	52	52	0	23	73	37.68	42
N10	45	60	60	0	38	75	50.24	39
N13	53	68	68	0	38	47	43.96	48

N15	60	73	73	0	65	54	62.8	42
N17	52	56	56	0	35	94	56.52	39
N19	52	56	56	0	18	35	50.24	44
N21	67	80	80	0	21	73	77.71	59
N22	75	90	90	0	46	99	56.52	52
N24	103	113	116	1	36	68	47.1	34
N25	103	116	116	0	46	124	77.72	41
Incubation (ID) 2016	date.First Found	date.Last Present	date.Last Checked	Fate	Distance to the cavity from the top (cm)	Cavity Height (cm)	Cavity Area (cm2)	Cavity Depth (cm)
N1	16	33	33	0	15	82	32.97	40
N2	19	36	37	1	6	63	43.96	40
N3	21	32	32	0	39	52	43.96	41
N4	21	38	38	0	50	98	94.99	39
N5	26	43	43	0	41	150	60.45	42
N6	28	42	42	0	42	96.5	50.24	31
N7	30	38	38	0	71	198	91.85	64
N8	33	50	50	0	23	32	28.26	41
N9	33	50	50	0	35	94	56.52	39
N10	36	50	50	0	26	45	56.52	36
N11	36	53	53	0	38	43	94.2	48
N12	39	55	55	0	93	87	43.96	42
N13	43	60	61	1	55	71	32.97	44
N14	46	53	53	0	38	39	37.68	35
N15	57	64	66	1	22	73	70.65	39
N16	64	80	80	0	115	111	49.46	44
N17	64	81	81	0	55	74	32.97	37
N18	69	86	86	0	26	53	43.96	51
N19	69	84	84	0	18	52	67.12	36
Nestlings (ID) 2016	date.First Found	date.Last Present	date.Last Checked	Fate	Distance to the cavity from the top (cm)	Cavity Height (cm)	Cavity Area (cm2)	Cavity Depth (cm)

N1	34	49	49	0	15	82	32.97	40
N3	33	48	48	0	39	52	43.96	41
N4	39	54	54	0	50	98	94.99	39
N5	44	59	59	0	41	150	60.45	42
N6	43	58	58	0	42	96.5	50.24	31
N7	39	54	54	0	71	198	91.85	64
N8	51	64	64	0	23	32	28.26	41
N9	51	64	64	0	35	94	56.52	39
N10	51	66	66	0	26	45	56.52	36
N11	54	56	61	1	38	43	94.2	48
N12	56	71	71	0	93	87	43.96	42
N14	54	69	69	0	38	39	37.68	35
N16	81	94	94	0	115	111	49.46	44
N17	82	97	97	0	55	74	32.97	37
N18	87	101	101	0	26	53	43.96	51
N19	85	97	97	0	18	52	67.12	36
Incubation (ID) 2019	date.First Found	date.Last Present	date.Last Checked	Fate	Distance to the cavity from the top (cm)	Cavity Height (cm)	Cavity Area (cm²)	Cavity Depth (cm)
N1	24	41	42	1	33	48	70.65	34
N2	26	43	43	0	31	42	54.95	53
N3	30	47	47	0	108	71	43.96	54
N4	30	46	47	1	25	33	75.36	44
N5	32	46	47	1	36	114	43.96	39
N6	35	47	47	0	45	85	94.2	41
N7	38	55	55	0	213	90	77.71	50
N8	46	54	55	1	135	133	122.46	64
N9	51	55	56	1	82	92	103.62	42
N10	51	68	70	1	38	93	43.96	41
N11	55	64	66	1	25	42	62.8	52
N12	68	84	84	0	88	36	50.24	38

N13	81	94	94	0	66	120	32.97	44
N15	91	108	108	0	51	53	28.26	39
N16	91	108	109	1	213	90	77.71	50
Nestlings (ID) 2019	date.First Found	date.Last Present	date.Last Checked	Fate	Distance to the cavity from the top (cm)	Cavity Height (cm)	Cavity Area (cm²)	Cavity Depth (cm)
N2	44	59	59	0	31	42	54.95	53
N3	48	63	63	0	108	71	43.96	54
N6	48	63	63	0	45	85	94.2	41
N7	56	71	71	0	213	90	77.71	50
N12	85	96	97	1	88	36	50.24	38
N13	95	102	104	1	66	120	32.97	44
N14	81	91	91	0	36	114	43.96	39
N15	109	124	124	0	51	53	28.26	39

Incubation and Nestlings (ID) = Nest phases for each year; date.First Found = The day the nest was found ; date.LastPresent = The last day the nest was checked alive; date.Last Checked = The last day the nest was checked; Fate = 0 (Successful); Fate = 1 (Failed)

2) Average daily rainfall data.

Date (2014)	rainfall (mm)	Date (2015)	rainfall (mm)	Date (2016)	rainfall (mm)	Date (2019)	rainfall (mm)
2014-08-18	13.2	2015-08-18	0	2016-08-18	0.2	2019-08-18	0
2014-08-19	0	2015-08-19	0	2016-08-19	0	2019-08-19	0
2014-08-20	0	2015-08-20	0.4	2016-08-20	0	2019-08-20	0
2014-08-21	0	2015-08-21	0.2	2016-08-21	1.6	2019-08-21	10.8
2014-08-22	0.2	2015-08-22	1	2016-08-22	2.6	2019-08-22	0
2014-08-23	0	2015-08-23	0	2016-08-23	0	2019-08-23	0
2014-08-24	0	2015-08-24	0.2	2016-08-24	0	2019-08-24	0
2014-08-25	0	2015-08-25	0	2016-08-25	0	2019-08-25	0
2014-08-26	0	2015-08-26	14.4	2016-08-26	0.2	2019-08-26	0
2014-08-27	0	2015-08-27	0.2	2016-08-27	0	2019-08-27	0
2014-08-28	0.2	2015-08-28	0	2016-08-28	0	2019-08-28	0
2014-08-29	3.6	2015-08-29	0	2016-08-29	0	2019-08-29	0
2014-08-30	0	2015-08-30	0	2016-08-30	0	2019-08-30	0
2014-08-31	0	2015-08-31	0.2	2016-08-31	0	2019-08-31	0
2014-09-01	1.2	2015-09-01	0	2016-09-01	6.8	2019-09-01	0
2014-09-02	0.4	2015-09-02	0	2016-09-02	0.2	2019-09-02	0
2014-09-03	12.4	2015-09-03	0	2016-09-03	0	2019-09-03	0
2014-09-04	0.2	2015-09-04	0	2016-09-04	0	2019-09-04	0
2014-09-05	0	2015-09-05	0.2	2016-09-05	0	2019-09-05	0
2014-09-06	0	2015-09-06	9.8	2016-09-06	0	2019-09-06	0
2014-09-07	0	2015-09-07	49.4	2016-09-07	0	2019-09-07	0
2014-09-08	0	2015-09-08	10.6	2016-09-08	6.6	2019-09-08	0
2014-09-09	0	2015-09-09	50.6	2016-09-09	0.2	2019-09-09	0
2014-09-10	0	2015-09-10	3	2016-09-10	0	2019-09-10	0
2014-09-11	0	2015-09-11	13	2016-09-11	0	2019-09-11	0
2014-09-12	0	2015-09-12	26.4	2016-09-12	0	2019-09-12	0
2014-09-13	0	2015-09-13	14.4	2016-09-13	0	2019-09-13	0
2014-09-14	0	2015-09-14	0.4	2016-09-14	0	2019-09-14	0
2014-09-15	0	2015-09-15	0	2016-09-15	0	2019-09-15	0
2014-09-16	0	2015-09-16	0	2016-09-16	0.4	2019-09-16	0
2014-09-17	0	2015-09-17	0.2	2016-09-17	0	2019-09-17	0
2014-09-18	0	2015-09-18	0	2016-09-18	0.4	2019-09-18	0
2014-09-19	0	2015-09-19	0	2016-09-19	0	2019-09-19	0
2014-09-20	0	2015-09-20	0	2016-09-20	1.4	2019-09-20	0
2014-09-21	0.4	2015-09-21	0	2016-09-21	0	2019-09-21	0
2014-09-22	0.4	2015-09-22	0	2016-09-22	0	2019-09-22	0
2014-09-23	0	2015-09-23	0	2016-09-23	0	2019-09-23	0
2014-09-24	0	2015-09-24	0	2016-09-24	0	2019-09-24	0
2014-09-25	0	2015-09-25	0	2016-09-25	18	2019-09-25	16.6
2014-09-26	0	2015-09-26	0	2016-09-26	8	2019-09-26	29.4
2014-09-27	0	2015-09-27	0	2016-09-27	0	2019-09-27	20
2014-09-28	0.2	2015-09-28	0	2016-09-28	0	2019-09-28	0

Date (2014)	rainfall (mm)	Date (2015)	rainfall (mm)	Date (2016)	rainfall (mm)	Date (2019)	rainfall (mm)
2014-09-29	0	2015-09-29	0	2016-09-29	0	2019-09-29	0
2014-09-30	0	2015-09-30	0.4	2016-09-30	0	2019-09-30	0
2014-10-01	0	2015-10-01	2.2	2016-10-01	0	2019-10-01	0
2014-10-02	1.2	2015-10-02	4.4	2016-10-02	0	2019-10-02	0
2014-10-03	0	2015-10-03	17	2016-10-03	0	2019-10-03	0
2014-10-04	0	2015-10-04	0	2016-10-04	20.8	2019-10-04	0
2014-10-05	0	2015-10-05	0	2016-10-05	9.8	2019-10-05	0
2014-10-06	0	2015-10-06	0	2016-10-06	9	2019-10-06	0
2014-10-07	0	2015-10-07	0	2016-10-07	5	2019-10-07	0
2014-10-08	0	2015-10-08	0	2016-10-08	0	2019-10-08	0.6
2014-10-09	0	2015-10-09	0	2016-10-09	0	2019-10-09	17.8
2014-10-10	0	2015-10-10	0	2016-10-10	0	2019-10-10	26.8
2014-10-11	0	2015-10-11	0	2016-10-11	0.2	2019-10-11	0.6
2014-10-12	0	2015-10-12	0	2016-10-12	0	2019-10-12	0
2014-10-13	0	2015-10-13	0	2016-10-13	1.2	2019-10-13	0
2014-10-14	0	2015-10-14	0	2016-10-14	11.6	2019-10-14	0
2014-10-15	0	2015-10-15	0	2016-10-15	0	2019-10-15	0
2014-10-16	0	2015-10-16	0	2016-10-16	2	2019-10-16	0
2014-10-17	0	2015-10-17	0	2016-10-17	0.2	2019-10-17	0
2014-10-18	0.8	2015-10-18	0	2016-10-18	0	2019-10-18	0
2014-10-19	4.4	2015-10-19	0	2016-10-19	34.2	2019-10-19	0
2014-10-20	12.8	2015-10-20	0	2016-10-20	0	2019-10-20	3.6
2014-10-21	15.6	2015-10-21	0	2016-10-21	2.6	2019-10-21	0
2014-10-22	0	2015-10-22	0	2016-10-22	19.2	2019-10-22	2.6
2014-10-23	0	2015-10-23	16	2016-10-23	0	2019-10-23	0
2014-10-24	0	2015-10-24	0	2016-10-24	0	2019-10-24	0
2014-10-25	0	2015-10-25	0	2016-10-25	0	2019-10-25	0
2014-10-26	17.6	2015-10-26	0	2016-10-26	1.4	2019-10-26	4.2
2014-10-27	4	2015-10-27	10.2	2016-10-27	0	2019-10-27	0
2014-10-28	0	2015-10-28	36.8	2016-10-28	3.8	2019-10-28	0.2
2014-10-29	0	2015-10-29	0.8	2016-10-29	0	2019-10-29	16
2014-10-30	0	2015-10-30	0	2016-10-30	0	2019-10-30	2.2
2014-10-31	0	2015-10-31	0	2016-10-31	0	2019-10-31	1.6
2014-11-01	1.4	2015-11-01	0	2016-11-01	0	2019-11-01	0
2014-11-02	11.2	2015-11-02	99.2	2016-11-02	6.8	2019-11-02	3
2014-11-03	0	2015-11-03	0.6	2016-11-03	0	2019-11-03	0
2014-11-04	0	2015-11-04	0.4	2016-11-04	84.6	2019-11-04	0.2
2014-11-05	0	2015-11-05	0	2016-11-05	12.8	2019-11-05	0
2014-11-06	1.4	2015-11-06	0	2016-11-06	8.2	2019-11-06	0
2014-11-07	1.8	2015-11-07	0	2016-11-07	0	2019-11-07	28.8
2014-11-08	5.2	2015-11-08	29	2016-11-08	4	2019-11-08	29.2
2014-11-09	0	2015-11-09	33	2016-11-09	0	2019-11-09	0
2014-11-10	3.4	2015-11-10	4.4	2016-11-10	3.8	2019-11-10	6
2014-11-11	0	2015-11-11	0.2	2016-11-11	0.2	2019-11-11	0
2014-11-12	0	2015-11-12	0	2016-11-12	0.4	2019-11-12	25.6

Date (2014)	rainfall (mm)	Date (2015)	rainfall (mm)	Date (2016)	rainfall (mm)	Date (2019)	rainfall (mm)
2014-11-13	29	2015-11-13	0.2	2016-11-13	15.2	2019-11-13	0
2014-11-14	7.8	2015-11-14	1.8	2016-11-14	43.6	2019-11-14	18.2
2014-11-15	17	2015-11-15	0.2	2016-11-15	70.4	2019-11-15	35
2014-11-16	0.2	2015-11-16	4.2	2016-11-16	1.4	2019-11-16	6.8
2014-11-17	0	2015-11-17	29.2	2016-11-17	0.4	2019-11-17	0
2014-11-18	0	2015-11-18	18	2016-11-18	10.4	2019-11-18	0
2014-11-19	0	2015-11-19	1.4	2016-11-19	9	2019-11-19	1.2
2014-11-20	0	2015-11-20	29.2	2016-11-20	0	2019-11-20	3
2014-11-21	0	2015-11-21	2.8	2016-11-21	0	2019-11-21	13.6
2014-11-22	0	2015-11-22	4.8	2016-11-22	0	2019-11-22	0
2014-11-23	24	2015-11-23	13.4	2016-11-23	16.2	2019-11-23	5.4
2014-11-24	55.2	2015-11-24	35.6	2016-11-24	22.8	2019-11-24	15.4
2014-11-25	0.8	2015-11-25	0.6	2016-11-25	0	2019-11-25	0.2
2014-11-26	1	2015-11-26	0.4	2016-11-26	0	2019-11-26	0
2014-11-27	51.6	2015-11-27	0.2	2016-11-27	0	2019-11-27	0
2014-11-28	48	2015-11-28	0.2	2016-11-28	0.2	2019-11-28	0
2014-11-29	38.8	2015-11-29	0	2016-11-29	0	2019-11-29	68
2014-11-30	7.6	2015-11-30	41.6	2016-11-30	43.2	2019-11-30	1.4
2014-12-01	2.2	2015-12-01	15.4	2016-12-01	0	2019-12-01	1
2014-12-02	2.8	2015-12-02	0.6	2016-12-02	0.8	2019-12-02	8.4
2014-12-03	0.8	2015-12-03	70.2	2016-12-03	0	2019-12-03	0
2014-12-04	0	2015-12-04	21.8	2016-12-04	5.8	2019-12-04	0
2014-12-05	8.2	2015-12-05	45.2	2016-12-05	23.2	2019-12-05	5.2
2014-12-06	0	2015-12-06	4.4	2016-12-06	0.4	2019-12-06	5
2014-12-07	0.2	2015-12-07	16	2016-12-07	0	2019-12-07	22.4
2014-12-08	0	2015-12-08	9.2	2016-12-08	0.2	2019-12-08	0
2014-12-09	0	2015-12-09	1.6	2016-12-09	3.4	2019-12-09	0
2014-12-10	0	2015-12-10	3.2	2016-12-10	33.2	2019-12-10	8.2
2014-12-11	0	2015-12-11	2	2016-12-11	16.4	2019-12-11	14.4
2014-12-12	0	2015-12-12	4.6	2016-12-12	3.2	2019-12-12	11
2014-12-13	19	2015-12-13	7.6	2016-12-13	7.8	2019-12-13	0
2014-12-14	14.2	2015-12-14	1.6	2016-12-14	19	2019-12-14	37.2
2014-12-15	13	2015-12-15	0	2016-12-15	6.6	2019-12-15	0
2014-12-16	0	2015-12-16	29.2	2016-12-16	27.6	2019-12-16	0
2014-12-17	0	2015-12-17	0	2016-12-17	0	2019-12-17	0
2014-12-18	0	2015-12-18	21.2	2016-12-18	0	2019-12-18	0
2014-12-19	1.8	2015-12-19	0.2	2016-12-19	0	2019-12-19	0
2014-12-20	0.8	2015-12-20	2	2016-12-20	0	2019-12-20	0.6
2014-12-21	2.2	2015-12-21	3.2	2016-12-21	0	2019-12-21	16.8
2014-12-22	0.2	2015-12-22	0	2016-12-22	0	2019-12-22	1.6
2014-12-23	0.6	2015-12-23	0	2016-12-23	0	2019-12-23	19
2014-12-24	13.4	2015-12-24	0	2016-12-24	0	2019-12-24	15
2014-12-25	0.2	2015-12-25	22.2	2016-12-25	0.4	2019-12-25	0.8
2014-12-26	0.2	2015-12-26	9	2016-12-26	1	2019-12-26	0

Chapter II: The future of suitable habitats of an endangered Neotropical grassland bird: a path to extinction?

RESUMO

As mudanças climáticas e seus efeitos terríveis preocupam cada vez mais pesquisadores e formuladores de políticas, e podem ter impactos irreversíveis na biodiversidade do planeta. Não diferente de outras fitofisionomias, os campos naturais sofrem os efeitos do aumento das temperaturas, causando perdas e reestruturação de comunidades animais e vegetais. As aves, por serem muito sensíveis a essas mudanças, são amplamente estudadas e fundamentais para entender a dinâmica dos ecossistemas em relação ao clima. O Mineiro do Campo é uma ave campestre do Cerrado brasileiro e ameaçada de extinção que vem sendo amplamente estudada nos últimos anos. Aqui, analisamos a diminuição de sua extensão de ocorrência (EOO) e os efeitos de diferentes cenários de mudanças climáticas para entender a adequação ambiental da espécie no presente e no futuro. Para isso, utilizamos 6 algoritmos comuns para produzir modelos de nicho ecológico, com 10 repetições para cada um. Para previsões futuras, usamos dois Modelos Gerais de Circulação (GCM) para dois períodos diferentes (2041-2060 e 2061-2080) e dois cenários diferentes de emissões de gases de efeito estufa com diferentes políticas climáticas, sendo um otimista (ssp245) e um pessimista (ssp585). A EOO atual apresentou uma redução de área de ~38,8% daquela apresentada pela EOO da IUCN. Os modelos gerados para o presente foram satisfatórios (TSS = 0,83 e ROC = 0,92) e mostraram alta adequação ambiental em áreas onde a espécie é encontrada atualmente e baixa adequação onde já está extinta. Ambos os cenários revelaram uma diminuição das áreas aptas para a espécie no futuro, mas os modelos de maior aumento de temperatura foram mais preocupantes. Nossos resultados reforçam a necessidade de olhar com cuidado sobre a disparidade de consciência do bioma e a importância de preservar ativamente as áreas gramíneas-arbustivas. Aparentemente, o estado de Minas Gerais será o único reduto da espécie nos próximos anos, porém, a falta de áreas protegidas que garantam sua sobrevivência precisa ser considerada.

Palavras-chave: andarilho, Cerrado, mudanças globais, espécies ameaçadas.

ABSTRACT

Climate change and its dire effects increasingly worry researchers and policy-makers, and may have irreversible impacts on planet biodiversity. No different from other phytophysognomies, natural grasslands suffer from the effects of rising temperatures, causing losses and restructuring of animal and plant communities. Birds, being very sensitive to these changes, are widely studied and fundamental to understand the dynamics of ecosystems in relation to climate. The Campo Miner is a grassland bird of the Brazilian Cerrado and threatened with extinction that has been widely studied in recent years. Here, we analyze the decrease in its extent of occurrence (EOO) and the effects of different climate change scenarios to understand the environmental suitability of the species in the present and future. For this, we used 6 common algorithms to produce ecological niche models, with 10 repetitions for each one. For future predictions, we use two General Circulation Models (GCM) for two different periods (2041-2060 and 2061-2080) and two different greenhouse gas emissions scenarios with different climate policies with an optimistic one (ssp245) and, a pessimist (ssp585). The current EOO presented an area reduction of ~38,8% of that presented by the IUCN EOO. The models generated for the present were satisfactory (TSS = 0.83 and ROC = 0.92) and showed high environmental suitability in areas where the species is currently found and low suitability where it is already extinct. Both scenarios revealed a decrease in suitable areas for the species in the future, but the models of greater temperature increase were more worrisome. Our results reinforce the need to look carefully over biome awareness disparity, and the importance of actively preserving grassy-shrub areas. Apparently, the state of Minas Gerais will be the only stronghold of the species in the coming years, however, the lack of protected areas that guarantee its survival needs to be considered.

Keywords: Campo Miner, Cerrado, Global Changes, threatened species.

1. INTRODUCTION

Climate change has been a recurring concern among researchers and policy-makers in recent years. According to the latest report of the Intergovernmental Panel on Climate Change, the world may experience an alarming increase in temperature, reaching or exceeding 1.5 degrees Celsius in the next two decades, leading to more dangerous extreme weather events and irreversible damage to the earth (IPCC 2022). Effects such as ocean acidification, rising seas, melting polar ice caps, among others, will intensify, causing, in addition to impacts on human survival, a great loss of biodiversity. Therefore, climate change, together with land use change, will be the main causes of species extinction by 2100 in virtually every terrestrial ecosystem of the planet (Sala *et al.* 2000).

For grassland environments, climate projections show a substantial increase in temperature and, added to land exploitation and habitat loss, may further compromise the composition of native species (Sala *et al.* 2000, Gibson & Newmann 2019). For the Brazilian Cerrado, a biogeographic province with different types of grassland, the projections are not encouraging either. Hofmann *et al.* (2021) show that the increase in temperature will reduce the relative humidity by ~15%, making these grasslands increasingly drier and hotter, directly affecting local biodiversity. This finding becomes even more worrying since open areas are still poorly understood and with many erroneous restoration policies (Silveira *et al.* 2021). Additionally, the Cerrado is one of the biogeographic provinces with great richness of animal and plant species in the world, being also a biodiversity hotspot (Myers *et al.* 2000).

As a group that is very sensitive to the global changes, birds are widely studied and are fundamental to understand the dynamics of ecosystems in relation to climate change (*e.g.* Marini *et al.* 2009a, Borges *et al.* 2019, Borges & Loyola 2020, Moraes *et al.* 2020). Among the Cerrado grassland birds, the Campo Miner *Geositta poeciloptera* is a threatened species that since 2012 has been subject to a long-term study that focused on its basic natural history (Machado *et al.* 2017, Lopes & Peixoto 2018), reproductive ecology (Meireles *et al.* 2018, Meireles *et al.* 2021), environmental endocrinology (Lopes *et al.* 2021), and movement ecology (Lopes *et al. in press*). Endemic to the Cerrado and with its range almost restricted to Brazil, the species inhabits open landscapes with sparse grass cover and exposed soil and is suffering a

marked decrease on its area of occurrence over the years (Machado *et al.* 2017, Lopes & Peixoto 2018), largely due to land use changes (Lopes *et al.* 2009, Silveira 2009). Marini *et al.* (2009a) in their study with several endemic birds of the Brazilian Cerrado, pointed to a dramatic decrease in their area of occurrence until 2100 due to climate change, however, the study considered only the few information about the natural history of the species that was available until that moment.

In this study, we used several occurrence records collected in different databases to understand the past, present and future distribution of Campo Miner. In addition, using ecological niche modeling, we investigate climate change and its effects on suitable habitats for the species to understand why its range is being reduced and where are the most suitable areas for the occurrence and conservation of the species. For this, we evaluated possible changes in the size of suitable areas in different scenarios of greenhouse gas emission policies and identified the most suitable areas for the occurrence and conservation of the species in the future. Due to the lack of prospect of returning to pre-industrial emission levels (IPCC 2022), we expect to find a decrease in suitable areas in all scenarios. However, the scenario with a substantial increase in emissions (and consequently the greatest increase in terrestrial temperature) will present greater loss of suitable areas.

With this study, added to all the knowledge acquired in ten years of study, seven of which of color-ringed monitoring individuals, it is expected to better understand the possible causes of the local extinction of Campo Miner and outline plans for its conservation, as well as understand the ecology of grassland environments in the face of climate change and its importance for biodiversity.

2. METHODS

2.1. Study species and area

The Campo Miner is a threatened grassland terrestrial passerine (Ridgely & Tudor 2009, Machado *et al.* 2017) classified as Vulnerable in Brazil (MMA 2022) and globally (Birdlife International 2022). In the state of São Paulo, the species is considered regionally extinct (Alesp 2018). For these reasons, and also for the low protection of the species in reserves (Marini *et al.* 2009b), it was included in the National Action Plan (PAN) for the Conservation of Endangered Species in the Cerrado (ICMBio 2021a).

It inhabits the more open grasslands of the Cerrado savannas (Ridgely & Tudor 2009, Machado *et al.* 2017, Lopes & Peixoto 2018), a Brazilian biogeographic province that suffers from anthropogenic impacts (ICMBio 2021b) and climate change, severely affecting the species conservation (Marini *et al.* 2009a, Hofmann *et al.* 2021). Due to its distribution and inclusion in the PAN, we used only the Brazilian Cerrado as a study area and also all the Brazilian states where there are occurrence records for the species (see Lopes *et al. in press*) (Fig. 1).

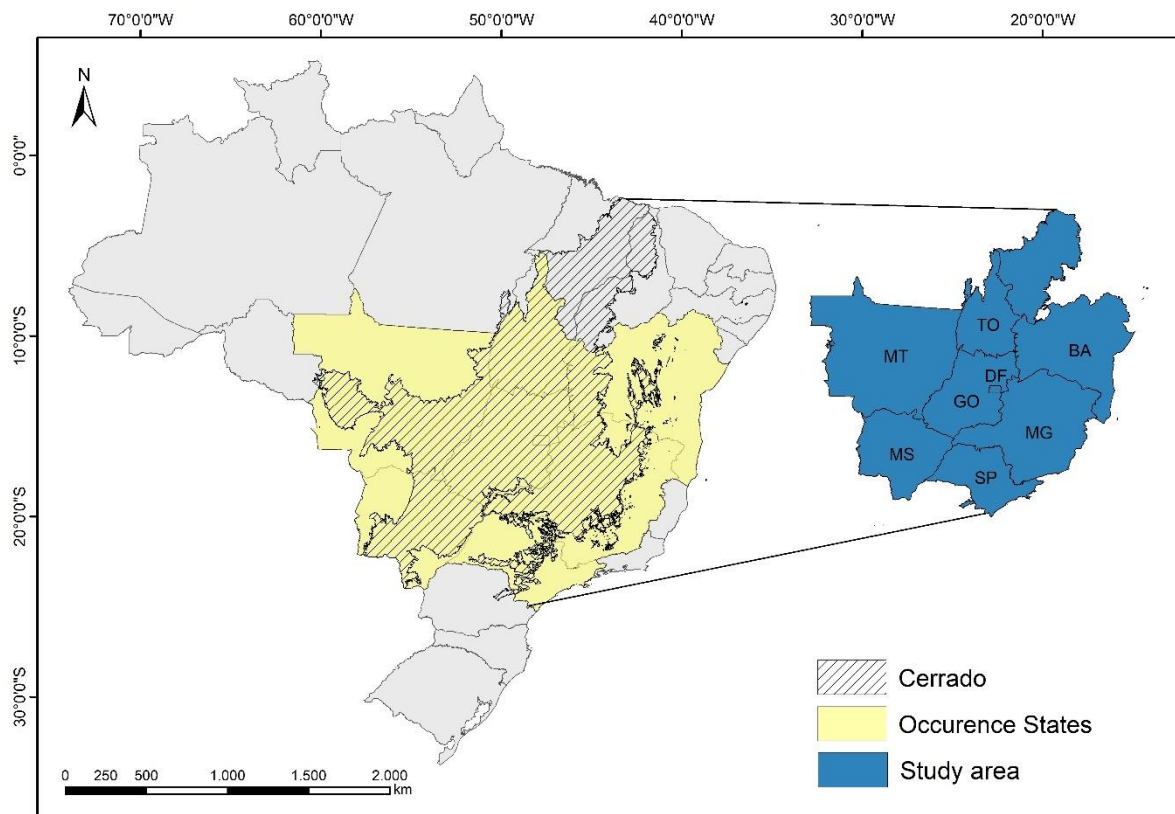


Figure 1. Study area encompassing the Cerrado biogeographic province and the Brazilian states with confirmed occurrences of the Campo Miner. States: BA = Bahia, DF = Distrito Federal, GO = Goiás, MG = Minas Gerais, MS = Mato Grosso do Sul, MT = Mato Grosso, SP = São Paulo, TO = Tocantins.

2.2. Species record data

To understand the distribution of the Campo Miner, we used the occurrence records previously collected by Lopes *et al. (in press)*. These data are from a literature review conducted in two searching engines (<https://scholar.google.com> and

www.biodiversitylibrary.org) using the following keywords: Campo Miner, *Geositta poeciloptera* and *Geobates poecilopterus* (a previous name of the species). This dataset also includes data from online sound archives (<http://macaulaylibrary.org>, www2.ib.unicamp.br/fnjv), citizen science platforms (www.xeno-canto.org, www.wikiaves.com.br and <http://ebird.org>), museum databases (www.vertnet.org, <http://splink.cria.org.br>) and general biodiversity databases (www.gbif.org). A total of five Brazilian and two overseas ornithological collections were also personally visited (see Lopes *et al.* *in press*).

Due to the author's previous field experience and knowledge about the species' natural history, habitat preference and strict nesting requirements (Machado *et al.* 2017; Meireles *et al.* 2018, Meireles *et al.* 2021), we excluded from the analysis records obtained in sites that do not harbor suitable habitat for it. We also excluded records for Paraguay and Bolivia, since the species was found only one time in each country (see del Casitillo *et al.* 2005, Herzog *et al.* 2016).

We also obtained records of occurrences from other ornithologists coming into direct contact with them, in addition to records made in the field by the authors themselves (see Machado *et al.* 2017, Meireles *et al.* 2018, Lopes & Peixoto 2018, Lopes *et al.* 2021, Meireles *et al.* 2021, Lopes *et al.* *in press*).

For all records found, we organized the database by location, date (<1950, 1950-1990 and >1990) and geographic coordinates. The choice of dates was based on the study by Lopes *et al.* (*in press*). For those records to which it was not possible to accurately identify their geographic location, we adopted the municipal seat as a reference. After constructing our database of occurrence data, we did a manual filtering removing all duplicate points and also very close points (<500m) to reduce spatial autocorrelation and avoid clustering (Aiello-Lammens *et al.* 2015).

2.3. Extent of Occurrence (EOO)

We used the occurrence points recorded after 1990 to estimate the current Extent of Occurrence (EOO) of Campo Miners. According to the IUCN (2012) definition, the EOO is "the area contained within the shortest continuous imaginary boundary that can be drawn to encompass all the known, inferred or projected sites of present occurrence of a taxon, excluding cases of vagrancy". For this, we build a convex hull polygon in the ConR package (Dauby 2020). We also performed a comparison between the EOO

generated by us and the EOO presented on the IUCN website and available by BirdLife International and Handbook of the Birds of the World (2021).

2.4. Predictions

a. Variables

To build the variables database, we obtained bioclimatic and elevation data from Brazil from the WorldClim v2 database (Fick & Hijmans 2017). We performed two tests of Variance Inflation Factor (VIF) analysis using the *usdm* package (Naimi *et al.* 2014) to minimize multicollinearity in the data (the default limit of 10 was used), including or excluding the elevation, since for some groups the use of this variable in the models may have a better performance (Hof & Allen 2019). Furthermore, the species seems to have a strong relationship with this variable, being currently found at elevations between approximately 550 and 1300m (Lopes *et al. in press*). All data were in 2.5-minute resolution, Datum WSG84 and were cropped according to the study area (Fig. 1).

b. Present prediction

To predict the current climatic areas suitable for Campo Miner we only used occurrence records with exact coordinates and after 1990 (n= 80) since historical records may not match the current climate reality of the species. We built all models using the *biomod2* package (Thuiller *et al.* 2021) and six algorithms of ecological niche modeling (ENM) (Table 1) with 10 independent runs for each one. To train and test the models, 75% and 25% of the data were kept during each run, respectively. Model performance was determined by threshold > 0.8 and assessed based on the average True Skill Statistic – TSS – (Allouche *et al.* 2006) and Receiver Operating Characteristics – ROC – curve (Fielding & Bell 1997).

Given the inner programming of selected algorithms being different, we followed Barbet-Massin *et al.* (2012) recommendations to generate background and pseudo absence data. We divided the algorithms in two groups according to the type of “absence” data it requires as shown in Table 1.

We built ensemble models following the method used by Köhler et al. (2020) using the weighted average of the binarized projections from the determined TSS threshold, resulting in a single map for each group. From the two ensemble models groups generated, we superimposed the maps to compute the average of the overlapping pixel values to generate a single map of present prediction.

Table 1 – Ecological Niche Modelling selected algorithms for the Campo Miner distribution (adapted from Raes & Aguirre-Gutiérrez 2018).

Group	Algorithm	Description	“Absence” data	Number of “absence” records	Generation	References
I	GAMs	Generalized additive models	Pseudo absence	1000	Random across the environment	Hastie & Tibshirani (1986); Yee & Mitchell (1991)
I	GLMs	Generalized linear models	Pseudo absence	1000	Random across the environment	McCullagh & Nelder (1989); Venables & Ripley (2002)
I	MAXENT	Maximum entropy	Background data	1000	Random across the environment	Phillips <i>et al.</i> (2006)
II	BRTs	Boosted regression trees	Pseudo absence	80	0.5 degree wide buffer around presence point	Elith <i>et al.</i> (2008)
II	SRE	Surface range envelope	Background data	80	0.5 degree wide buffer around presence point	Nix (1986); Busby (1991)
II	RFs	Random forests	Pseudo absence	80	0.5 degree wide buffer around presence point	Breiman (2001)

c. Future predictions

For the future predictions, two General Circulation Models (GCM) were used in this study: BCC-CSM2-MR and MIROC-ES2L. The scenarios modeled for the Campo Miner comprise the years 2041–2060 and 2061–2080. For both GCMs, we evaluated two different greenhouse gas emissions scenarios with different climate policies (Shared Socioeconomic Pathways – SSPs), one being an optimistic scenario – ssp245 – with a slow decrease in greenhouse gas emissions limit warming around 2.5°C over the years and, a pessimistic scenario, with substantially higher greenhouse gas emissions – ssp585 – increasing ~5°C until 2100 (Riahi *et al.* 2017, Gidden *et al.* 2019). All scenarios were based on the Coupled Model Intercomparison Project Phase 6 (CMIP6) by Eyring *et al.* (2016) and the data were also obtained from the WorldClim v2 database (Fick & Hijmans 2017). All analysis (EOO, present and future predictions) that used specific packages were performed in R (R Core Team 2022).

3. RESULTS

We found a total of 1107 occurrence points for the species in 67 municipalities in 6 Brazilian states. After manual filtering to remove duplicate and very close points, we obtained about 264 records. The first records of the species were obtained in the state of São Paulo in 1819 in Ipanema (today Ipanema National Forest, municipality of Iperó) and along the road to the municipality of Sorocaba. Almost all records for the state of São Paulo were obtained before 1950, with only one record obtained between 1950 and 1990. Records for the northwest part of Mato Grosso and southwest part of Mato Grosso do Sul were also obtained before 1950. Most of the records, irrespective of the period considered, are from the states of Goiás, Minas Gerais and Distrito Federal (Fig. 2).

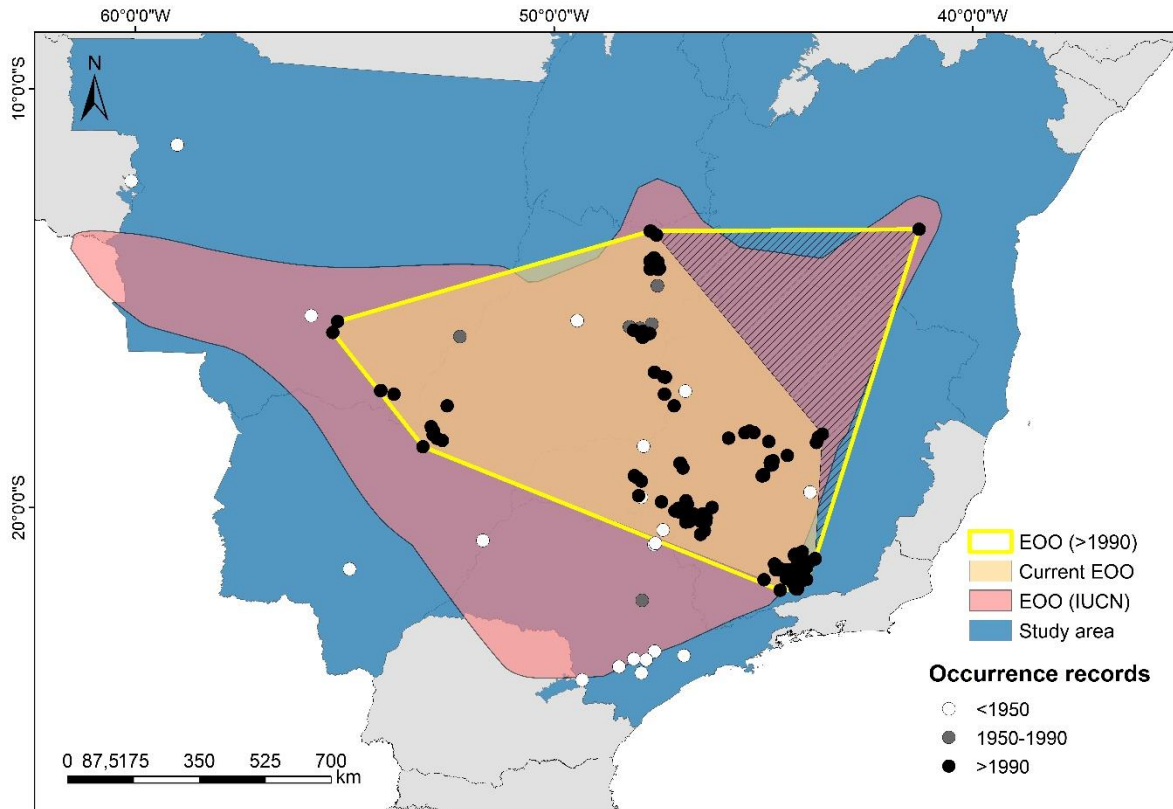


Figure 2. All occurrence records of Campo Miners in Brazil and the comparison between the EOO based only on records > 1990, with or without considered the isolated occurrence in the Bahia state (hatched area), where the species is probably extinct, and the EOO available on the IUCN website.

3. 1. *Extent of occurrence*

The current extent of occurrence covers an area of $\sim 882,800 \text{ km}^2$, $\sim 38.8\%$ smaller than that estimated by the IUCN for Brazil ($1,443,437 \text{ km}^2$). Both estimates cover the states of Minas Gerais, Goiás, Mato Grosso, Mato Grosso do Sul, Bahia, Tocantins and Distrito Federal, with a larger (IUCN EOO) or smaller (current EOO) area delimited for each state. In addition, the IUCN EOO also extends to the state of São Paulo and beyond Brazil, covering a small part of Bolivia (Fig. 2).

3. 2. *Predictions*

The test with the inclusion of the elevation variable showed the best performance and after verifying the multicollinearity of the 19 bioclimatic variables plus the elevation, only 8 variables were selected (Table 2). Elevation proved to be the main variable representing 66.4% of contribution to the occurrence of Campo Miners, followed by precipitation of the wettest month (BIO13) with 32% of contribution (Table 2).

Table 2 - Selected environmental variables used to predict the present distribution of the Campo Miner in Brazil.

Variables	Description	Percent contribution (%)
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	15.0
BIO3	Isothermality	15.0
BIO13	Precipitation of Wettest Month	32.0
BIO14	Precipitation of Driest Month	20.0
BIO15	Precipitation Seasonality	17.0
BIO16	Precipitation of Wettest Quarter	24.6
BIO18	Precipitation of Warmest Quarter	17.2
Elev	Elevation	66.4

All 60 models generated from the 6 chosen algorithms (10 runs for each one) had good performances, presenting an average of the values of TSS = 0.83 and ROC = 0.92, higher than the 0.8 threshold previously determined.

The estimate of areas above 50% suitable for the occurrence of Campo Miners was ~259,242.18 km² and covered, as expected, mainly the Cerrado (Fig. 3) and all regions where the species was currently recorded, which shows a good performance of the models generated for the present.

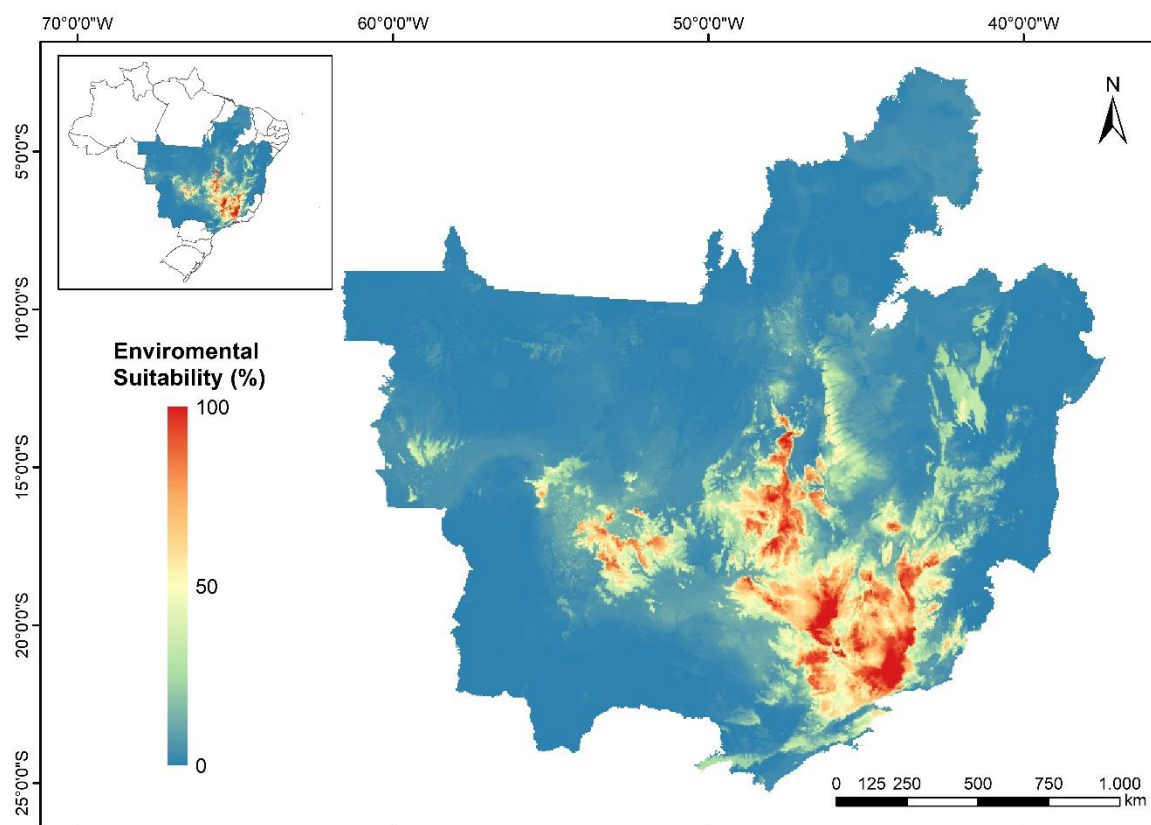


Figure 3. Ensemble model generated for the prediction of the current suitable areas for the occurrence of Campo Miners in Brazil.

As with the current prediction, the maps generated by the two groups of algorithms were superimposed, generating a total of eight projections. They were separated by period (2041–2060 and 2061–2080), GCMs (BCC-CSM2-MR and MIROC-ES2L) and greenhouse gas emissions scenario (optimistic – ssp245 and pessimistic – ssp585) (Fig. 4).

All models show the reduction of suitable habitats for the occurrence of the Campo Miner (> 50%) in a period of approximately 50 years (2061–2080). The ssp585 scenarios with substantially higher increase in greenhouse gas emissions showed the greatest reduction in area according to each GCM. The GCM BCC-CSM2-MR showed a considerably greater reduction (25877.49 km² – ssp245 and 99508.38 km² – ssp585) of area than the GCM MIROC-ES2L (987.64 km² – ssp245 and 12964.3 km² – ssp585).

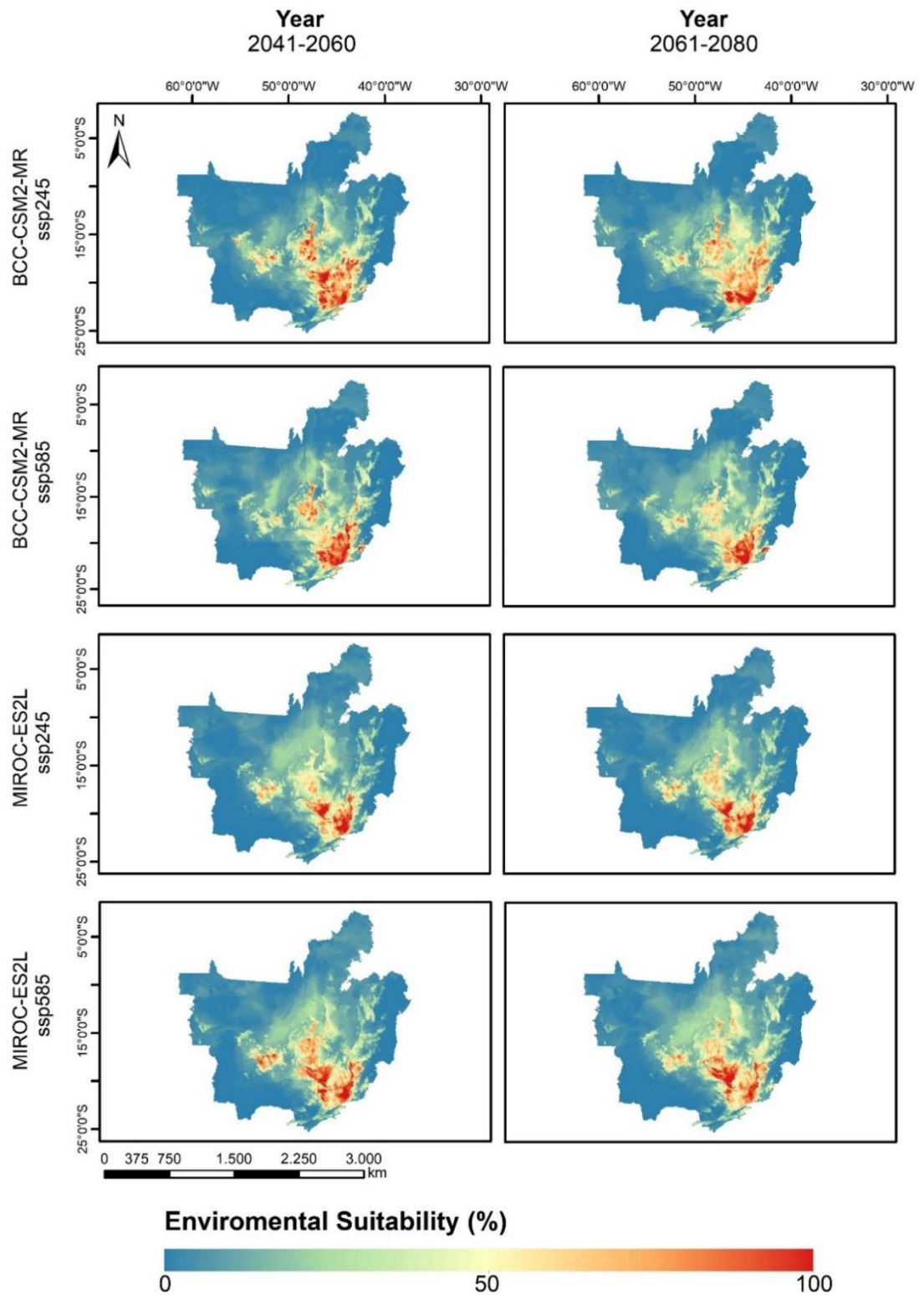


Figure 4. Future prediction of suitable areas for the occurrence of Campo Miners in Brazil in two different greenhouse gas emissions scenarios (ssp245 and ssp585) and GCMs (BCC-CSM2-MR and MIROC-ES2L).

4. DISCUSSION

The current EOO of Campo Miners in Brazil has suffered a dramatic reduction in recent years, with several regions exhibiting no record after 1950. Although the IUCN EOO covers almost the entire area with records of Campo Miners in the last two centuries (including Bolivia) and excludes records from where the species is extinct (e.g. São Paulo and Paraguay), it is currently outdated, because other regions with historical records no longer harbor the species. Furthermore, the current EOO may be even smaller, as the single record of the species for Bahia was published by Parrini *et al.* (1999), who recorded the species close to the locality of Brejo, along the road from Ibicoara to Jussiape, on 9 December 1995 (Parrini pers. com.). Most of the grasslands that originally covered this region have been lost, mainly converted to temporary crops (Parrini pers. com., Google Earth images). We suspect that the species is extinct in Bahia and, therefore, if we do not consider the point for the state, the entire hatched area needs to be excluded from the current EOO of Campo Miner (see Fig. 2). Therefore, the current EOO will be ~659,918.3 Km², about 54.27% smaller than the EOO proposed by the IUCN for Brazil.

4.1. Present prediction

Why elevation was the most important variable for the species is not entirely clear. Hof *et al.* (2012), in a study comparing the performance of several studies that included or not elevation in species distribution modelling, showed that this variable can often be related to other variables that are not directly linked to climate. Campo Miners inhabited an elevation range of about 1000 m (between 300 and 1300 m asl), but it is currently extinct in lower elevations, as no record below 550 m has been obtained during the last eight decades. Meireles *et al.* (2018), in a study about how soil attributes drive nest-site selection by Campo Miners, found that higher areas had shallower and poorly developed soils with high concentration of silt, which would facilitate nest excavation and favors the development of open grasslands. On the other hand, lower areas had more developed soils and greater concentration of clay, making nest excavation difficult. Although the relationship between elevation and soil type may be a factor to

be considered, other unknown and unstudied factors may also be included in this relationship, for example, interactions between species (Hof *et al.* 2012).

Four regions that harbor important strictly protected areas for the species (ICMBio, 2011) showed high levels of environmental suitability, namely: 1) Brasília National Park, Distrito Federal; 2) Chapada dos Veadeiros National Park, Goiás; 3) Emas National Park, Goiás; and 4) Serra da Canastra National Park, Minas Gerais. All of them harbor vast expanses of grasslands and can be of paramount importance for the conservation of the species (ICMBio, 2021b). However, in Brasília National Park the species seems to be currently very rare (Braz 2008, WikiAves data).

The areas with the lowest environmental suitability (<50%) are mostly in regions where the species has already been declared extinct, as follows:

- 1) São Paulo State: Although researchers still indicate the possibility of the species occurring in the state (Bressan *et al.* 2009), the Alesp (2018) decree and other studies point to its extinction (Willis 2004; Motta-Junior *et al.* 2008). The last record for the state was obtained in 1987.
- 2) Mato Grosso state: The records for the northwest region refer to Chapada dos Parecis, a poorly studied place but briefly visited by LEL in the 2010s, where no individual was found, despite still containing vast areas of natural grassland with apparently suitable habitat for the species. For Chapada dos Guimarães, the latest bird surveys did not find the species, and only century old museum records were found (Lopes *et al.* 2009, Dornas 2019). All the records for these regions occurred before 1950.
- 3) Bahia state (Chapada Diamantina): As mentioned earlier, only one record of the species was made there in the 1990s (Parrini *et al.* 1999). As it is a highly tourist area and with a high flow of people (including birdwatchers), the lack of records in the last thirty years (see www.wikiaves.com.br) seems to confirm the hypothesis of extinction in the region.
- 4) Mato Grosso do Sul: Only two records of the species for the Southwest region were found in 1938 on the Corralinho farm. There is still a record for the eastern region in the municipality of Três Lagoas in 1932 and there is no further information about the species for these regions.

The possible cause of extinction of the species in these regions is attributed to the wiping of natural grasslands, replaced by exotic pastures and crops (Lopes *et al.* 2009, Silveira 2009). The lack of fire management is also considered, as the species

is fire dependent, occupying recently burned areas (Willis 2004; Machado *et al.* 2017, Lopes *et al. in press*). None of the studies point to climate change as a possible cause of extinction of the Campo Miner.

4.2. Future predictions

While there are explicit differences for the GCMs scenarios, all of them show reductions in environmental suitability. These differences can be explained by equilibrium climate sensitivity values for each one, which estimate long-term global warming by doubling atmospheric concentrations of CO₂ (Nijsee *et al.* 2020). Even with differences between models, it is possible to observe a reduction of suitable areas mainly in the lower and northern parts of the Cerrado in the states of Mato Grosso, Mato Grosso do Sul, Goiás and Distrito Federal, with these reductions being even greater in a pessimistic scenario and projecting a better suitability for the state of Minas Gerais. This projection seems to agree with other studies that have verified the influence of climate and land use changes on bird communities in the Cerrado. Apparently, the southern region of the Cerrado will host the largest refuge area for these species (Marini *et al.* 2009a, Marini *et al.* 2009b, Borges *et al.* 2019, Borges & Loyola 2020). However, as mentioned by Borges *et al.* (2019), the southern region is the most developed in the Cerrado, with much of its vegetation converted to pastures and crops (Sano *et al.* 2010), which can be an impediment to the establishment of new bird populations or even to the conservation of species already existing in the site.

Even if the areas predicted by the model are indeed climatically suitable for the species, other factors must also be considered. As a specialist grassland bird that tolerates only little changes in land use (Machado *et al.* 2017), the Campo Miner needs vast areas of natural grasslands, however, these areas are less common (Borges *et al.* 2019) and poorly represented in reserves. Protected areas are important because, by suffering less anthropogenic pressures and land use changes, they can, in addition to preserving species and environments, help to mitigate the effects of long-term climate change (Dudley *et al.* 2009). Although Minas Gerais is the region with the best conditions for Campo Miners in the future, currently only one protected area (Serra da Canastra National Park) can be a stronghold for the preservation of the species in the state.

Some regions identified here proved to be extremely important for the creation of new protected areas, such as the Upper Rio Grande Grasslands (URRGs), which seems to be the most important stronghold for this resident species. However, the URGGS is poorly protected, with only two noteworthy reserves in the region, the Ibitipoca State Park (1,488 ha) and the Wildlife State Refuge Libélulas da Serra de São José (3,710 ha). These two small reserves do not harbor suitable habitat for Campo Miners, which, ironically, is not protected within its main stronghold. The creation of large reserves in the URGGs should be a priority that will also benefit grassland specialists from other major taxonomic groups, including the Critically Endangered Leaf Frog *Pithecopus ayeaye* (Anura, Phyllomedusidae) (Magalhães *et al.* 2017). The importance of this region is acknowledged since Drummond *et al.* (2005), who considered the mountains of São João-del-Rei and Tiradentes as of extreme priority for the creation of reserves. Another important region that deserves attention and needs further study is the Três Marias microregion, especially the municipality of Pompéu, which has a high number of records (http://www.wikiaves.com.br/mapaRegistros_andarilho) not only for Campo Miners, but for several other threatened grassland birds (Souza *et al.* 2018). This region also does not have protected areas with suitable habitats to ensure the survival of the species.

The reserves would also protect a landscape that is naturally vulnerable and highly susceptible to erosive processes that lead to the loss of soil, habitat, and biodiversity (Lima *et al.* 2011). However, the strategy of creating new protected areas for the species needs a lot of caution, since, despite being a territorial species, Campo Miner depends on a dynamic habitat in time and space that is often determined by fire, so these areas need to be carefully managed (Lopes *et al. in press*).

The Campo Miner exhibit a suit of ecological requirements that can be very worrying for its preservation as it is a habitat specialist and territorial species (Machado *et al.* 2017, Lopes *et al.* 2021). Viana & Chase (2022), in their recent study on traits, ecology and demography of American birds and their relationship with climate change, showed that habitat specialist and territorial species are more vulnerable to climate since they are more limited to specific environments and have a strong association with the type of vegetation. The impacts of climate change and the consequent reduction of suitable areas can also have profound consequences on bird communities, as several other species, including threatened ones, depend on the

same environment (Lopes & Peixoto 2018). In addition, a possible displacement of species that need an environment similar to Campo Miner can cause an environmental collapse since habitat specialist birds seem to have an advantage over generalists. When moving to suitable areas, they can cause the homogenization of species in the environment since generalists prefer to move to other locations rather than compete with specialists (Straude *et al.* 2021).

5. CONCLUSION

Campo Miner is a threatened species that has been suffering a marked reduction in its range in recent years and its survival in the face of climate change is not guaranteed. The effects of local extinctions are not only limited to the impact caused on its conservation, because interspecific interactions can be affected. Campo Miners build their nests within cavities they excavate in steep soil banks that are later used by other animals as shelter or even for nesting (Meireles *et al.* 2021), so its disappearance can cause impacts at the community level.

We show in this study a not optimistic future for the species, since important areas with ideal climatic suitability will be considerably reduced. Even in a scenario with reduced greenhouse gas emissions, the species will lose a large part of its areas. However, in a scenario with high emissions, the areas lost will be even greater, therefore, an aggressive plan to mitigate CO₂ emissions limiting warming up to 1.5°C by the end of the century as proposed (IPCC 2022) is very important to ensure the future of the species.

Reducing CO₂ emissions is crucial to ensure the future not only of the Campo Miner, but also of several other bird species (Marini *et al.* 2009a, Borges *et al.* 2019, Borges & Loyola 2020). However, as suggested by Marini *et al.* (2009a), plans are needed that assess not only climate change, but also land use change, as species distribution can be influenced by different factors. In addition, there is no point in areas that show good climatic suitability if they may have already been converted to pasture, agriculture or even urbanized.

The state of Minas Gerais will shelter the largest area climatically suitable for the species in approximately 50 years. However, the lack of protected areas in the state with adequate habitats may be a hindrance to its preservation. As it is a non-migratory bird (Lopes *et al. in press*), it is likely that the main refuges for the species in

the future will be within reserves, so the creation of new protected areas or even as mentioned by Lopes *et al.* (*in press*), a mosaic of fully protected and sustainable use reserves that cover their locations is very important to ensure the survival of Campo Miners. This is especially true in the URGGs, an area that is being silently devastated and that shelters the most important population of the species outside protected areas.

REFERENCES

- Aiello-Lammens, M. E., Boria, R. A., Radosavljevic, A., Vilela, B. & Anderson, R. P. (2015). spThin: an R package for spatial thinning of species occurrence records for use in ecological niche models. *Ecography* 38, 541–545.
- Alesp. (2018). Assembleia Legislativa do Estado de São Paulo. Available at: <https://www.al.sp.gov.br/repositorio/legislacao/decreto/2018/decreto-63853-27.11.2018.html>. Accessed 06.05.2021.
- Allouche, O., Tsoar, A. & Kadmon, R. (2006). Assessing the accuracy of species distribution models: prevalence, kappa and true skill statistic (TSS). *Journal of Applied Ecology* 43, 1223–1232.
- Álvares C. A., Stape J. L., Sentelhas P. C., de Moraes Gonçalves J. L. & Sparovek G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* 22, 711–28.
- Barbet-Massin, M., Jiguet, F., Albert, C. H. & Thuiller, W. (2012). Selecting pseudo-absences for species distribution models: how, where and how many? *Methods in Ecology and Evolution* 3, 327–338.
- BirdLife International and Handbook of the Birds of the World (2021) Bird species distribution maps of the world. Version 2021.1. Available at: <http://datazone.birdlife.org/species/requestdis>.
- BirdLife International. (2022). Species factsheet: *Geositta poecilopectera*. Available at: <http://datazone.birdlife.org/species/factsheet/campo-miner-geositta-poecilopectera>. Accessed 12.01.2022.
- Borges, F. J. A. & Loyola, R. (2020). Climate and land-use change refugia for Brazilian Cerrado birds. *Perspectives in Ecology and Conservation* 18, 109–115.
- Borges, F. J. A., Ribeiro, B. R., Lopes, L. E. & Loyola, R. (2019). Bird vulnerability to climate and land use changes in the Brazilian Cerrado. *Biological Conservation* 236, 347–355.

- Braz, V. S. (2008). Ecologia e conservação das aves campestres do bioma Cerrado. Tese para obtenção do título em Doutor em Ecologia. Universidade de Brasília, Brasília, Brasil.
- Breiman, L. (2001). Random forests. *Machine Learning* 45, 5–32.
- Bressan, P. M, Kierulff, M. C. M. & Sugieda, A. M. (2009). Fauna ameaçada de extinção no estado de São Paulo: vertebrados. Fundação Parque Zoológico de São Paulo: Secretaria do Meio Ambiente.
- Busby, J.R. (1991). Bioclim, a bioclimatic analysis and prediction system. in C. R. Margules & M. P. Austin (Eds.). *Nature Conservation: Cost Effective Biological Surveys and Data Analysis*. (pp. 64–68). CSIRO, Canberra, Australia.
- Dauby, G. (2020). ConR: Computation of Parameters Used in Preliminary Assessment of Conservation Status. R package version 1.3.0. <https://CRAN.R-project.org/package=ConR>.
- del Castillo, H., Clay, R. P., Egea, J. & Asociación Guyra Paraguay (2005). Atlas de las aves de Paraguay. Guyra Paraguay, Asunción, Paraguay.
- Dornas, T. (2020). Registros relevantes e incrementos para a avifauna da região da Chapada dos Guimarães, bioma Cerrado, no Centro-Oeste do Brasil. *Atualidades Ornitológicas* 212, 1–8.
- Drummond, G. M., Martins, C. S., Machado, Â. B. M., Sebaio, F. A. & Antonini, Y. (2005). Biodiversidade em Minas Gerais: um atlas para sua conservação (2nd ed.). Fundação Biodiversitas, Belo Horizonte, Brazil.
- Dudley, N., Stolton, S., Belokurov, A., Krueger, L., Lopoukhine, N., MacKinnon, K. *et al.* (2009). *Natural Solutions: Protected Areas Helping People cope with climate change*. IUCN-WCPA, TNC, UNDP, WCS, the World Bank, and WWF, Gland, Switzerland, Washington, DC, and New York, USA.
- Elith, J., Leathwick, J.R. & Hastie, T. (2008). A working guide to boosted regression trees. *Journal of Animal Ecology* 77, 802–813.

- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J. & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development* 9, 1937–1958.
- Fick, S.E. & Hijmans, R.J. (2017). WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* 37, 4302–4315.
- Fielding, A. H. & Bell, J. F. (1997). A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation* 24, 38–49.
- Gibson, D. J. & Newman, J. A. (2019). *Grasslands and Climate Change*, Cambridge University Press, Cambridge, UK.
- Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., *et al.* (2019). Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. *Geoscientific Model Development* 12, 1443–1475.
- Hastie, T. & Tibshirani, R. (1986). Generalized additive models. *Statistical Science* 1, 297–310.
- Herzog, S. K., Terrill, R. S., Jahn, A. E., Remsen, J. V., Maillard, O. Z., *et al.* (2016). *Birds of Bolivia: field guide*. Asociación Armonía, Santa Cruz de la Sierra, Bolivia.
- Hof, A. R. & Allen, A. M. (2019). An uncertain future for the endemic Galliformes of the Caucasus. *Science of the Total Environment* 651, 725–735.
- Hof, A. R., Jansson, R. & Nilsson, C. (2012). The usefulness of elevation as a predictor variable in species distribution modelling. *Ecological Modelling* 246, 86–90.
- Hofmann, G. S., Cardoso, M. F., Alves, R. J. V., Weber, E. J., Barbosa, A. A. *et al.* (2021). The Brazilian Cerrado is becoming hotter and drier. *Global Change Biology*, 27, 4060–4073.

- ICMBio. (2011). Atlas da Fauna Brasileira Ameaçada de Extinção em Unidades de Conservação Federais. Brasília. Pp. 276.
- ICMBio. (2021a). Sumário executivo do plano de ação nacional para a conservação de aves do cerrado e pantanal. Available at: <https://www.icmbio.gov.br/portal/faunabrasileira/plano-de-acao-nacional-lista/3618-plano-de-acao-nacional-para-a-conservacao-das-aves-do-cerrado-e-pantanal>. Accessed 06.05.2021.
- ICMBio. (2021b). Cerrado. Available at: <https://www.icmbio.gov.br/portal/unidadesdeconservacao/biomas-brasileiros/cerrado>. Accessed 06.05.2021.
- IPCC. (2022). Climate Change 2022: impacts, adaptation, and vulnerability. in H-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem & B. Rama (Eds). Contribution of working group II to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- Köhler, M. Esser, L. F., Font, F., Souza-Chies, T. T. & Majure, L. C. (2020). Beyond endemism, expanding conservation efforts: What can new distribution records reveal? *Perspectives in Plant Ecology, Evolution and Systematics* 45, 125543.
- Lima, L. P. Z., Louzada, J., Carvalho, L. M. T. & Scolforo, J. R. (2011). Análise da vulnerabilidade natural para a implantação de unidades de conservação na microrregião da Serra de Carrancas, MG. *Cerne* 17, 151–159.
- Lopes, L. E. & Peixoto, H. J. C. (2018) Aves campestres ameaçadas de extinção encontradas nos Campos do Alto Rio Grande, sul de Minas Gerais: notas sobre sua história natural e proposições para estudos futuros. *Atualidades Ornitológicas* 201, 40–48.
- Lopes, L. E., Meireles, R. C., Peixoto, H. J. C., Teixeira, J. P. G., Machado, T. L. S. S. & Lombardi, V. T. (*In Press*). Movement ecology of the threatened Campo Miner *Geositta poeciloptera* and its implications for conservation of tropical open grassland birds. *Bird Conservation International*.

- Lopes, L. E., Pinho, J. B., Bernardon, B., Oliveira, F. F., Ferreira, L. P., Vasconcelos, M. F., Maldonado-Coelho, M., Nóbrega, P. F. A. & Rubio, T. C. (2009). Aves da Chapada dos Guimarães, Mato Grosso, Brasil: uma síntese histórica do conhecimento. *Papéis Avulsos de Zoologia* 49, 9–47.
- Lopes, L. E., Teixeira, J. P. G., Meireles, R. C., Bastos, D. S. S., Oliveira, L. L. & Solar, R. (2021). High seasonal variation of plasma testosterone levels for a tropical grassland bird resembles patterns of temperate birds. *Physiological and Biochemical Zoology* 94, 143–151.
- Machado, T. L. S. S., Lombardi, V. T., Meireles, R. C., Teixeira, J. P. G., Solar, R. & Lopes, L. E. (2017). Breeding biology of the threatened Campo Miner (*Geositta poeciloptera* (Aves: Scleruridae), a Neotropical grassland specialist. *Journal of Natural History* 51, 1–13.
- Magalhães, R. F., Lemes, P., Camargo, A., Oliveira, U., Brandão, R. A., Thomassen, H., Garcia, P. C. A., Leite, F. S. F. & Santos, F. R. (2017). Evolutionarily significant units of the critically endangered leaf frog *Pithecopus ayeaye* (Anura, Phyllomedusidae) are not effectively preserved by the Brazilian protected areas network. *Ecology and Evolution* 7, 8812– 8828.
- Marini, M. Â., Barbet-Massin, M., Lopes, L.E. & Jiguet, F. (2009a). Predicted climate-driven bird distribution changes and forecasted conservation conflicts in a Neotropical savanna. *Conservation Biology* 23, 1558–1567.
- Marini, M. Â., Barbet-Massin, M., Lopes, L. E. & Jiguet, F. (2009b). Major current and future gaps of Brazilian reserves to protect Neotropical savanna birds. *Biological Conservation* 142, 3039–3050.
- McCullagh, P. & Nelder, J.A. (1989). *Generalized Linear Models*.: CRC Press, Boca Raton, FL.
- Meireles, R. C., Lopes, L. E., Pichorim, M., Machado, T. L. S. S., Duca, C. & Solar, R. (2021). Nest survival of the threatened Campo Miner *Geositta poeciloptera*: a tropical cavity-nesting grassland bird. *Austral Ecology* 46, aec.13079.

- Meireles, R. C., Teixeira, J. P. G., Solar, R., Vasconcelos, B. N. F., Fernandes, R. B. A. & Lopes, L. E. (2018). Soil attributes drive nest-site selection by the Campo Miner *Geositta poeciloptera*. PLoS ONE 13, e0192185.
- MMA (2022). Lista Nacional oficial de espécies da fauna ameaçadas de extinção. Ministério do Meio Ambiente. Diário Oficial da União – Portaria MMA nº 148, DE 7 DE JUNHO DE 2022.
- Moraes, K. F., Santos, M. P. D., Gonçalves, G. S. R., Oliveira, G. L., Gomes, L. B. & Lima, M. G. M. (2020). Climate change and bird extinctions in the Amazon. PLoS ONE 16, e0252260.
- Motta-Junior, J. C., Granzinolli, M. A. M. & Develey, P. F. (2008). Aves da estação ecológica de Itirapina, estado de São Paulo, Brasil. Biota Neotropica 8.
- Myers, N., Mittermeier, R. A., Mittermeier, C. G., Fonseca, G. A. B. & Kent, J. (2000). Biodiversity hotspots for conservation priorities. Nature 403, 853–858.
- Naimi, B., Hamm, N., Groen, T. A., Skidmore, A. K. & Toxopeus, A. G. (2014). Where is positional uncertainty a problem for species distribution modelling? Ecography 37, 191–203.
- Nijssen, F. J. M. M., Cox, P. M & Williamson, M. S. (2020). Emergent constraints on transient climate response (TCR) and equilibrium climate sensitivity (ECS) from historical warming in CMIP5 and CMIP6 models. Earth System Dynamics 11, 737-750.
- Nix, H.A. (1986). A biogeographic analysis of Australian Elapid snakes. In: Atlas of Australian Elapid Snakes (Ed. Longmore, R.). Australia Flora and Fauna Series 8, 4–15.
- Parrini, R., Raposo, M. A., Pacheco, J. F., Carvalhães, A. M. P., Júnior, T. A. M., Fonseca, P. S. M. & Minns, J. (1999). Birds of the Chapada Diamantina, Bahia, Brazil. Cotinga 11, 86–95.

- Phillips, S.J., Anderson, R.P. & Schapire, R.E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling* 190, 231–259.
- R Development Core Team. (2021). R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. <https://www.R-project.org>.
- Raes, N. & Aguirre-Gutiérrez, J. (2018). A modeling framework to estimate and project species distributions in space and time. In C. Hoorn, A. Perrigo & A. Antonelli (Eds) *Mountains, Climate and Biodiversity*. Wiley-Blackwell, Chichester, UK.
- Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C. *et al.* (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 42, 153–168.
- Ridgely, R. S. & Tudor, G. (2009). *Field guide to the songbirds of South America: The Passerines*. University of Texas Press, Austin, TX.
- Sala, O. E., Chapin, F. S., Armesto, J. J., Berlow, E., Bloomfield, J., *et al.* (2000). Global biodiversity scenarios for the year 2100. *Science* 287, 1770–1774.
- Sano, E. E., Rosa, R., Brito, J. L. S. & Ferreira Jr., L.G. (2010). Land cover mapping of the tropical savanna region in Brazil. *Environmental Monitoring and Assessment* 166, 113–124.
- Silveira, F. A. O., Ordóñez-Parra, C. A., Moura, L. C., Schmidt, I. B., Andersen, A. N., *et al.* (2021). Biome Awareness Disparity is BAD for tropical ecosystem conservation and restoration. *Journal of Applied Ecology*.
- Silveira, L. F. (2009). *Geositta poeciloptera* (Wied, 1830) Passeriformes, Scleruridae. in P. M. Bressan, M. C. M. Kierulff & A. M. Sugieda (Eds). *Fauna ameaçada de extinção no estado de São Paulo: vertebrados*. Fundação Parque Zoológico de São Paulo: Secretaria do Meio Ambiente.
- Souza, T. O., Teixeira, F. D., Oliveira, L. A. S., Oliveira, A. C. S., Garcia, F. I. A., *et al.* (2018). Levantamento ornitológico do município de Pompéu, região Central de

Minas Gerais, Brasil. *Atualidades Ornitológicas* 202, 49–66.

Staude, I. R., Overbeck, G. E., Fontana, C. S., Bencke, G. A., Silva, T. W., Mimet, A. & Pereira, H. M. (2021). Specialist birds replace generalists in grassland remnants as land use change intensifies. *Frontiers in Ecology and Evolution* 8, 1–8.

Thuiller, W., Georges, D., Gueguen, M., Engler, R. & Breiner, F. (2021). *Biomod2: Ensemble platform for species distribution modeling*. R package version 3.5.1. <https://cran.r-project.org/package=biomod2>.

Venables, W.N. & Ripley, B.D. (2002). *Modern Applied Statistics with S-PLUS*, 4th edn. Springer, New York, NY.

Viana, D. S. & Chase, J. M. (2022). Ecological traits underlying interspecific variation in climate matching of birds. *Global Ecology & Biogeography*, 01–14.

WikiAves (2022). [*Mapa de registros da espécie Andarilho (Geositta poeciloptera)*]. WikiAves, a Enciclopédia das Aves do Brasil. Available at: http://www.wikiaves.com.br/mapaRegistros_andarilho. Accessed 08.03.2022.

WikiAves (2022). WikiAves, a Enciclopédia das Aves do Brasil. Available at: <http://www.wikiaves.com.br>. Accessed 08.03.2022.

Willis, E. O. (2004). Birds of a habitat spectrum in the Itirapina savanna, São Paulo, Brazil (1982-2003). *Brazilian Journal of Biology* 64, 901–910.

Yee, T.W. & Mitchell, N.D. (1991). Generalized additive models in plant ecology. *Journal of Vegetation Science* 2, 587–602.

Supplementary Material

Table 1. All occurrence records from Campo Miner after manual filtering

State	Locality	Longitude	Latitude	Year
Goiás	Rio das Almas	-49.4500	-15.5333	<1950
Mato Grosso	Chapada dos Guimarães	-55.8000	-15.4167	<1950
Mato Grosso	Uaiquiriu, Parecis Serra do Norte	-59.0000	-11.3333	<1950
Mato Grosso	Rio Nicolau Bueno	-60.1000	-12.2000	<1950
Mato Grosso do Sul	Três Lagoas	-51.7000	-20.7833	<1950
Mato Grosso do Sul	Fazenda Curralinho	-54.8833	-21.4667	<1950
Minas Gerais	São Domingos	-47.8667	-18.5333	<1950
Minas Gerais	Uberaba	-47.9167	-19.7500	<1950
Minas Gerais	Paracatu	-46.8667	-17.2167	<1950
Minas Gerais	Lagoa Santa	-43.8833	-19.6333	<1950
São Paulo	Sorocaba	-46.9000	-23.5333	<1950
São Paulo	Ipanema	-47.6000	-23.4333	<1950
São Paulo	Araraquara	-47.9167	-23.9500	<1950
São Paulo	Batatais	-47.6167	-20.8833	<1950
São Paulo	Franca	-47.4000	-20.5333	<1950
São Paulo	Sarapuí	-47.8000	-23.6333	<1950
São Paulo	Batatais	-47.5833	-20.8500	<1950
São Paulo	Itararé	-49.3333	-24.1167	<1950
São Paulo	Buri	-48.4500	-23.8000	<1950
São Paulo	Itapetininga	-48.1000	-23.6167	<1950
Distrito Federal	Brasília	-47.9167	-15.7833	1950-1990
Distrito Federal	Planaltina	-47.6667	-15.6167	1950-1990
Distrito Federal	Brazilândia	-48.2000	-15.6833	1950-1990

State	Locality	Longitude	Latitude	Year
Distrito Federal	Brasília	-47.9167	-15.7667	1950-1990
Distrito Federal	Brasília	-47.9500	-15.716700	1950-1990
Distrito Federal	Brasília	-47.8833	-15.933300	1950-1990
Distrito Federal	Brasilia	-47.6247	-14.166100	1950-1990
Goiás	Aragarças	-52.2500	-15.916700	1950-1990
Goiás	São João da Aliança	-47.5333	-14.700000	1950-1990
Goiás	Emas National Park	-52.8884	-18.261200	1950-1990
São Paulo	Itirapina	-47.9000	-22.216700	1950-1990
Bahia	Between Mucugê and Ibicoara	-41.2833	-13.350000	>1990
Distrito Federal	Brasília	-47.8998	-15.928531	>1990
Distrito Federal	Brasília	-47.8667	-15.916700	>1990
Distrito Federal	Brasilia	-47.9241	-15.868900	>1990
Distrito Federal	Brasília	-47.7158	-15.843589	>1990
Distrito Federal	Brasília	-47.8879	-15.794100	>1990
Distrito Federal	Brasília	-48.0885	-15.771500	>1990
Distrito Federal	Brasília	-48.1005	-15.764250	>1990
Goiás	Chapadão do Céu	-52.6708	-18.394000	>1990
Goiás	Parna Emas	-52.8884	-18.261000	>1990
Goiás	Mineiros	-52.8841	-18.164978	>1990
Goiás	Mineiros	-52.9242	-18.096200	>1990
Goiás	Chapadão do Céu	-52.9242	-18.095700	>1990
Goiás	Emas National Park	-52.9352	-18.067400	>1990
Goiás	Mineiros	-52.5547	-17.566200	>1990
Goiás	Cristalina	-47.3414	-16.885567	>1990
Goiás	Cristalina	-47.3819	-16.875814	>1990
Goiás	Cristalina	-47.6068	-16.769400	>1990
Goiás	Cristalina	-47.6000	-16.766700	>1990

State	Locality	Longitude	Latitude	Year
Goiás	Alto paraíso de Goiás	-47.5132	-14.312861	>1990
Goiás	Alto paraíso de Goiás	-47.5136	14.30700	>1990
Goiás	Alto paraíso de Goiás	-47.7051	-14.302472	>1990
Goiás	Alto paraíso de Goiás	-47.7061	-14.300556	>1990
Goiás	Fazenda FIRMEZA	-47.4854	-14.290100	>1990
Goiás	road to Catarata dos Couros	-47.5297	-14.281400	>1990
Goiás	Alto paraíso de Goiás	-47.5297	-14.281383	>1990
Goiás	Alto paraíso de Goiás	-47.5707	-14.196306	>1990
Goiás	Alto paraíso de Goiás	-47.6318	-14.137147	>1990
Goiás	Alto paraíso de Goiás	-47.5191	-14.136200	>1990
Goiás	Estrada Rio dos Couros	-47.6730	-14.135400	>1990
Goiás	Chapada dos Veadeiros	-47.7098	-14.110900	>1990
Goiás	Chapada dos Veadeiros	-47.6167	-14.033300	>1990
Goiás	Fazenda Piqui	-47.5542	-13.490300	>1990
Mato Grosso	Itiquira	-53.8247	-17.288611	>1990
Mato Grosso	Itiquira	-54.1443	-17.206800	>1990
Mato Grosso	Itiquira	-54.1365	-17.200300	>1990
Mato Grosso	Campo Verde	-55.2870	-15.817680	>1990
Mato Grosso	Campo Verde	-55.1717	-15.553700	>1990
Mato Grosso do Sul	Costa Rica	-53.1330	-18.543500	>1990
Mato Grosso do Sul	Parna Emas	-52.7966	-18.342400	>1990
Minas Gerais	Carrancas	-44.6667	-21.450000	>1990
Minas Gerais	Carrancas	-44.4667	-21.483300	>1990
Minas Gerais	Bom Jardim de Minas	-44.1894	-21.945900	>1990
Minas Gerais	São Vicente de Minas	-44.4547	-21.697500	>1990
Minas Gerais	Santana do Garambéu	-44.0667	-21.616700	>1990
Minas Gerais	Madre de Deus de Minas	-44.3409	-21.477300	>1990
Minas Gerais	Piedade do Rio Grande	-44.2025	-21.469700	>1990
Minas Gerais	Ibertioga	-43.9681	-21.429500	>1990

State	Locality	Longitude	Latitude	Year
Minas Gerais	Itutinga	-44.7167	-21.366700	>1990
Minas Gerais	Aiuruoca	-44.6028	-21.975900	>1990
Minas Gerais	Carrancas	-44.6436	-21.491600	>1990
Minas Gerais	Andrelândia	-44.2928	-21.695600	>1990
Minas Gerais	Carrancas	-44.6155	-21.472800	>1990
Minas Gerais	Bom Jardim de Minas	-44.1833	-21.933300	>1990
Minas Gerais	Arantina	-44.2470	-21.916100	>1990
Minas Gerais	Andrelândia	-44.3177	-21.737000	>1990
Minas Gerais	Lima Duarte	-44.0500	-21.733300	>1990
Minas Gerais	São Thomé das Letras	-44.9870	-21.720700	>1990
Minas Gerais	Andrelândia	-44.2833	-21.716700	>1990
Minas Gerais	Carrancas	-44.5833	-21.466700	>1990
Minas Gerais	Barbacena	-43.7662	-21.228400	>1990
Minas Gerais	Barbacena	-43.7762	-21.224900	>1990
Minas Gerais	Barbacena	-43.7667	-21.216700	>1990
Minas Gerais	São João del-Rei	-44.1570	-21.208200	>1990
Minas Gerais	São João del-Rei	-44.1787	-21.201900	>1990
Minas Gerais	São João del-Rei	-44.1950	-21.179700	>1990
Minas Gerais	São João del-Rei	-44.1742	-21.178300	>1990
Minas Gerais	São João del-Rei	-44.1975	-21.173500	>1990
Minas Gerais	São João del-Rei	-44.1671	-21.166600	>1990
Minas Gerais	São João del-Rei	-44.1965	-21.161300	>1990
Minas Gerais	São João del-Rei	-44.2507	-21.159800	>1990
Minas Gerais	Serra do Carvoeiro	-44.1949	-21.156100	>1990
Minas Gerais	Unnamed Road	-44.1938	-21.154800	>1990
Minas Gerais	São João del-Rei	-44.2610	-21.135500	>1990
Minas Gerais	São João del-Rei	-44.2529	-21.129700	>1990
Minas Gerais	São João del-Rei	-44.2500	-21.116700	>1990
Minas Gerais	Tiradentes	-44.1727	-21.107000	>1990

State	Locality	Longitude	Latitude	Year
Minas Gerais	Prados	-44.0733	-21.056000	>1990
Minas Gerais	São João Batista do Glória	-46.5035	-20.639000	>1990
Minas Gerais	Serra da Canastra	-46.4084	-20.546800	>1990
Minas Gerais	Delfinópolis	-46.8582	-20.345800	>1990
Minas Gerais	Serra de Canastra	-46.7750	-20.333800	>1990
Minas Gerais	São Roque de Minas	-46.3833	-20.333300	>1990
Minas Gerais	Vargem Bonita	-46.3725	-20.326800	>1990
Minas Gerais	São Roque de Minas	-46.4179	-20.326400	>1990
Minas Gerais	Serra da Canastra	-46.5090	-20.324100	>1990
Minas Gerais	Serra da Canastra	-46.5190	-20.297900	>1990
Minas Gerais	Serra da Canastra	-46.4065	-20.260100	>1990
Minas Gerais	São Roque de Minas	-46.5512	-20.253900	>1990
Minas Gerais	São Roque de Minas	-46.3690	-20.250700	>1990
Minas Gerais	Serra da Canastra	-46.4955	-20.250600	>1990
Minas Gerais	Serra da Canastra	-46.6167	-20.250000	>1990
Minas Gerais	São Roque de Minas	-46.3673	-20.246800	>1990
Minas Gerais	Serra da Canastra National Park	-46.5065	-20.233900	>1990
Minas Gerais	Serra da Canastra National Park	-46.5563	-20.224400	>1990
Minas Gerais	Unnamed locality	-46.4587	-20.223700	>1990
Minas Gerais	Unnamed locality	-46.5666	-20.219700	>1990
Minas Gerais	Serra da Canastra	-46.4763	-20.218300	>1990
Minas Gerais	Serra da Canastra	-46.6667	-20.166700	>1990
Minas Gerais	São João Batista da Canastra	-46.6631	-20.152500	>1990
Minas Gerais	Serra da Canastra	-46.7586	-20.143500	>1990
Minas Gerais	Sacramento	-46.8084	-20.138700	>1990
Minas Gerais	Sacramento	-46.9874	-20.112100	>1990
Minas Gerais	Sacramento	-47.1155	-20.075500	>1990
Minas Gerais	Ribeirão Rolinho	-47.0358	-20.017100	>1990

State	Locality	Longitude	Latitude	Year
Minas Gerais	Medeiros	-46.2267	-19.993300	>1990
Minas Gerais	Tapira	-46.8219	-19.925600	>1990
Minas Gerais	Tapira	-46.8167	-19.916700	>1990
Minas Gerais	Sacramento	-47.4366	-19.863600	>1990
Minas Gerais	Tapira	-46.8500	-19.833300	>1990
Minas Gerais	Uberaba	-47.9836	-19.713500	>1990
Minas Gerais	Uberaba	-48.0167	-19.283300	>1990
Minas Gerais	Duratex entorno	-48.0855	-19.242100	>1990
Minas Gerais	Pompéu	-45.0333	-19.241700	>1990
Minas Gerais	Pompéu	-44.9935	-19.228600	>1990
Minas Gerais	Pompéu	-45.0162	-19.227800	>1990
Minas Gerais	Pompéu	-45.0185	-19.227700	>1990
Minas Gerais	Pompéu	-45.0019	-19.221000	>1990
Minas Gerais	Pompéu	-44.9986	-19.218900	>1990
Minas Gerais	Pompéu	-44.9958	-19.214300	>1990
Minas Gerais	Pompéu	-45.0022	-19.210800	>1990
Minas Gerais	Patrocínio	-46.9247	-19.053100	>1990
Minas Gerais	Unnamed Road	-44.8235	-18.986300	>1990
Minas Gerais	Pompéu	-44.8223	-18.986000	>1990
Minas Gerais	Fazenda Laranjo	-44.7881	-18.976700	>1990
Minas Gerais	Patrocínio	-46.9974	-18.940800	>1990
Minas Gerais	Patrocínio	-46.9833	-18.933300	>1990
Minas Gerais	Unnamed Road	-44.8374	-18.927400	>1990
Minas Gerais	Curvelo	-44.4284	-18.755500	>1990
Minas Gerais	Gouveia	-43.7340	-18.443000	>1990
Minas Gerais	São Gonçalo do Abaeté	-45.8342	-18.341100	>1990
Minas Gerais	Diamantina	-43.6871	-18.314900	>1990
Minas Gerais	Diamantina	-43.5945	-18.242100	>1990

State	Locality	Longitude	Latitude	Year
Minas Gerais	Três Marias	-45.2257	-18.205900	>1990
Minas Gerais	Fragmento BC-4	-47.1333	-17.566700	>1990
Minas Gerais	Paracatu	-47.3612	-17.288731	>1990
Minas Gerais	São João del-Rei	-44.2228	-21.939867	>1990
Minas Gerais	São João del-Rei	-44.2165	-21.926200	>1990
Minas Gerais	São João del-Rei	-44.2131	-21.907100	>1990
Minas Gerais	São João del-Rei	-44.2967	-21.797589	>1990
Minas Gerais	São João del-Rei	-44.2952	-21.777122	>1990
Minas Gerais	São João del-Rei	-44.2922	-21.773856	>1990
Minas Gerais	São João del-Rei	-44.1669	-21.739206	>1990
Minas Gerais	São João del-Rei	-43.9691	-21.715189	>1990
Minas Gerais	São João del-Rei	-44.0733	-21.668964	>1990
Minas Gerais	São João del-Rei	-44.0640	-21.668875	>1990
Minas Gerais	São João del-Rei	-44.0710	-21.665897	>1990
Minas Gerais	São João del-Rei	-44.1440	-21.613667	>1990
Minas Gerais	São João del-Rei	-44.3875	-21.564383	>1990
Minas Gerais	São João del-Rei	-44.3529	-21.563050	>1990
Minas Gerais	São João del-Rei	-44.3894	-21.561353	>1990
Minas Gerais	São João del-Rei	-44.3584	-21.560253	>1990
Minas Gerais	São João del-Rei	-44.0419	-21.553439	>1990
Minas Gerais	São João del-Rei	-44.0377	-21.551247	>1990
Minas Gerais	São João del-Rei	-44.0572	-21.526875	>1990
Minas Gerais	Carrancas	-44.7023	-21.484142	>1990
Minas Gerais	Carrancas	-44.6672	-21.454575	>1990
Minas Gerais	São João del-Rei	-44.6669	-21.451433	>1990
Minas Gerais	São João del-Rei	-44.6540	-21.432442	>1990
Minas Gerais	São João del-Rei	-44.6509	-21.428867	>1990
Minas Gerais	São João del-Rei	-44.1369	-21.422228	>1990

State	Locality	Longitude	Latitude	Year
Minas Gerais	São João del-Rei	-44.1392	-21.416892	>1990
Minas Gerais	São João del-Rei	-44.7379	-21.348342	>1990
Minas Gerais	São João del-Rei	-43.9782	-21.344797	>1990
Minas Gerais	São João del-Rei	-43.9820	-21.342489	>1990
Minas Gerais	São João del-Rei	-43.8945	-21.293108	>1990
Minas Gerais	São João del-Rei	-44.1656	-21.261630	>1990
Minas Gerais	São João del-Rei	-44.1644	-21.261056	>1990
Minas Gerais	São João del-Rei	-44.1637	-21.259861	>1990
Minas Gerais	São João del-Rei	-44.1483	-21.259194	>1990
Minas Gerais	São João del-Rei	-44.1822	-21.257860	>1990
Minas Gerais	São João del-Rei	-44.0698	-21.250928	>1990
Minas Gerais	São João del-Rei	-44.1736	-21.249680	>1990
Minas Gerais	São João del-Rei	-44.0636	-21.247814	>1990
Minas Gerais	São João del-Rei	-44.1100	-21.240069	>1990
Minas Gerais	São João del-Rei	-44.1796	-21.228848	>1990
Minas Gerais	São João del-Rei	-44.1772	-21.228600	>1990
Minas Gerais	São João del-Rei	-44.1749	-21.225070	>1990
Minas Gerais	São João del-Rei	-44.1738	-21.222530	>1990
Minas Gerais	São João del-Rei	-44.1744	-21.222300	>1990
Minas Gerais	São João del-Rei	-44.1836	-21.213725	>1990
Minas Gerais	São João del-Rei	-44.1546	-21.211767	>1990
Minas Gerais	São João del-Rei	-44.1779	-21.211544	>1990
Minas Gerais	São João del-Rei	-44.1533	-21.209332	>1990
Minas Gerais	São João del-Rei	-44.1580	-21.208516	>1990
Minas Gerais	São João del-Rei	-44.1700	-21.201860	>1990
Minas Gerais	São João del-Rei	-44.1750	-21.199165	>1990
Minas Gerais	São João del-Rei	-44.1822	-21.194475	>1990
Minas Gerais	São João del-Rei	-44.1825	-21.194431	>1990

State	Locality	Longitude	Latitude	Year
Minas Gerais	São João del-Rei	-44.186	-21.189450	>1990
Minas Gerais	São João del-Rei	-44.1769	-21.185720	>1990
Minas Gerais	São João del-Rei	-44.1933	-21.184930	>1990
Minas Gerais	São João del-Rei	-44.1768	-21.184673	>1990
Minas Gerais	São João del-Rei	-44.1953	-21.179870	>1990
Minas Gerais	São João del-Rei	-44.1992	-21.179170	>1990
Minas Gerais	São João del-Rei	-44.1954	-21.177851	>1990
Minas Gerais	São João del-Rei	-44.1957	-21.177400	>1990
Minas Gerais	São João del-Rei	-44.1748	-21.17543	>1990
Minas Gerais	São João del-Rei	-44.1951	-21.170970	>1990
Minas Gerais	São João del-Rei	-44.1951	-21.170721	>1990
Minas Gerais	São João del-Rei	-44.1953	-21.170397	>1990
Minas Gerais	São João del-Rei	-44.1967	-21.165359	>1990
Minas Gerais	São João del-Rei	-44.1957	-21.162402	>1990
Minas Gerais	São João del-Rei	-44.1968	-21.161731	>1990
Minas Gerais	São João del-Rei	-44.1982	-21.161700	>1990
Minas Gerais	São João del-Rei	-44.2100	-21.157616	>1990
Minas Gerais	São João del-Rei	-44.2149	-21.152977	>1990
Minas Gerais	São João del-Rei	-44.2129	-21.152654	>1990
Minas Gerais	São João del-Rei	-44.2154	-21.151050	>1990
Minas Gerais	São Roque de Minas	-46.4065	-20.260100	>1990
Minas Gerais	Serra da canastra	-46.4293	-20.255467	>1990
Minas Gerais	Serra da canastra	-46.3734	-20.254406	>1990
Minas Gerais	São Roque de Minas	-46.5497	-20.249167	>1990
Minas Gerais	Serra da canastra	-46.5134	-20.244336	>1990
Minas Gerais	Serra da canastra	-46.7197	-20.154205	>1990
Minas Gerais	Serra da canastra	-46.4438	-20.142578	>1990
Minas Gerais	Serra da canastra	-46.8536	-20.134444	>1990

State	Locality	Longitude	Latitude	Year
Minas Gerais	Uberlândia	-47.9183	-19.365605	>1990
Minas Gerais	Uberlândia	-48.0826	-19.234707	>1990
Minas Gerais	Pompéu	-45.0194	-19.234028	>1990
Minas Gerais	Pompéu	-44.8057	-18.979389	>1990
Minas Gerais	Pompéu	-44.8064	-18.962444	>1990
Minas Gerais	Pompéu	-44.8354	-18.928278	>1990
Minas Gerais	Pompéu	-44.8222	-18.898333	>1990
Minas Gerais	Curvelo	-44.7708	-18.878917	>1990
Minas Gerais	Três Marias	-44.8741	-18.421517	>1990
Minas Gerais	Três Marias	-45.4438	-18.212772	>1990
Minas Gerais	Três Marias	-45.3348	-18.170181	>1990
Minas Gerais	Paracatu	-47.3659	-17.290301	>1990
Minas Gerais	Paracatu	-47.3644	-17.290211	>1990
Tocantins	Paranã	-47.6833	-13.400000	>1990
Tocantins	Paranã	-47.7056	-13.395800	>1990

Chapter III: The effects of climate change along an altitudinal gradient: the case of *Geositta* miners

RESUMO

Mudanças de alcance ao longo de gradientes latitudinais e de elevação são uma resposta de diferentes grupos de espécies para lidar com as mudanças climáticas. Nos trópicos, já se observou que a elevação tem um efeito mais intenso, pois as mudanças de temperatura são maiores para este parâmetro. Neste estudo, utilizando modelagem de nicho ecológico, investigamos a relação entre os padrões de distribuição atuais e futuros e as mudanças climáticas das sete aves residentes do gênero *Geositta*, um grupo de espécies neotropicais que habitam ambientes abertos áridos e semiáridos em diferentes altitudes. Utilizamos três algoritmos para produzir os modelos, com 10 repetições para cada um. Para previsões futuras, usamos dois Modelos Gerais de Circulação para o período entre 2061 e 2080 e dois cenários diferentes de emissões de gases de efeito estufa com diferentes políticas climáticas. Também verificamos a adequação climática para o registro de ocorrência de cada espécie em relação à sua elevação. Todas as espécies perderão aptidão e área em ambos os cenários, mas o cenário pessimista é mais preocupante. Aqueles que ocorrem em altitudes médias mais baixas perderão proporcionalmente mais área do que aqueles que vivem em altitudes médias mais altas. Houve diferença no padrão de adequação climática entre espécies de altitudes mais baixas e espécies de altitudes mais altas, o que parece ser devido ao zoneamento vegetacional e elevacional das encostas andinas, que proporcionam maior umidade em áreas de transição. Nossos resultados alertam para um destino incerto do gênero nos próximos anos se nenhuma política concreta for aplicada para mitigar as emissões de gases de efeito estufa e as mudanças climáticas. No entanto, alertamos que as políticas de conservação devem ser baseadas em evidências, uma vez que a resposta às mudanças climáticas pode apresentar padrões diferentes.

Palavras-chave: Cerrado brasileiro, áreas climaticamente adequadas, modelagem de nicho ecológico, Andes tropicais.

ABSTRACT

Range shifts throughout latitudinal and elevational gradients are a response of different species groups to cope with climate change. In the tropics, it has been already observed that elevation has a more intense effect, as temperature changes are greater for this parameter. In this study, we investigated the relationship between the current and future distribution patterns and climate changes of the seven resident birds of the genus *Geositta*, a group of neotropical species inhabiting from arid and semi-arid open habitats in different altitudes. For this, we used ecological niche modeling to identify current and future habitat climatic suitability for each species. We used three algorithms to produce the models, with 10 repetitions for each. For future predictions, we used two General Circulation Models for the period between 2061 and 2080 and two different scenarios of greenhouse gas emissions with different climate policies. We also verified the climatic suitability for each species occurrence record relative to its elevation. All species will lose suitability and area in both scenarios, but the pessimistic scenario is more worrying. Those occurring in lower average elevations will lose proportionally more area than those living in higher average elevations. There was a difference in the pattern of climatic suitability between species from lower altitudes and species from higher altitudes, which seems to be due to the vegetational and elevational zonation of the Andean slopes, which provide higher humidity in transition areas. Our results warn for an uncertain fate of the genus in the coming years if no concrete policy is enforced to mitigate greenhouse gases emissions and climate change. However, we avert that conservation policies should be evidence based, since the response to climate change may present different patterns.

Keywords: Brazilian Cerrado, climatically suitable areas, ecological niche modeling, tropical Andes.

1. INTRODUCTION

Changes in the geographic range of a species along elevational and/or latitudinal gradients are strong evidence of climate changes (Grabherr *et al.* 1994, Boisvert-Marsh *et al.* 2014, La Sorte *et al.* 2014). However, for tropical species, latitude does not have a potentially strong effect in driving such range shifts, since the latitudinal gradient is small and with little temperature variation compared to elevation (Forero-Medina *et al.* 2011, La Sorte *et al.* 2014, Perillo *et al.* 2021). Therefore, species in search of more suitable climatic locations end up moving to higher areas, so range changes end up causing loss of habitat area and potentially threatening the fate of the species (Raxworthy *et al.* 2008, Freeman *et al.* 2018, Lele *et al.* 2020).

As in mountain environments, the future of species in open habitats does not look so bright either (Marini *et al.* 2009, Borges *et al.* 2019). This is because these are very dynamic habitats that suffer from constant natural and anthropic pressures in time and space, being therefore very sensitive to climate changes (Gibson & Newman 2019). Consequently, these environments will experience a great biodiversity loss if mitigation measures are not taken (Hidasi-Neto *et al.* 2019, Hofmann *et al.* 2021). According to the latest report of the Intergovernmental Panel on Climate Change (IPCC 2022), the rise in temperature in the coming years will be decisive for the future of open habitat biodiversity, contributing to large-scale extinctions and losses in the functional diversity of these ecosystems. This finding is even more worrying because some of these environments contain a unique set of species, with some of them considered biodiversity hotspots (Myers *et al.* 2000).

Among the species inhabiting open habitats along different altitudinal ranges, we can highlight those included in the genus *Geositta* (Scleruridae). Composed of eleven species of terrestrial birds distributed in South America, most are found in the Andean region. They have similar habitat preferences, closely associated with open and dry environments, such as grasslands, arid shrublands, deserts and barren rocky areas (Fjeldså & Krabbe 1990, Remsen 2003, Ridgely & Tudor 2009). They also share similar behaviors such as a mostly insectivorous diet and breeding within cavities excavated in the soil by the bird itself or by other animals (Fjeldså & Krabbe 1990, Remsen 2003, Ridgely & Tudor 2009, Machado *et al.* 2017, Gómez 2019). Five species have declining populations, but only one (*Geositta poeciloptera*) is currently threatened with extinction and classified globally as Vulnerable (IUCN 2022).

Considering the relative biological homogeneity on behavior and habitat preferences for *Geositta* miners, we investigate what will be the effects of climate change on the range of each species, using ecological niche models. Because members of the genus occur along an altitudinal gradient spanning from sea level to 5000 m, with some species distributed at low and others at high elevations, we expect that their responses to climate change will be influenced by their altitude. In addition, we also evaluated the effects of these changes on different greenhouse gas emission scenarios and policies for approximately 50 years. We believe that the climatic suitability in the range of occurrence of each species will be greater at higher areas, and also that species at lower altitudes will lose a more climatically suitable area than those at higher altitudes for all scenarios, forcing them to move altitudinally.

2. METHODS

2.1. Study species

Out of the eleven species belonging to the genus *Geositta*, only the non-migrant ones were chosen for this study, totaling seven species (Table 1), since migrant species are often composed of different populations which possibly have different migratory habits and timing, presenting partial migration and/or altitudinal migration, making data analysis difficult or even unfeasible. Furthermore, few details are known about the areas and periods of migration of these species. Distributed at different elevations but in a small latitudinal range (between 0 and 30 degrees mostly), two species are currently in decline according to the IUCN red list (2022) (Table 1). For easy data interpretation, we will call the predominantly coastal species as “lowland species”, including those with a strong foothill component, while species with predominantly distributed along the Andes Mountain Range will be called “highland species”.

Table 1. The seven species of *Geositta* miners included in this study, their countries of occurrence, elevational range, conservation status, and population trends*.

Species	Countries	Upper elevation limit (m)	Lower elevation limit (m)	Status	Population Trend
<i>G. crassirostris</i>	PE	3500	300	LC	Decreasing
<i>G. maritima</i>	CL, PE	2600	0	LC	Stable
<i>G. peruviana</i>	PE	700	0	LC	Stable
<i>G. poeciloptera</i>	BO, BR	1250	500	VU	Decreasing
<i>G. punensis</i>	AR, BO, CL, PE	5000	3050	LC	Stable
<i>G. saxicolina</i>	PE	4900	3700	LC	Stable
<i>G. tenuirostris</i>	AR, BO, CL, EC, PE	4600	2500	LC	Stable

Countries: AR: Argentina; BO: Bolivia; BR: Brazil; CL: Chile; EC: Ecuador; PE: Peru. **Status:** LC: Least Concer; VU: Vulnerable.

*According to the IUCN red list (2022).

2.2. Predictions

a. Occurrence data and variables

To predict the current and future climatic niche of all species, we searched species occurrence records in the Global Biodiversity Information Facility database (GBIF available at www.gbif.com) an open access platform that provides data on all types of life on Earth. We did a filtering to eliminate duplicate points and also, points without geographic coordinates. As elevation was important for modeling the niche of *G. poeciloptera* (Chapter 2), we decided to make the correlation test using this variable for all species in addition to the 19 bioclimatic variables, all taken from the WorldClim v2 database (Fick & Hijmans 2017). To minimize multicollinearity in the data, we performed Variance Inflation Factor (VIF) analysis tests (the default limit of 10 was used) using the `usdm` package (Naimi *et al.* 2014) implemented in the R program (R Core team 2022). All variables were cropped for South America and were set to the same resolution (2.5-minute) and Datum WGS 84.

b. Present predictions

To build the current models, we performed the projections using the `biomod2` package (Thuiller *et al.* 2021) also implemented in the R program (R Core Team 2022) and three ecological niche modeling algorithms: 1) Generalized additive models - GAM - (Hastie & Tibshirani 1986; Yee & Mitchell 1991); 2) Generalized Linear Models - GLM - (McCullagh & Nelder 1989; Venables & Ripley 2002); and 3) Maximum entropy model - MAXENT - (Phillips *et al.* 2006). Ten thousand (10000) pseudo-absence points (GAM and GLM) and background (Maxent) were defined with 10 independent runs for each one. To assess the predictive performance of the models, for each species, we used 75% of the data for calibration and the remaining 25% for evaluation. A threshold > 0.8 was determined to evaluate the performance of the models based on the average True Skill Statistic (TSS) (Allouche *et al.* 2006) and Receiver Operating Characteristics (ROC) curve (Fielding & Bell 1997). For each species, we built ensemble models following the method used by Köhler *et al.* (2020) using the weighted average of the binarized projections from the determined TSS threshold, resulting in a single map.

c. Future predictions

To build the future models for each species, we used two General Circulation Models (GCM), BCC-CSM2-MR and MIROC-ES2L for approximately 50 years (2061-2080). All data were also taken from the WorldClim v2 database (Fick & Hijmans 2017). We evaluated two different climate policy scenarios for greenhouse gas emissions based on Shared Socio-Economic Pathways - SSPs: 1) Optimistic (ssp245), with climate policies to reduce greenhouse gas emissions over the years and limit warming to $\sim 2.5^{\circ}\text{C}$; and 2) Pessimistic (ssp585), with a substantial increase in greenhouse gas emissions ($\sim 5^{\circ}\text{C}$) (Riahi *et al.* 2017, Gidden *et al.* 2019). All models generated were based on the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring *et al.* 2016).

2.3. Statistical analysis

We measured the climatically suitable area by species ($> 50\%$ suitability) for the present and future for both scenarios and relate it to the mean elevation of occurrence for each species. Through the MuMin package, implemented in R (R Core 2022 team) we evaluated the relationship between area loss and mean elevation of occurrence using multi-model inference, based on a global model with all candidate variables (area loss, mean elevation of occurrence and model) followed by model selection (Burnham *et al.* 2011). Model performance was evaluated based on AICc and the best model set was selected among all possibilities derived from global models via multi-model inference (Burnham *et al.* 2011). From the full set of possible models, we calculated the coefficients average of all models within $\Delta\text{AICc} < 2$. We also extract suitability and elevation values for each occurrence record by species for current and future models and checked the distribution fit and model using residuals analysis (Crawley 2012).

3. RESULTS

A total of 4335 records were compiled for the seven species (Table 2). The VIF analyzes for all species revealed different variables for each one, however two variables were important for all of them: Precipitation of Driest Month (Bio 14) and

Precipitation Seasonality (Bio 15). Among the two variables, precipitation of driest month was more important, ranging from 9.8 to 41% depending on the species (Table 2).

Table 2. Selected environmental variables and percent contribution to predict present climate niche for each species.

Variables	Description	Percent contribution for each species (%)						
		<i>G. crassirostris</i> (159)*	<i>G. maritima</i> (549)*	<i>G. peruviana</i> (1267)*	<i>G. poeciloptera</i> (113)*	<i>G. punensis</i> (1065)*	<i>G. saxicolina</i> (273)*	<i>G. tenuirostris</i> (909)*
Bio 1	Annual Mean Temperature	-	-	-	-	-	-	-
Bio 2	Mean Diurnal Range (Mean of monthly)	-	-	-	22.0	4.0	33.3	9.5
Bio 3	Isothermality	-	-	-	47.6	20.0	59.8	6.2
Bio 4	Temperature Seasonality	49.8	25.8	54.7	-	-	35.5	-
Bio 5	Max Temperature of Warmest Month	-	29.7	-	-	-	-	-
Bio 6	Min Temperature of Coldest Month	-	-	-	-	-	-	-
Bio 7	Temperature Annual Range	51.3	11.7	9.0	-	-	-	-
Bio 8	Mean Temperature of Wettest Quarter	59.9	35.7	-	-	-	81.7	36.5
Bio 9	Mean Temperature of Driest Quarter	-	-	13.0	-	31.3	-	-
Bio 10	Mean Temperature of Warmest Quarter	-	-	-	-	-	-	-
Bio 11	Mean Temperature of Coldest Quarter	-	-	-	-	-	-	-
Bio 12	Annual Precipitation	-	67.4	-	-	-	-	-
Bio 13	Precipitation of Wettest Month	53.7	-	25.0	27.5	-	50.7	19.2
Bio 14	Precipitation of Driest Month	41.0	20.0	40.2	36.7	13.6	39.3	9.8
Bio 15	Precipitation Seasonality	31.5	3.0	2.0	25.8	18.7	33	19.2
Bio 16	Precipitation of Wettest Quarter	-	-	-	55.0	-	-	-
Bio 17	Precipitation of Driest Quarter	-	-	-	-	-	-	-
Bio 18	Precipitation of Warmest Quarter	-	-	-	45.9	4.3	47.4	8.0
Bio 19	Precipitation of Coldest Quarter	-	17.0	16.0	-	27.9	-	-
Elev	Elevation	-	-	29.0	49.9	66.8	46.5	46.3

*Number of occurrence records

The performance of all generated models (10 runs per algorithm) was satisfactory and superior to the previously determined threshold of 0.8, with its average varying between 0.85 and 0.95 for TSS and 0.94 and 0.98 for ROC (Table 3).

Table 3. Average of TSS and ROC values to evaluate the performance of all models.

Species	TSS	ROC
<i>G. crassirostris</i>	0.85	0.96
<i>G. maritima</i>	0.95	0.98
<i>G. peruviana</i>	0.92	0.97
<i>G. poeciloptera</i>	0.87	0.94
<i>G. punensis</i>	0.95	0.98
<i>G. saxicolina</i>	0.92	0.97
<i>G. tenuirostris</i>	0.93	0.98

The ecological niche models generated for all species in the present proved to be well adjusted and according to the occurrence records for each species, and for at least three of them, the limits of climatic suitability extrapolated the limits of the occurrence records (Fig. 1 and Supplementary material – Fig.1).

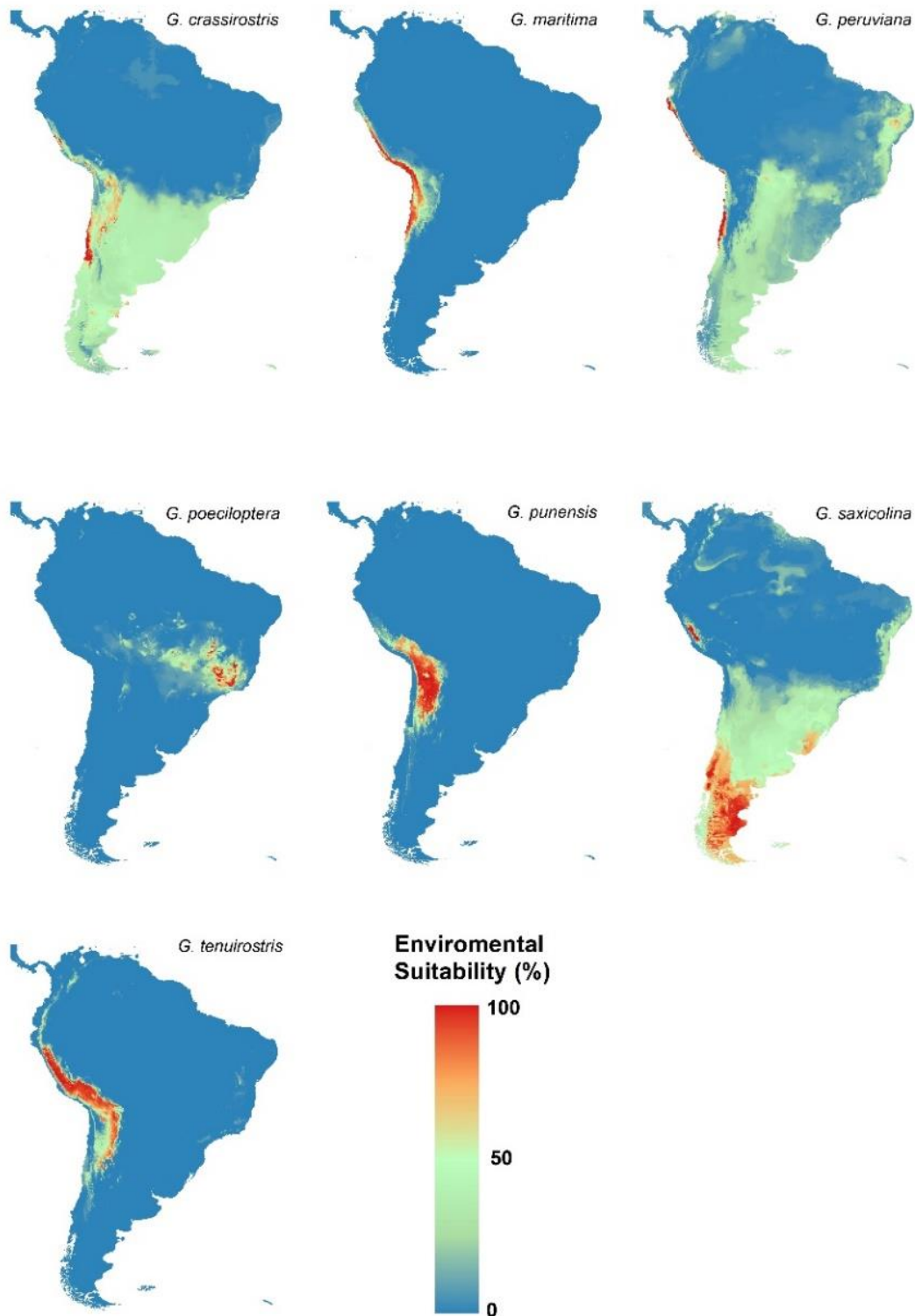


Figure 1. Ensemble models generated for the prediction of the current suitable areas for the occurrence of the *Geositta* miners in South America. The maps of occurrence records can be found in the Supplementary Material (Fig.1).

For future predictions, all GCM models (BCC-CSM2-MR and MIROC-ES2L) showed a considerable reduction of suitable climatic areas for each species between the years 2061 and 2080. However, the models with scenarios without mitigation policies of greenhouse gas emissions (ssp585) and consequently greater global warming showed a greater reduction in area (Figs. 2 and 3).

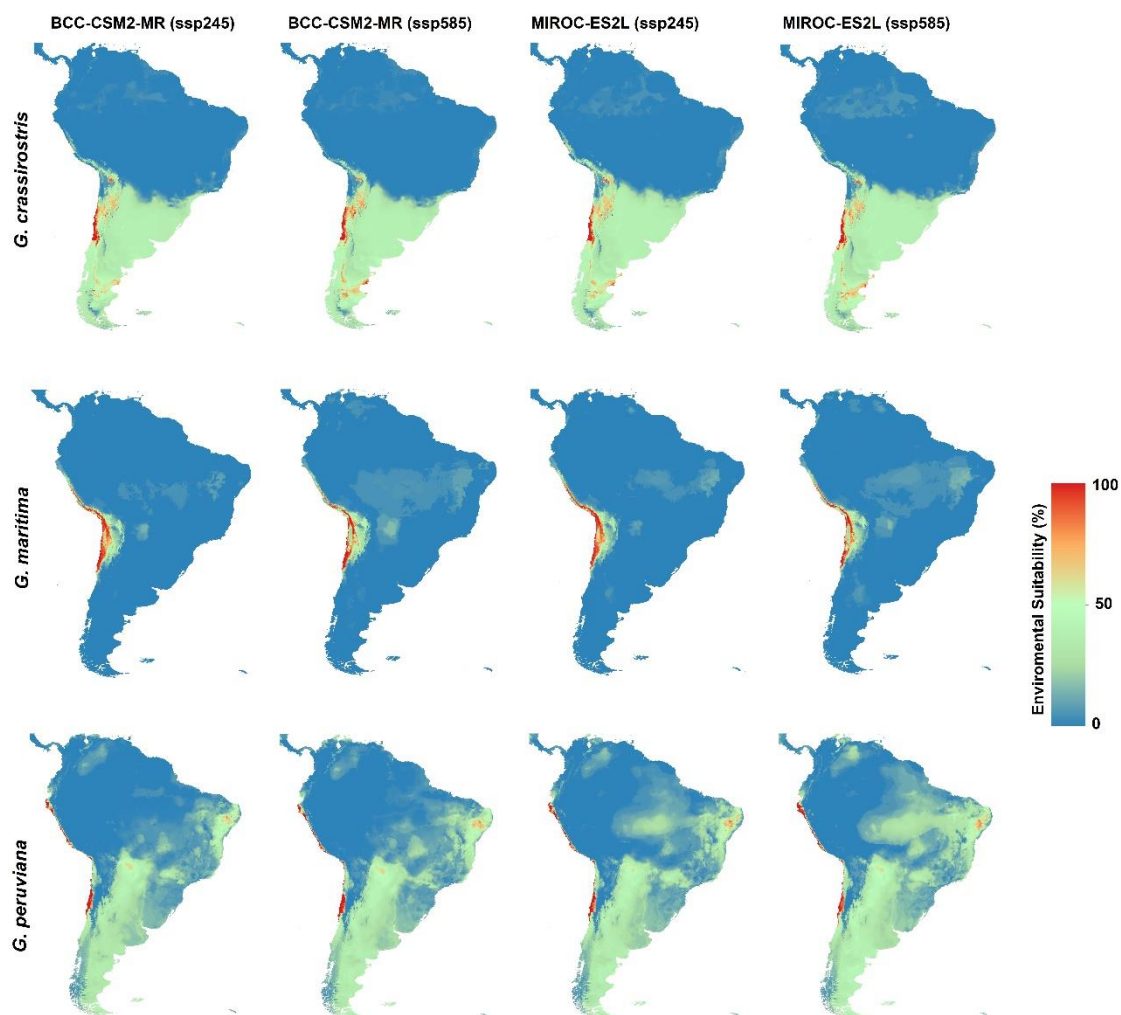


Figure 2. Ensemble models of future predictions (2061-2080) of suitable areas for the occurrence of *Geositta* miners in South America for the optimistic (ssp245) and pessimistic (ssp585) scenarios (Lowland species). Models for all species in large size (including the current model) can be seen in Supplementary Material (Figs. 2–8).

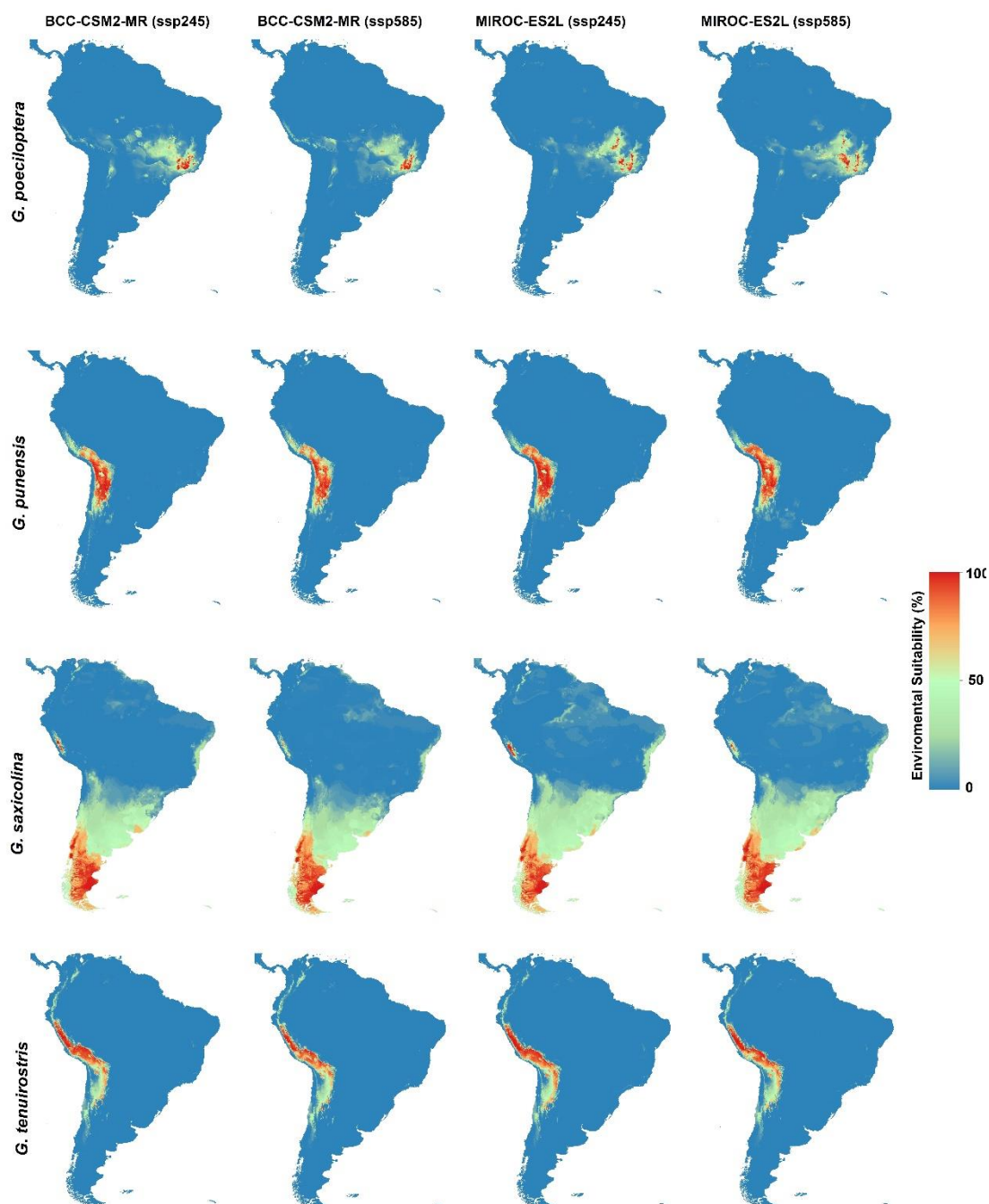


Figure 3. Ensemble models of future predictions (2061-2080) of suitable areas for the occurrence of *Geositta* miners in South America for the optimistic (ssp245) and pessimistic (ssp585) scenarios (*G. poeciloptera* and highland species). Models for all species in large size (including the current model) can be seen in Supplementary Material (Figs. 2–8).

As for the model selection, the model that presents a mean elevation of occurrence, as well as the null model, had the same probability within a $\Delta AICc = 1.52$, however, accounting for only 30% of the weight (w) of the independent effect. The pattern presented shows that species with lower mean elevation will lose a proportionately greater area than those with higher mean elevations, and this loss will also be greater for scenarios with higher greenhouse gas emissions and without mitigation policies (Fig. 4).

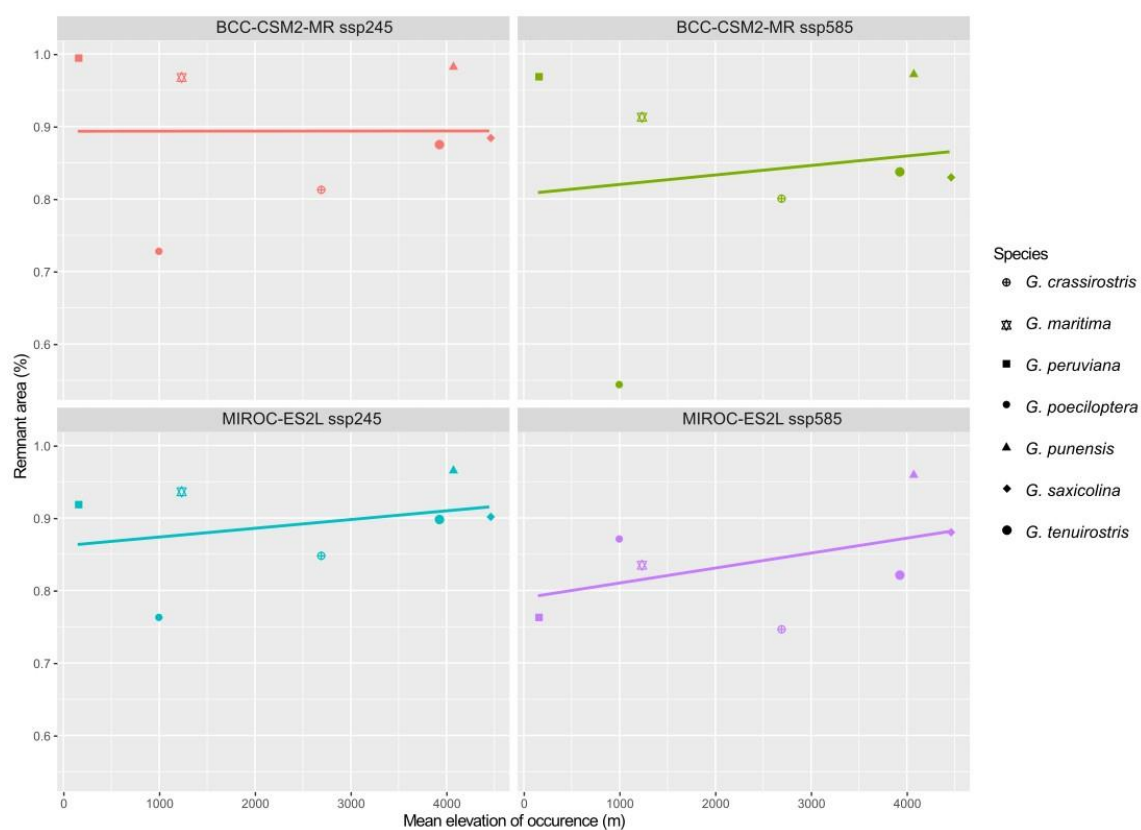


Figure 4. Remnants area by mean elevation of occurrence for *Geositta* miners for two GCM's and two greenhouse gas emission scenarios.

The climatic suitability extracted for all occurrence records by species at present, although not showing a significant relationship with altitude ($\chi^2 = 1.06$, Df = 1, $P = 0.30$), showed a similar pattern for two highland species that presented a minimum limit of occurrence in areas above 3000 meters and for *G. poeciloptera*, a non-Andean species with a minimum elevation limit of occurrence above 300 meters. These species showed greater suitability in higher areas and lower suitability in lower areas. The lowland species ($n = 2$) with minimum elevation limits of occurrence below 200 meters

presents an inverse pattern. For *G. maritima* (lower elevation limits <300) and *G. punensis* (lower elevation limits >3050) these patterns did not show substantial differences, with a slight decrease or increase in suitability at higher altitudes, respectively (Fig. 5).

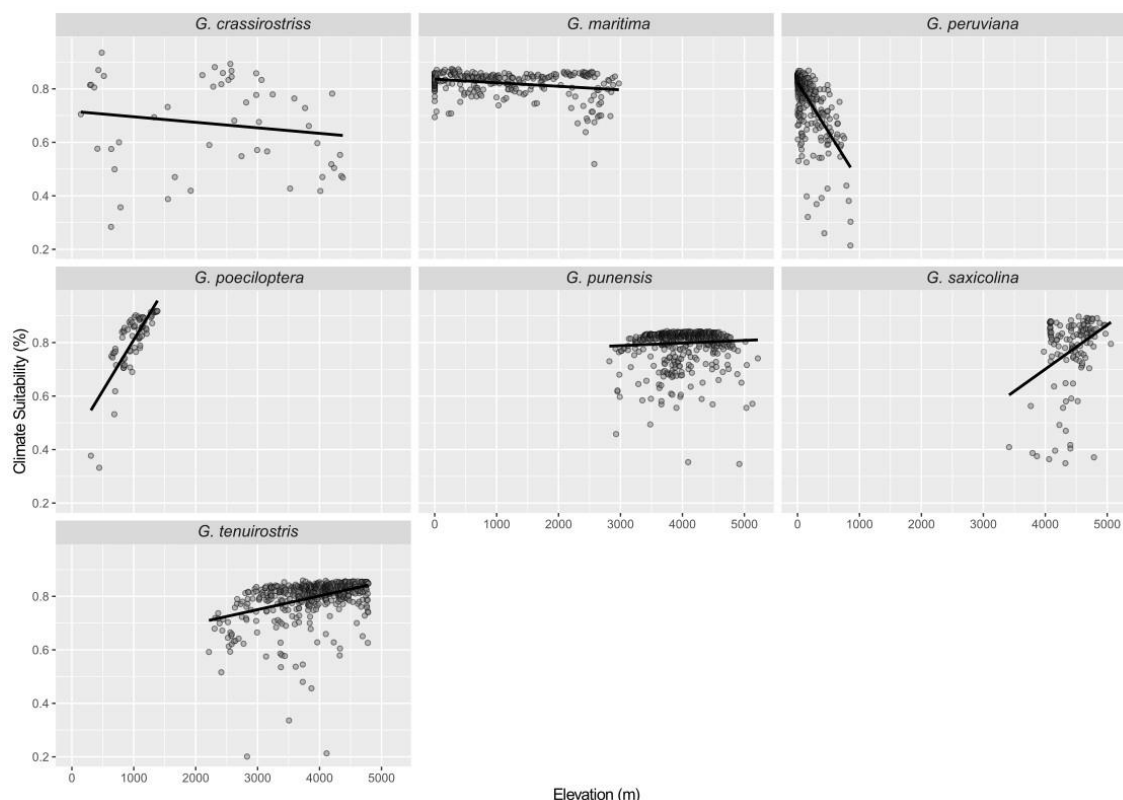


Figure 5. Current climate suitability for all occurrence records of *Geositta* miners in South America in relation to elevation.

The relationship between climate suitability and elevation were significant for both future scenarios ($\chi^2 = 22.31$, Df = 1, $P < 0.001$ – Optimistic) and ($\chi^2 = 30.60$, Df = 1, $P < 0.001$ – Pessimistic) and follow the same pattern presented by each species in the current period. However, for the pessimistic scenario of greenhouse gas emissions, this suitability will be smaller than in an optimistic scenario (Fig. 6).

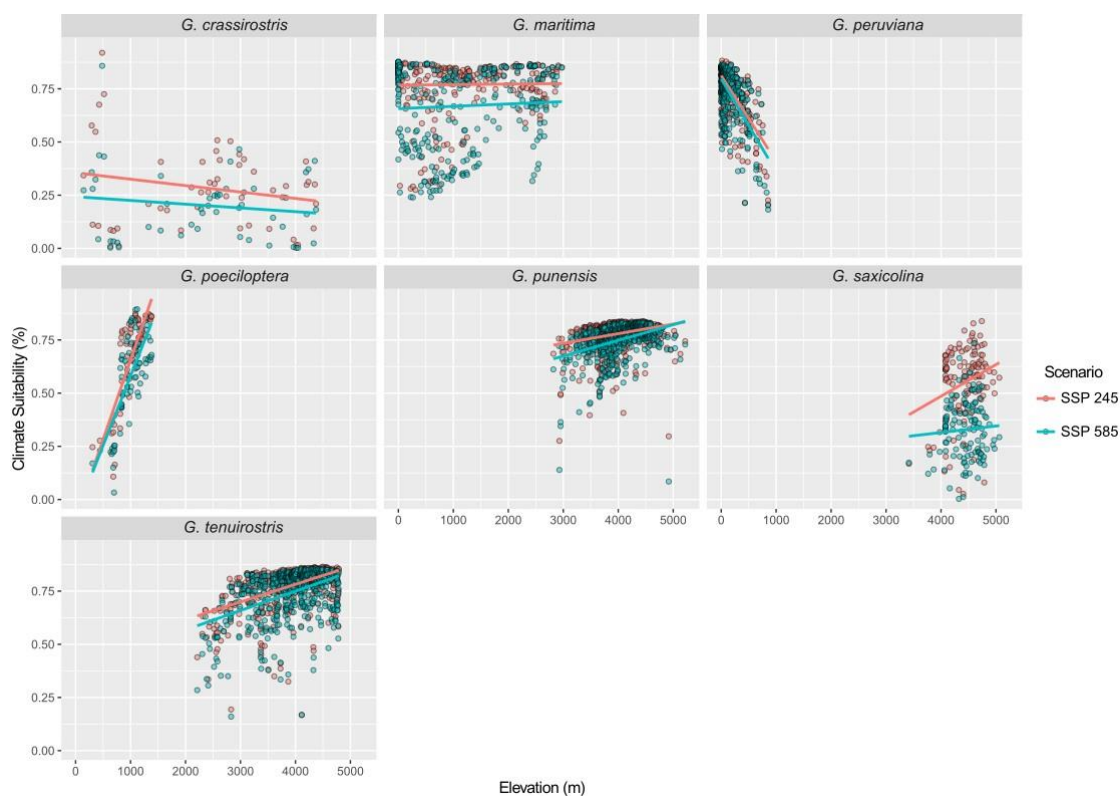


Figure 6. Future climate suitability for all occurrence records of *Geositta* miners in South America for two greenhouse gas emission scenarios: Optimistic (ssp245) and pessimistic (ssp585).

4. DISCUSSION

The fact that all species share the Precipitation of Driest Month (Bio 14) and Precipitation Seasonality (Bio 15) variables, although not the most important for each species, are strong evidence of the preference for similar habitats for all *Geositta* miners. The variable Bio 14, which presented the variation between 9.8 and 41%, shows how extreme conditions of precipitation during the year can influence the potential range of the genus (O'Donnell & Ignizio 2012). The variable Bio 15 shows the variation of precipitation throughout the year and, the greater the percentage of this variable, the greater its variability (O'Donnell & Ignizio 2012). However, because it does not present high values for all species (between 2 and 33%), showed how much this genus prefers more stable places with low precipitation rainfall throughout the year.

The current projections showed great similarity with the projections made by Ribeiro *et al.* (2016), where ecological niche models were created to predict the diversification of the genus *Geositta*. The climatically suitable areas corresponded to

the occurrence records for each species, however some discrepancies between the projections in the two studies were found, with different extrapolations for the climatically suitable areas. This can be explained by the difference in the choice and treatment of data for each study, in addition to the choice of algorithms used. Ribeiro *et al.* (2017) used, in addition to GBIF data, data from the speciesLink portal, and only used the MAXENT algorithm for ecological niche modeling. The fact is that the Andes, due to its extremely mountainous topography with deep valleys that isolate islands, a very complex vegetation zonation, with areas of forests, shrublands, grasslands, and deserts varying between different altitudes and rivers that separate bioregions (Fjeldså & Krabbe 1990, Borsdorf & Stadel 2015, Hazzi *et al.* 2018), create barriers that prevent the colonization of some areas (Haffer 1967, Vuilleumier 1970).

Even though species from lower altitudes are expected to proportionally lose more suitable areas, some studies show that high-altitude species may experience extinction more quickly when moving to higher areas, since mountain tops have less area (Raxworthy *et al.* 2008, Freeman *et al.* 2018, Lele *et al.* 2020). Although this prediction is a worrying fact and several studies point to this scenario, each case must be analyzed separately, taking into account not only climatic factors, but also interactions between species, human impacts (such as land use changes for agriculture and livestock), and geographic barriers (Terborgh 1971, Terborgh & Weske 1975, Forero-Medina *et al.* 2011, Chapter 2).

Geositta poeciloptera, the most distinctive of all species of the genus – it is the only endemic to the Brazilian Cerrado – (Ridgely & Tudor 2003) and the most studied species among them (see Machado *et al.* 2017, Meireles *et al.* 2018, Lopes *et al.* 2021, Meireles *et al.* 2021, Lopes *et al.* *in press*), even occurring in lower areas in relation to most of its Andean congeners, it is the only one considered threatened of extinction. In Chapter 2, it was shown that the lowest altitude records of the species are from places where it has already been extinct and is linked not only to climate change, but also to the intense anthropization of the natural grasslands, which suffer from frequent fires, conversion of vegetation in pasture for cattle raising and also agriculture.

The reasons for the differences between the pattern of the climatic suitability extracted for the occurrence records of the seven studied species seem to be linked to the vegetation and elevation zonation. The highland species (*G. punensis*, *G. saxicolina* and *G. tenuirostris*) showed a similar and expected pattern, with higher suitability in higher areas and lower suitability in lower areas, although for *G. punensis*

this difference is not so marked. This is because these species are located in higher and more homogeneous environments, mainly in puna areas with little variation in vegetation and very dry habitat. These areas are bordered by a wetter tree line in the lower slopes of the Andes (Fjeldså & Krabbe 1990, Ridgely & Tudor 1994, Schulenberg *et al.* 2010), which possibly gives this ascending characteristic of climatic suitability.

The lowland species (*G. cassirostris*, *G. maritima* and *G. peruviana*) showed an inverse pattern, with higher suitability in lower areas and lower suitability in higher areas. As *G. punensis*, this pattern is not as marked for *G. maritima*. These species also have lower elevation limits records (<300m) like Peruvian coast and slopes on the western side of the Andes (Fjeldså & Krabbe 1990, Ridgely & Tudor 1994, Schulenberg *et al.* 2010). The western Andean slope, although drier than the eastern slope of the Andes, which receives moisture from the Amazon Forest (Schulenberg *et al.* 2010), has punctual areas in transition with humid areas such as the Lomas formations (Dillon *et al.* 2003, Borsdorf & Stadel 2015), with some populations found in this environment (Ridgely & Tudor 1994, Schulenberg *et al.* 2010, Gómez 2019). The Lomas formation is a vegetation belt that extends from Peru to Chile located approximately between 200 and 1000m in a fog-dependent region, therefore, wetter and with different types of vegetation than coastal areas and high-altitude deserts of the Andes (Rundel *et al.* 1991, Péfaur 1982, Borsdorf & Stadel 2015), what might be working for this suitability pattern.

For *G. poeciloptera*, despite having occurrence records in lower areas, it showed the same pattern of its highland congeners, with more climatically suitable areas at higher altitudes. The reason for this pattern is that the areas inhabited by the species are geographically distant and with different vegetation characteristics from the Andes Mountains, and that the higher altitudes have characteristics of seasonally dry natural grasslands, with poorly developed soils and little woody vegetation, and lower areas with more developed soils and with a predominance of seasonal semideciduous forests, being more humid in the lower areas (Meireles *et al.* 2018).

Species of the genus *Geositta* are associated with dry environments, such as the grasslands of the Brazilian Cerrado (Sick 1997, Machado *et al.* 2017) and desert and semi-desert environments, such as the highlands and coastal deserts along the Andes Mountains (Fjeldså & Krabbe 1990, Remsen 2003, Ridgely and Tudor 2009). The fact is that differences in humidity caused by vegetation transitions and altitude zonation may be the causes of this unexpected pattern of climatic suitability.

5. CONCLUSION

In this study, we showed a not very optimistic future for the species of *Geositta* miners. However, the speed of loss of climatically suitable areas for them will depend on environmental policies so that the requirements for the reduction of greenhouse gases (IPCC 2022) are met. Highland species, even with less loss of climatically suitable areas, are at greater risk of extinction because they do not have a greater limit of displacement beyond the mountain tops (Raxworthy *et al.* 2008, Freeman *et al.* 2018, Lele *et al.* 2020), regardless of the region of occurrence. *Geositta poeciloptera*, for example, although it does not occur at very high altitudes, has been losing areas in the lower parts (<500) and is currently found only in the middle to upper portions of the Brazilian Cerrado with a tendency to occur in the future only in the higher parts (Chapter 2).

The difference in the suitability pattern between species with lower occurrence limits and those with higher occurrence limits in the Andes is related to the elevational zonation that this mountain range has, presenting a complex vegetation mosaic, mainly on the slopes of the Pacific. The humidity coming from the ocean is trapped at a certain altitude creating fog-dependent, wetter areas, with different types of vegetation depending on the altitude (Rundel *et al.* 1991, Péfaur 1982, Dillon *et al.* 2003, Borsdorf & Stadel 2015) thus decreasing the suitability for the lowland species, which prefer more arid environments (Fjeldså & Krabbe 1990, Remsen 2003, Ridgely & Tudor 2009, Machado *et al.* 2017, Gómez 2019).

We also showed that caution is needed when studying climatic niches of species. Even if these occupy similar habitats, present and future distribution patterns may differ. A careful analysis must be done individually for each species since areas of vegetational and altitudinal transition act as climatic barriers, decreasing or increasing the environmental suitability for the establishment of populations. We cannot say that the pattern for species with greater suitability at lower altitudes will persist, since the surrounding vegetation will also be affected by global changes and according to other studies the tendency is to move upwards (*e.g.* Grabherr *et al.* 1994, Petitpierre *et al.* 2015, Steinbauer *et al.* 2018). Other factors must also be considered, such as anthropogenic effects as land use changes (Borges *et al.* 2019, Chapter 2) and biotic effects as interactions between species, (Forero-Medina *et al.* 2011), as

shown for *G. poeciloptera*, which, even in lower areas, is the only one threatened with extinction (Chapter 2).

REFERENCES

- Allouche, O., Tsoar, A. & Kadmon, R. (2006). Assessing the accuracy of species distribution models: prevalence, kappa and true skill statistic (TSS). *Journal of Applied Ecology* 43, 1223–1232.
- Boisvert-Marsh, L., Périé, C. & Blois, S. (2014). Shifting with climate? Evidence for recent changes in tree species distribution at high latitudes. *Ecosphere* 5, 1–33.
- Borges, F. J. A., Ribeiro, B. R., Lopes, L. E. & Loyola, R. (2019). Bird vulnerability to climate and land use changes in the Brazilian Cerrado. *Biological Conservation* 236, 347–355.
- Borsdorf, A. & Stadel, C. (2015). *The Andes: a geographical portrait*. Springer, New York, NY.
- Burnham, K. P., Anderson, D. R. & Huyvaert, K. P. (2011). AIC model selection and multimodel inference in behavioral ecology: some background, observations, and comparisons. *Behavioral Ecology and Sociobiology* 65, 23–35.
- Crawley, M. J. (2012) *The R Book* (second ed), Wiley, London, UK.
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J. & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development* 9, 1937–1958.
- Fick, S.E. & Hijmans, R.J. (2017). WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* 37, 4302–4315.
- Fielding, A. H. & Bell, J. F. (1997). A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation* 24, 38–49.

- Fjeldså, J. & Krabbe, N. (1990) Birds of the High Andes. Zoological Museum, University of Copenhagen, Copenhagen, Denmark.
- Freeman, B. G., Scholer, M. N., Ruiz-Gutierrez, V. & Fitzpatrick, J. W. (2018). Climate change causes upslope shifts and mountaintop extirpations in a tropical bird community. PNAS 115, 11982–11987.
- GBIF: The Global Biodiversity Information Facility (2022) What is GBIF? Available at: <https://www.gbif.org/what-is-gbif>. Accessed 01.04.2022.
- Gibson, D. J. & Newman, J. A. (2019). Grasslands and Climate Change, Cambridge University Press, Cambridge, UK.
- Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., *et al.* (2019). Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. Geoscientific Model Development 12, 1443–1475.
- Gómez L. (2019) Biología reproductiva de *Geositta peruviana* (Passeriformes: Furnariidae) en la zona reservada Lomas de Ancón, Lima-Perú. Thesis to opt for the Professional Title of Biologist with a mention in Zoology. Universidad Nacional Mayor de San Marcos, Lima, Peru.
- Grabherr G., Gottfried M. & Pauli H (1994). Climate effects on mountain plants. Nature 369: 448–448.
- Haffer, J. (1967). On the dispersal of highland birds in tropical South and Central America. Hornero 10, 436–438.
- Hastie, T. & Tibshirani, R. (1986). Generalized additive models. Statistical Science 1, 297–310.
- Hazzi, N. A., Moreno, J. S., Ortiz-Movliav, C. & Palacio, R. D. (2018). Biogeographic regions and events of isolation and diversification of the endemic biota of the

tropical Andes. *Proceedings of the National Academy of Sciences* 115, 7985–7990.

Hidasi-Neto, J., Joner, D. C., Monteiro, F. R. L. M., Faleiro, f. V., Loyola, R. D. & Cianciaruso, M. V. (2019). Climate change will drive mammal species loss and biotic homogenization in the Cerrado Biodiversity Hotspot. *Perspectives in Ecology and Conservation* 17, 57–63.

Hofmann, G. S., Cardoso, M. F., Alves, R. J. V., Weber, E. J., Barbosa, A. A., *et al.* (2021). The Brazilian Cerrado is becoming hotter and drier. *Global Change Biology*, 27, 4060–4073.

IPCC. (2022). *Climate Change 2022: impacts, adaptation, and vulnerability*. in H-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem & B. Rama (Eds). *Contribution of working group II to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

IUCN. (2022). *The IUCN Red List of Threatened Species*. Available at: www.iucnredlist.org. Accessed 07.12.2021.

Köhler, M. Esser, L. F., Font, F., Souza-Chies, T. T. & Majure, L. C. (2020). Beyond endemism, expanding conservation efforts: What can new distribution records reveal? *Perspectives in Plant Ecology, Evolution and Systematics* 45, 125543.

La Sorte, F. A., Butchart, S. H. M., Jetz, W. & Böhning-Gaese, K. (2014). Range-Wide Latitudinal and Elevational Temperature Gradients for the World's Terrestrial Birds: Implications under Global Climate Change. *PLoS ONE* 9(5): e98361.

Lele, A., Arasumani, M., Vishnudas, C. K., Joshi, V., Jathanna, D. & Robin, V. V. (2020). Elevation and landscape change drive the distribution of a montane, endemic grassland bird. *Ecology and Evolution* 10, 7755-7767.

- Lopes, L. E., Meireles, R. C., Peixoto, H. J. C., Teixeira, J. P. G., Machado, T. L. S. S. & Lombardi, V. T. (*In Press*). Movement ecology of the threatened Campo Miner *Geositta poeciloptera* and its implications for conservation of tropical open grassland birds. Bird Conservation International.
- Lopes, L. E., Teixeira, J. P. G., Meireles, R. C., Bastos, D. S. S., Oliveira, L. L. & Solar, R. (2021) High seasonal variation of plasma testosterone levels for a tropical grassland bird resembles patterns of temperate birds. *Physiological and Biochemical Zoology* 94, 143–151.
- Machado, T. L. S. S., Lombardi, V. T., Meireles, R. C., Teixeira, J. P. G., Solar, R. & Lopes, L. E. (2017). Breeding biology of the threatened Campo Miner (*Geositta poeciloptera* (Aves: Scleruridae), a Neotropical grassland specialist. *Journal of Natural History* 51, 1–13.
- Marini, M. Â., Barbet-Massin, M., Lopes, L.E. & Jiguet, F. (2009). Predicted climate-driven bird distribution changes and forecasted conservation conflicts in a Neotropical savanna. *Conservation Biology* 23, 1558–1567.
- McCullagh, P. & Nelder, J.A. (1989). *Generalized Linear Models.*: CRC Press, Boca Raton, FL.
- Meireles R. C., Teixeira J. P. G., Solar R., Vasconcelos B. N. F., Fernandes R. B. A. & Lopes L. E. (2018). Soil attributes drive nest-site selection by the Campo Miner *Geositta poeciloptera*. *PLoS One* 13, e0192185.
- Meireles, R. C., Lopes, L. E., Pichorim, M., Machado, T. L. S. S., Duca, C. & Solar, R. (2021). Nest survival of the threatened Campo Miner *Geositta poeciloptera*: a tropical cavity-nesting grassland bird. *Austral Ecology* 46, aec.13079.
- Myers, N., Mittermeier, R. A., Mittermeier, C. G., Fonseca, G. A. B. & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature* 403, 853–858.

- Naimi, B., Hamm, N., Groen, T. A., Skidmore, A. K. & Toxopeus, A. G. (2014). Where is positional uncertainty a problem for species distribution modelling? *Ecography* 37, 191–203.
- O'Donnell, M. S. & Ignizio, D. A. (2012). Bioclimatic predictors for supporting ecological applications in the conterminous United States: U.S. Geological Survey Data Series 691, 10 p.
- Péfaur, J. E. (1983). Dynamics of plant communities in the Lomas of southern Peru. *Plant Ecology* 49, 163–171.
- Perillo, L. N., Castro, F. S., Solar, R. & Neves, F. S. (2021). Disentangling the effects of latitudinal and elevational gradients on bee, wasp, and ant diversity in an ancient neotropical mountain range. *Journal of Biogeography* 48, 1564–1578.
- Petitpierre, B., McDougall, K., Seipel, T., Broennimann, O., Guisan, A. & Kueffer, C. Will. (2015). Climate change increase the risk of plant invasions into mountains? *Ecological Applications* 26, 530–544.
- Phillips, S. J., Anderson, R. P. & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling* 190, 231–259.
- R Development Core Team (2022). R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. <https://www.R-project.org>.
- Raxworthy, C. J., Pearson, R. G., Rabibisoa, N., Rakotondrazafy, A. M., Ramanamanjato, J-B., Raselimanana, A. P., WU, S., Nussbaum, R. A. & Stone, D. A. (2008). Extinction vulnerability of tropical montane endemism from warming and upslope displacement: a preliminary appraisal for the highest massif in Madagascar. *Global Change Biology* 14, 1703–1720.
- Remsen, J. V., Jr. (2003) Family Furnariidae (Ovenbirds). Pp. 162-357 in J. del Hoyo, A. Elliott & J. Sargatal (Eds.) *Handbook of the birds of the World*, vol. 8. Broadbills

to Tapaculos. Lynx Edicions, Barcelona, Spain.

- Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C. *et al.* (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 42, 153–168.
- Ribeiro, V., Peterson, A. T., Werneck, F. P. & Machado, R. B. (2017). Ecological and historical views of the diversification of *Geositta* miners (Aves: Furnariidae: Sclerurinae). *Journal of Ornithology* 158, 15–23.
- Ridgely, R. S. & Tudor, G. (1994). *The Birds of South America: Vol. II, the Suboscine Passerines: 2*. University of Texas Press, Austin, Tx.
- Ridgely, R. S. & Tudor, G. (2009). *Field guide to the songbirds of South America: The Passerines*. University of Texas Press, Austin, TX.
- Rundel, P. W., Dillon, M. O., Palma, B., Mooney, H. A., Gulmon, S. L. & Ehleringer, J. R. (1991). The phytogeography and ecology of the coastal Atacama and Peruvian deserts. *A Journal of Systematic and Floristic Botany* 13, 1–49.
- Schulenberg, T. S., Stotz, D. F., Lane, D. F., O'Neill, J. P. & Parker III, T. A. (2010). *Birds of Peru: Revised and Updated Edition*. Princeton University Press, New Jersey, US.
- Sick, H. (1997). *Ornitologia brasileira: uma introdução*. 2nd ed. Nova Fronteira, Rio de Janeiro, BR.
- Steinbauer, M. J., Grytnes, J.-A., Jurasinski, G., Kulonen, A., Lenoir, J. *et al.* (2018). Accelerated increase in plant species richness on mountain summits is linked to warming. *Nature* 556, 231–234.
- Terborgh, J. & Weske, J. S. (1975) The role of competition in the distribution of Andean birds. *Ecology* 56: 562–576.

- Terborgh, J. (1971). Distribution on environmental gradients: theory and a preliminary interpretation of distributional patterns in the avifauna of the Cordillera Vilcabamba, Peru. *Ecology* 52, 23–40.
- Thuiller, W., Georges, D., Gueguen, M., Engler, R. & Breiner, F. (2021). Biomod2: Ensemble platform for species distribution modeling. R package version 3.5.1. <https://cran.r-project.org/package=biomod2>.
- Venables, W.N. & Ripley, B.D. (2002). *Modern Applied Statistics with S-PLUS*, 4th edn. Springer, New York, NY.
- Vickery, P. D., Herkert, J. R., Knopf, F. L., Ruth, J. & Keller, C.E. (2000). Grassland birds - An overview of threats and recommended management strategies. in R. E. Bonney, D. N. Pashley, D.N., R. Cooper & L. Niles (Eds). *Strategies for bird conservation - Creating the Partners in Flight planning process*. (pp. 74–77). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
- Vuilleumier, F. (1970). Insular biogeography in continental region. I. The northern Andes of South America. *The American Naturalist*. 104: 373–388.
- Yee, T.W. & Mitchell, N.D. (1991). Generalized additive models in plant ecology. *Journal of Vegetation Science* 2, 587–602.

Supplementary material

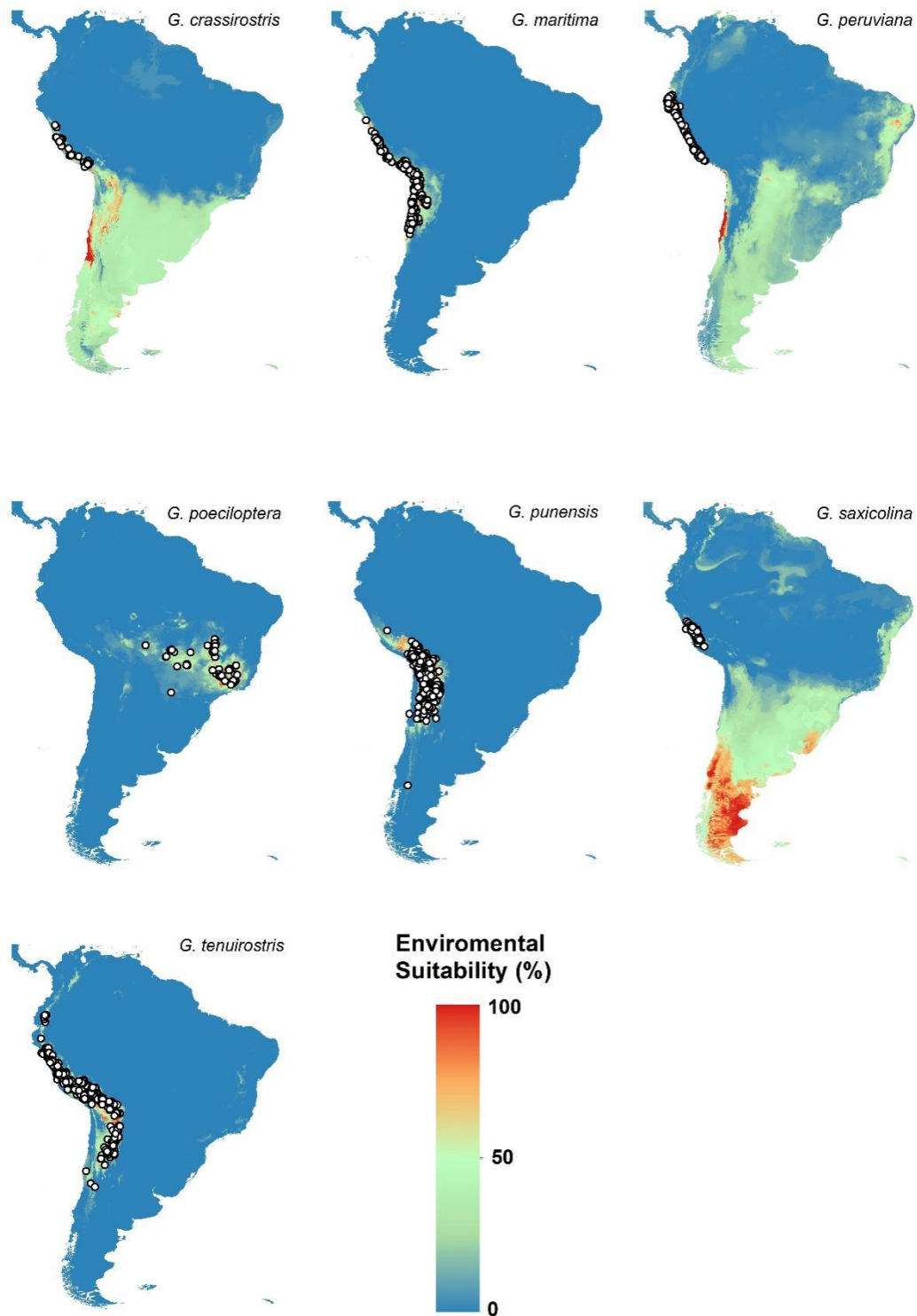


Figure 1. Occurrence records of *Geositta* miners in South America compared with created models of current climate suitability.

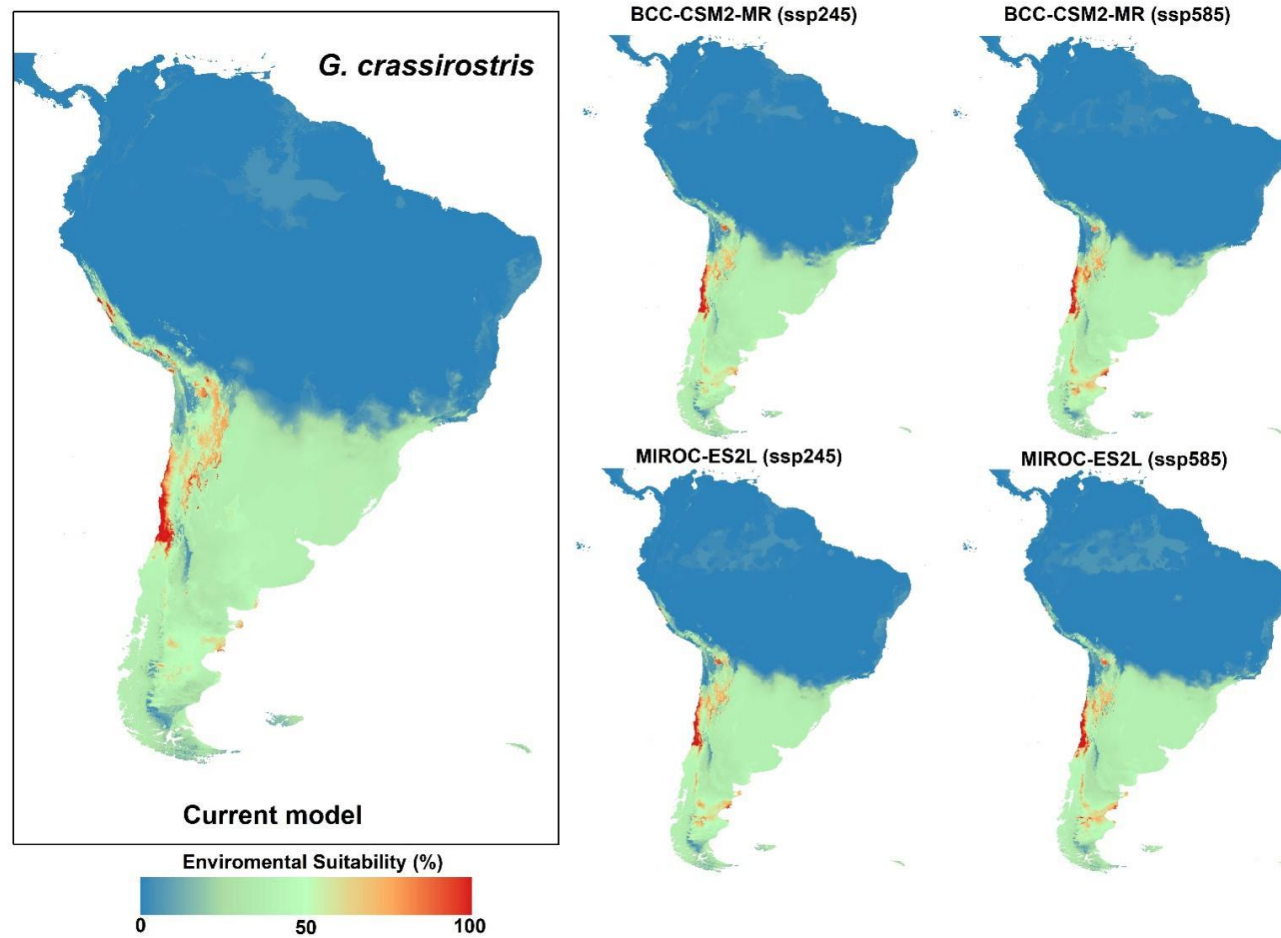


Figure 2. Current and future predictions ensemble models (2061-2080) of climatically suitable areas for *G. crassirostris* for two GCM's and two scenarios for each one.

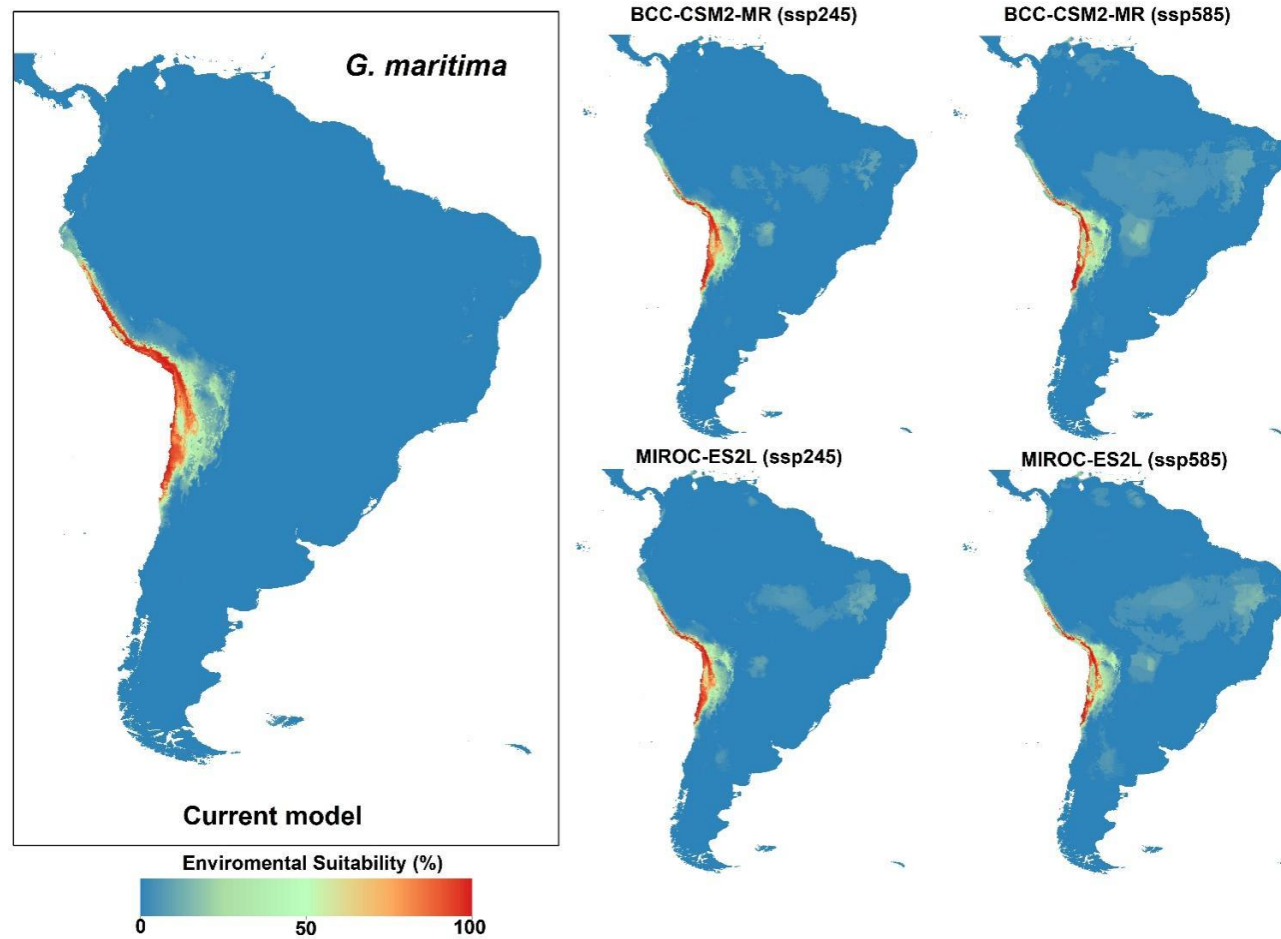


Figure 3. Current and future predictions ensemble models (2061-2080) of climatically suitable areas for *G. maritima* for two GCM's and two scenarios for each one.

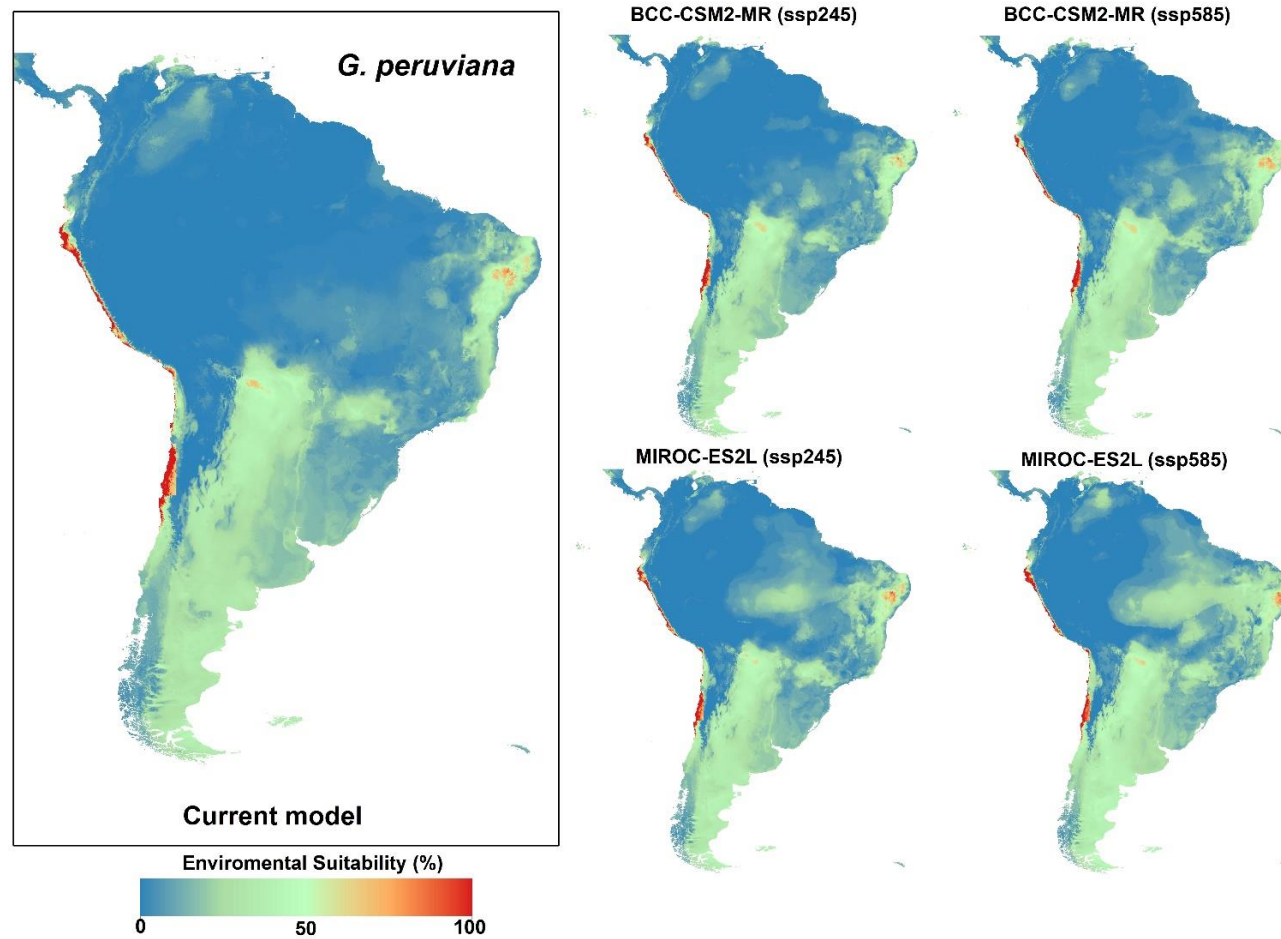


Figure 4. Current and future predictions ensemble models (2061-2080) of climatically suitable areas for *G. peruviana* for two GCM's and two scenarios for each one.

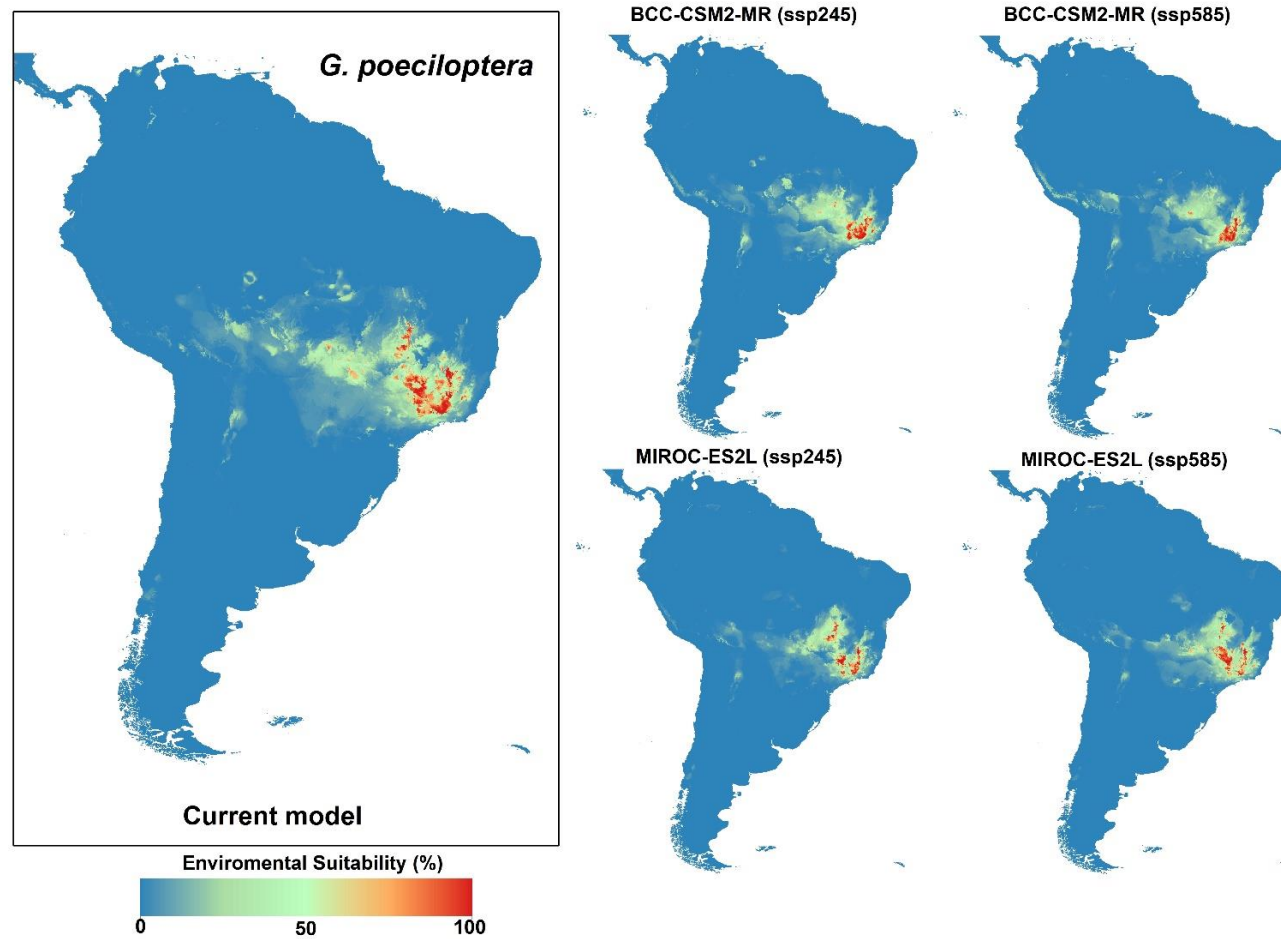


Figure 5. Current and future predictions ensemble models (2061-2080) of climatically suitable areas for *G. poecilopectera* for two GCM's and two scenarios for each one.

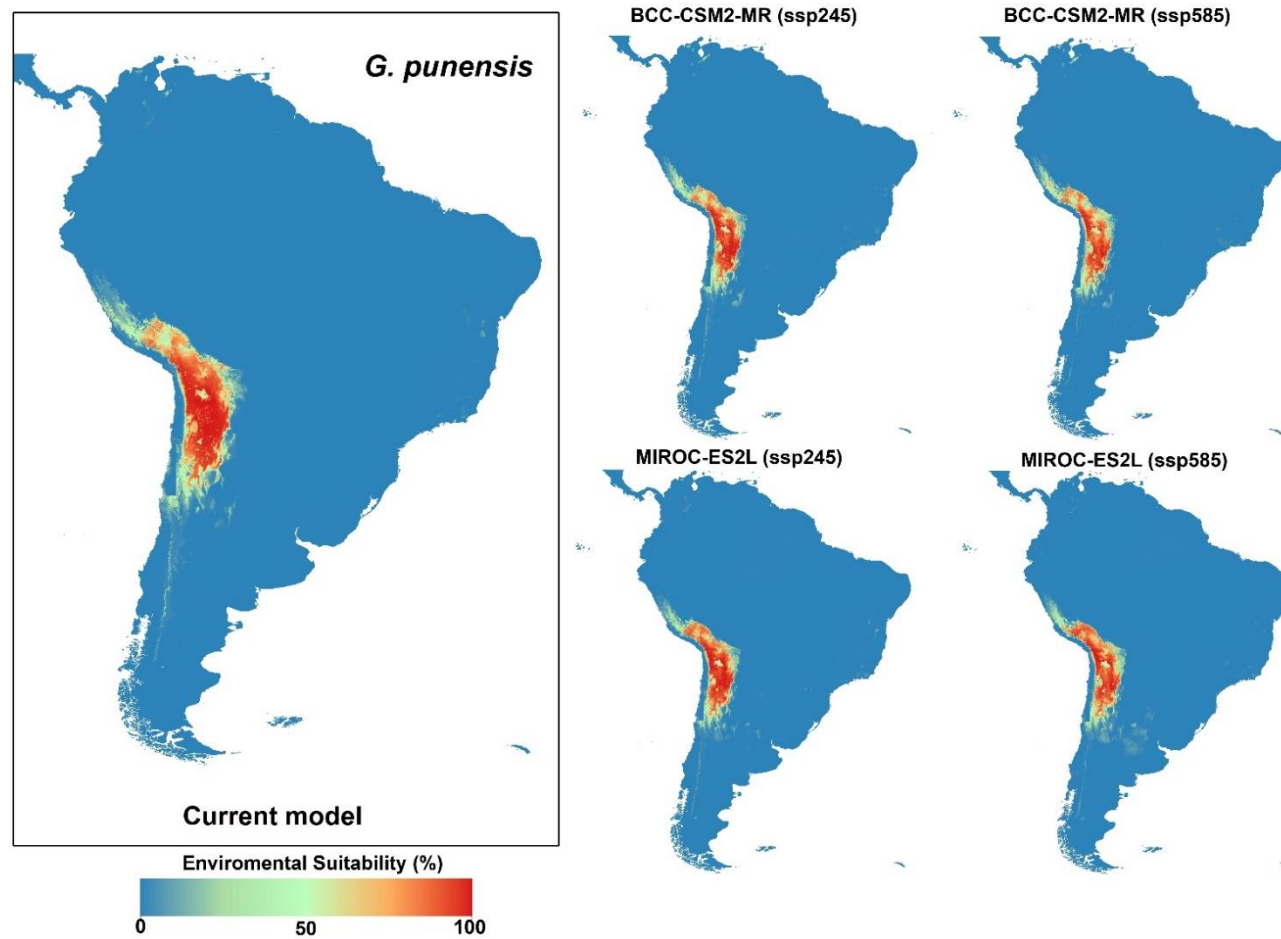


Figure 6. Current and future predictions ensemble models (2061-2080) of climatically suitable areas for *G. punensis* for two GCM's and two scenarios for each one.

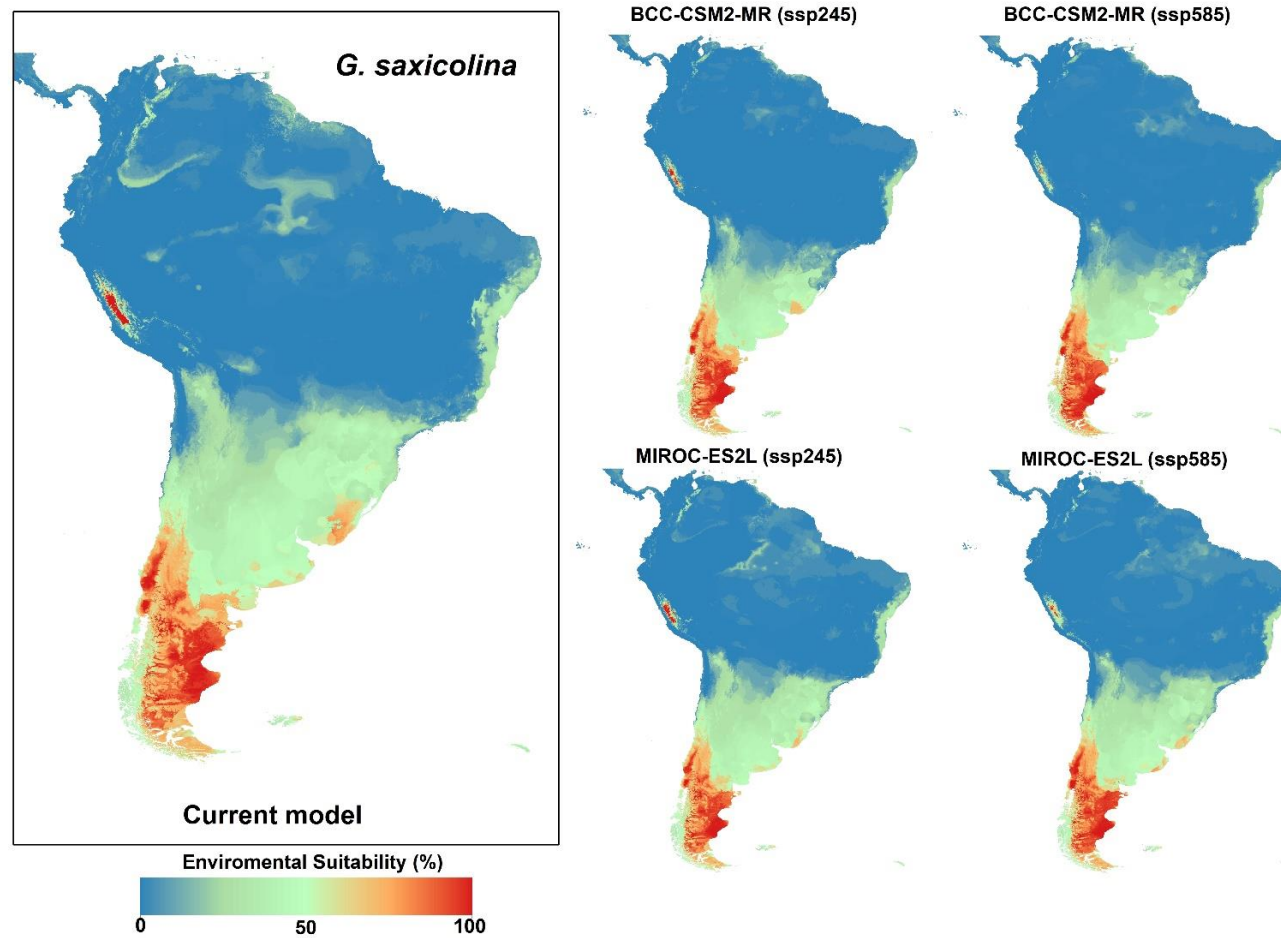


Figure 7. Current and future predictions ensemble models (2061-2080) of climatically suitable areas for *G. saxicolina* for two GCM's and two scenarios for each one.

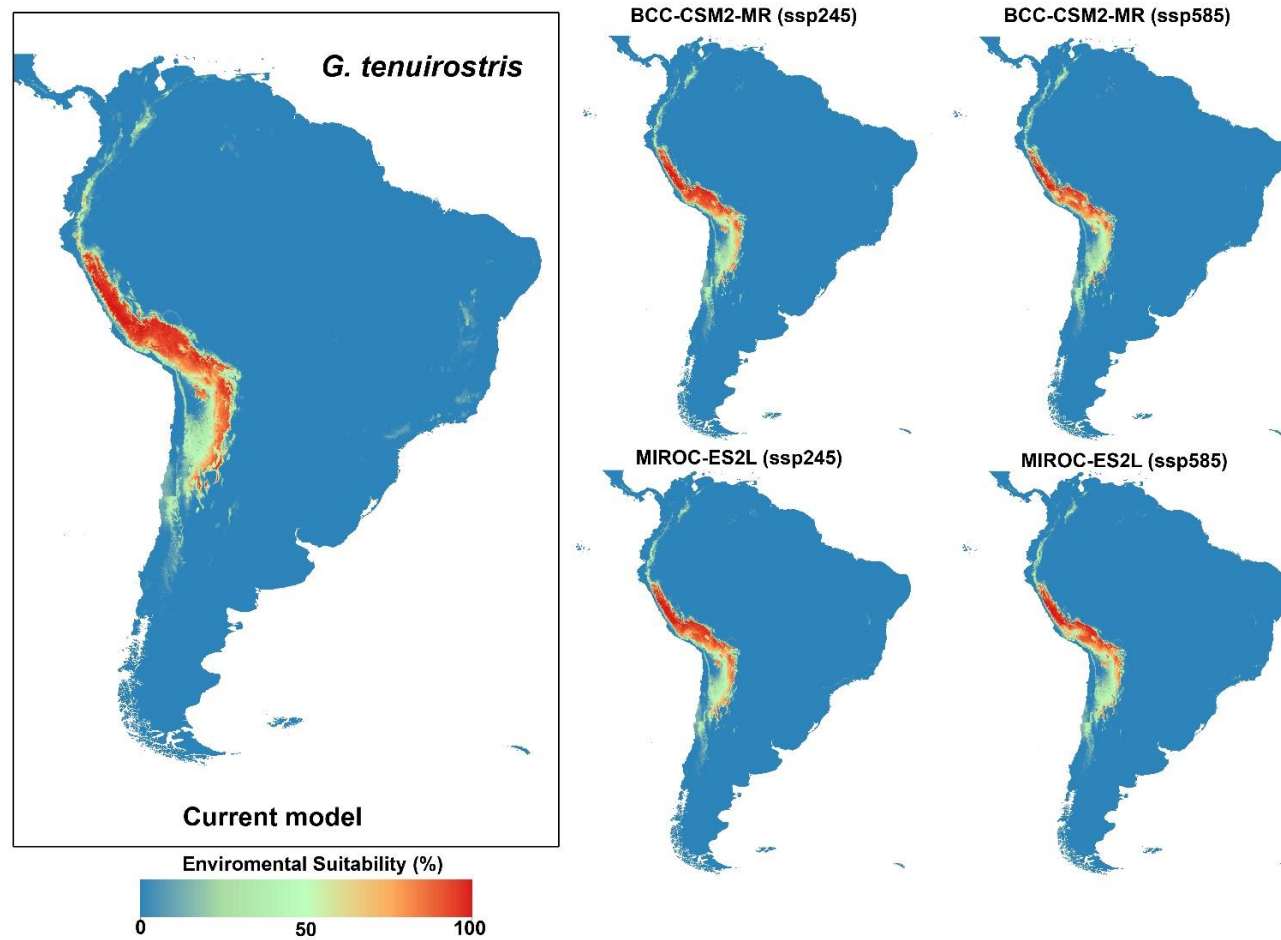


Figure 8. Current and future predictions ensemble models (2061-2080) of climatically suitable areas for *G. tenuirostris* for two GCM's and two scenarios for each one.

CONSIDERAÇÕES FINAIS

Neste estudo, avaliamos aspectos da ecologia de um grupo de aves de habitats abertos, acrescentando conhecimento acerca da história natural da única espécie do gênero ameaçada de extinção, além de darmos o primeiro passo para o entendimento da distribuição das espécies do gênero frente às mudanças climáticas. A arquitetura da cavidade de ninho, aparentemente é uma boa proteção contra intempéries e predadores, no entanto, o alto sucesso reprodutivo apresentado para *G. poeciloptera*, se comparado a outras espécies campestres, não é um fator relevante frente às grandes alterações sofridas em seu habitat como as mudanças no uso do solo e mudanças climáticas, ocasionando a perda cada vez maior de áreas adequadas para sua ocorrência, além de extinções locais nos últimos duzentos anos.

Apontamos também áreas prioritárias para a conservação, levando em consideração diferentes políticas de mitigação de gases de efeito estufa. Minas Gerais, possivelmente será o único refúgio climaticamente adequado para a espécie nos próximos anos, logo é necessário que políticas ambientais para delimitação de áreas protegidas no estado sejam urgentemente aplicadas. Chamamos atenção para três regiões no estado com alta ocorrência da espécie, no entanto, duas regiões não apresentam nenhuma área protegida que abarque características de habitat que possam abrigar a espécie, o município de Pompéu e principalmente os Campos do Alto Rio Grande. Por estarem em áreas ocupadas por fazendas e já com alto grau de antropização, essas políticas devem ser cuidadosamente estudadas, levando também em consideração a população que se beneficia do uso da terra nessas áreas, logo a criação de áreas protegidas de uso sustentável com manejo adequado dos campos naturais seria de extrema importância para evitar conflitos futuros.

Assim como *G. poeciloptera*, seus congêneres tropicais residentes também perderão áreas climaticamente adequadas nos próximos anos, independente de políticas de mitigação de gases de efeito estufa. No entanto, as características do ambiente de ocorrência serão um condicionante para garantir maior ou menor adequabilidade climática para cada espécie. As áreas de transição vegetacional e a elevação criam barreiras naturais que retêm a umidade em zonas específicas impedindo assim que as espécies, principalmente as costeiras se desloquem para

áreas mais altas de montanhas, logo, ao se estudar possíveis efeitos de mudanças climáticas sobre alguma espécie, deve-se levar em conta não só a biologia da espécie, mas também todo o ambiente ao qual ela está inserida, além de possíveis interações com o ambiente e com outras espécies.

Geositta poeciloptera, é hoje uma das espécies campestres mais bem estudadas. Os estudos previamente publicados somado a estes três capítulos são de grande importância para o conhecimento da ecologia deste grupo de aves ainda muito pouco conhecido. Esperamos que todo o conhecimento e informações passadas durante os mais de sete anos de estudos, possam garantir a conservação assim como o manejo adequado dessas espécies de ambientes tão sensíveis.

REFERÊNCIAS

- Azpiroz, A. B., Isacch, J.P., Dias, R. A., Di Giacomo, A., Fontana, C. S. & Palarea, C.M. (2012). Ecology and conservation of grassland birds in southeastern South America: a review. *Journal of Field Ornithology* 83, 217–246.
- Bates, J. M., Parker, T. A., III, Caparella, P. and Davis, T. J. (1992). Observations on the campo, Cerrado and forest avifaunas of eastern Dpto. Santa Cruz, Bolivia, including 21 species new to the country. *Bulletin of The British Ornithologists' Club* 112, 86–98.
- BirdLife International. (2022). Species factsheet: *Geositta poeciloptera*. Downloaded from <http://www.birdlife.org>. Accessed 14.04.2022
- del Castillo, H., Clay, R. P., Egea, J. & Asociación Guyra Paraguay (2005). Atlas de las aves de Paraguay. Guyra Paraguay, Asunción, Paraguay.
- Gibson, D. J. & Newman, J. A. (2019). *Grasslands and Climate Change*, Cambridge University Press, Cambridge, UK.
- Gómez L. (2019). Biología reproductiva de *Geositta peruviana* (Passeriformes: Furnariidae) en la zona reservada Lomas de Ancón, Lima-Perú. Thesis to opt for the Professional Title of Biologist with a mention in Zoology. Universidad Nacional Mayor de San Marcos, Lima, Peru.
- Herzog, S. K., Terrill, R. S., Jahn, A. E., Remsen, J. V., Maillard, O. Z., *et al.* (2016). *Birds of Bolivia: field guide*. Asociación Armonía, Santa Cruz de la Sierra, Bolivia.
- ICMBio. (2011). Atlas da Fauna Brasileira Ameaçada de Extinção em Unidades de Conservação Federais. Brasília. pp. 276.
- IUCN (2016). The IUCN Red List of Threatened Species. Version 2016–3. Available at: www.iucnredlist.org. Acesso em 19.04.2022.
- Lopes, L. E. & Peixoto, H. J. C. (2018). Aves campestres ameaçadas de extinção encontradas nos Campos do Alto Rio Grande, sul de Minas Gerais: notas sobre

sua história natural e proposições para estudos futuros. *Atualidades Ornitológicas* 201, 40–48.

Lopes, L. E., Meireles, R. C., Peixoto, H. J. C., Teixeira, J. P. G., Machado, T. L. S. S. & Lombardi, V. T. (*In Press*). Movement ecology of the threatened Campo Miner *Geositta poeciloptera* and its implications for conservation of tropical open grassland birds. *Bird Conservation International*.

Lopes, L. E., Pinho, J. B., Bernardon, B., Oliveira, F. F., Ferreira, L. P., Vasconcelos, M. F., Maldonado-Coelho, M., Nóbrega, P. F. A. & Rubio, T. C. (2009). Aves da Chapada dos Guimarães, Mato Grosso, Brasil: uma síntese histórica do conhecimento. *Papéis Avulsos de Zoologia* 49, 9–47.

Machado T. L. S. S., Lombardi V. T., Meireles R. C., Teixeira J. P. G., Solar R. & Lopes L. E. (2017). Breeding biology of the threatened Campo Miner (*Geositta poeciloptera* (Aves: Scleruridae), a Neotropical grassland specialist. *Journal of Natural History* 51, 1–13.

Marini, M. Â., Barbet-Massin, M., Lopes, L.E. & Jiguet, F. (2009). Predicted climate-driven bird distribution changes and forecasted conservation conflicts in a Neotropical savanna. *Conservation Biology* 23, 1558–1567.

MMA (2022). Lista Nacional oficial de espécies da fauna ameaçadas de extinção. Ministério do Meio Ambiente. Diário Oficial da União – Portaria MMA nº 148, DE 7 DE JUNHO DE 2022.

Parker, T. A., III & Willis, E. O. (1997). Notes on three tiny grassland flycatchers, with comments on the disappearance of South American fire-diversified savannas. *Ornithological Monographs* 48, 549–555.

Peixoto, H. J. C. (2014). Ecologia e conservação de aves campestres ameaçadas de extinção no sul de Minas Gerais, Brasil. M.Sc. dissertation. Viçosa, Brazil: Universidade Federal de Viçosa.

Remsen, J. V., Jr. (2003). Family Furnariidae (Ovenbirds). in J. Del Hoyo, A. Elliott, & J. Sargatal (Eds). *Handbook of the birds of the World*, vol. 8. Broadbills to

- Tapaculos. (pp. 162-357). Lynx Editions, Barcelona, Spain.
- Remsen, J. V., Jr. and Sharpe, C. J. (2020). Campo Miner (*Geositta poeciloptera*), version 1.0. in J. del Hoyo, A. Elliott, J. Sargatal, D. A. Christie & E. Juana (Eds). Birds of the World. Ithaca, NY, USA: Cornell Lab of Ornithology.
- Ribeiro, V., Peterson, A. T., Werneck, F. P. and Machado, R. B. (2017). Ecological and historical views of the diversification of *Geositta* miners (Aves: Furnariidae: Sclerurinae). *Journal of Ornithology* 158, 15–23.
- Sick H. (1997). *Ornitologia brasileira: uma introdução*. 2nd ed. Nova Fronteira, Rio de Janeiro, BR.
- Silva e Silva R. (2005) *Biologia reprodutiva de Geositta poeciloptera* (Passeriformes: Furnariidae) em Minas Gerais. In: Aleixo A, editor. XIII Congresso Brasileiro de Ornitologia. Resumos. Belém: Museu Paraense Emílio Goeldi, Universidade Federal do Pará. pp. 28.
- Silveira, L. F. (2009). *Geositta poeciloptera* (Wied, 1830) Passeriformes, Scleruridae. in P. M. Bressan, M. C. M. Kierulff, & A. M. Sugieda (Eds). *Fauna ameaçada de extinção no estado de São Paulo: vertebrados*. Fundação Parque Zoológico de São Paulo: Secretaria do Meio Ambiente.
- Stotz, D.F.; Fitzpatrick, J.W.; Parker, T.A., III & Moskovits, D.K. (1996). *Neotropical birds: ecology and conservation*. University of Chicago Press, Chicago, USA.
- Vickery, P. D., Herkert, J. R., Knopf, F. L., Ruth, J. & Keller, C.E. (2000). Grassland birds - An overview of threats and recommended management strategies. in R. E. Bonney, D. N. Pashley, D.N., R. Cooper & L. Niles (Eds). *Strategies for bird conservation - Creating the Partners in Flight planning process*. (pp. 74–77). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.