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FLÁVIO MARIANO MACHADO MOTA

IMPACTO DAS MUDANÇAS CLIMÁTICAS SOBRE A DIVERSIDADE DE AVES

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Orientadora: Dra. Daniela Custódio Talora
Co-orientadores: Dr. Neander Marcel Heming e Dr. José Carlos Morante-Filho

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FLÁVIO MARIANO MACHADO MOTA

IMPACTO DAS MUDANÇAS CLIMÁTICAS SOBRE A DIVERSIDADE DE AVES

Dr. Marcos de Souza Lima Figueiredo
Universidade Federal do Estado do Rio de Janeiro

Dr. Leonardo de Sousa Miranda
Lancaster University

Dra. Gabriela Silva Ribeiro Gonçalves
Universidade Federal do Pará

Dra. Eliana Cazetta
Universidade Estadual de Santa Cruz

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Resumo

As mudanças climáticas representam uma ameaça crescente à biodiversidade, com rápidas alterações nos padrões de precipitação e temperatura que superam os registros históricos. As aves, em particular, são sensíveis a essas mudanças, sendo um grupo modelo para avaliar potenciais alterações em suas distribuições no futuro. Nesta tese, tivemos como objetivos: i) investigar os fatores morfológicos, ecológicos e geográficos que afetam a resposta das aves às mudanças climáticas em escala global; ii) avaliar alterações na diversidade taxonômica (TD), funcional (FD) e filogenética (PD) de aves florestais do Corredor Central da Mata Atlântica (CCMA) entre cenários climáticos e a representatividade de áreas altamente diversas dentro de áreas protegidas; iii) identificar as características que tornam essas aves mais vulneráveis às mudanças climáticas e onde estão localizadas; iv) avaliar como as mudanças climáticas afetam a riqueza e a composição de espécies de aves frugívoras florestais do CCMA; e v) apresentar uma ferramenta para facilitar o cálculo de métricas de diversidade a partir de dados espacializados. Nossos resultados indicaram que, em escala global, aves com distribuição ampla, menor massa corporal, encontradas primariamente em florestas e na Oceania tendem a perder mais área climaticamente adequada no futuro. Em escala regional, observamos uma perda de diversidade taxonômica (TD), funcional (FD) e filogenética (PD), e um aumento da representatividade de áreas altamente diversas dentro de áreas protegidas. Houve também substituição de funções ecológicas compartilhadas pelas aves florestais e diferenças nas relações filogenéticas compartilhadas por elas dentro do CCMA. Além disso, as aves florestais que apresentam menor distribuição, alta dependência de florestas e que são encontradas em altitudes elevadas são mais vulneráveis às mudanças climáticas. As aves frugívoras, em particular, devem apresentar redução da riqueza, tornando as comunidades do futuro um subconjunto das comunidades atuais na porção oeste do CCMA. Por fim, a ferramenta que desenvolvemos para calcular métricas de diversidade a partir dos resultados da modelagem de nicho apresentou desempenho satisfatório, facilitando análises macroecológicas. Nesta tese, ressaltamos a importância de considerar múltiplas métricas de diversidade simultaneamente para identificar potenciais áreas para a conservação, e que diferenças entre escalas (global e regional), dimensões (TD, FD e PD) e espécies podem ocorrer. Além disso, destacamos que a manutenção das áreas florestadas e protegidas nas porções norte e sul do CCMA, bem como o aumento da conectividade entre áreas adequadas para as aves florestais, é fundamental para garantir a persistência das espécies no futuro, especialmente daquelas mais vulneráveis às mudanças climáticas. Esperamos que os resultados apresentados aqui sejam úteis para o

planejamento de conservação da região, bem como inspirem futuros estudos com outros grupos e em outras localidades.

Palavras-chave: Macroecologia, MaxEnt, Aquecimento global, Conservação, Avifauna, Floresta tropical

Abstract

Climate change poses an increasing threat to biodiversity, with rapid changes in precipitation and temperature patterns surpassing historical records. Birds, in particular, are sensitive to these changes, making them a model group for assessing potential shifts in their distributions in the future. In this thesis, our objectives were: i) to investigate the morphological, ecological, and geographical factors affecting birds' responses to climate change on a global scale; ii) to assess changes in taxonomic diversity (TD), functional diversity (FD), and phylogenetic diversity (PD) of forest birds in the Central Corridor of the Atlantic Forest (CCMA) under different climate scenarios and the representation of highly diverse areas within protected areas; iii) to identify characteristics that make these birds more vulnerable to climate change and their geographical distribution; iv) to evaluate how climate change affects the richness and species composition of frugivorous forest birds in the CCMA; and v) to present a tool for facilitating the calculation of diversity metrics from spatial data. Our results indicated that globally, birds with wide distribution, lower body mass, primarily found in forests, and in Oceania are likely to lose more climatically suitable areas in the future. Regionally, we observed a loss of taxonomic (TD), functional (FD), and phylogenetic diversity (PD), along with an increase in the representation of highly diverse areas within protected areas. There was also a shift in shared ecological functions among forest birds and differences in their phylogenetic relationships within the CCMA. Additionally, forest birds with limited distribution, high dependence on forests, and found at higher altitudes are more vulnerable to climate change. Frugivorous birds, in particular, are expected to experience reduced richness, resulting in future communities being a subset of current communities in the western part of the CCMA. Finally, the tool we developed to calculate diversity metrics from niche modeling results performed well, facilitating macroecological analyses. In this thesis, we emphasize the importance of simultaneously considering multiple diversity metrics to identify potential conservation areas, noting differences across scales (global and regional), dimensions (TD, FD, and PD), and species. Moreover, we highlight that maintaining forested and protected areas in the northern and southern parts of the CCMA, and enhancing connectivity between suitable areas for forest

birds, is crucial for ensuring species persistence in the future, especially for those most vulnerable to climate change. We hope the findings presented here will be useful for regional conservation planning and inspire future studies in other groups and locations.

Keywords: Macroecology, MaxEnt, Global warming, Conservation, Avifauna, Tropical forest

Introdução geral

As rápidas mudanças nos padrões de precipitação e temperatura têm provocado alterações significativas nas distribuições das espécies, aumentando seu risco de extinção (Román-Palacios and Wiens, 2020). Estima-se que o aquecimento global possa resultar numa perda de 22,7% a 30,7% de insetos, 23% a 31% de plantas e 35% a 44% de vertebrados (Wiens and Zelinka, 2024). Por exemplo, projeções indicam que entre a década de 2050 e o fim do século, 74% dos primatas da Mata Atlântica e 58% das aves da Amazônia podem perder mais da metade de sua área climaticamente adequada (Miranda et al., 2019; Pinto et al., 2023). Essas mudanças na distribuição das espécies têm impactos profundos na estrutura das comunidades, alterando a composição de espécies através da redução de especialistas e da possível substituição por espécies generalistas. Isso pode afetar significativamente o funcionamento dos ecossistemas (Gallagher et al., 2013; Hidasi-Neto et al., 2019; Prieto-Torres et al., 2020).

As aves desempenham papéis cruciais nos ecossistemas, atuando como dispersoras de sementes, especialmente em florestas tropicais. Além disso, contribuem para uma série de outros serviços ecológicos, como polinização, controle de pragas e prevenção de doenças (Şekercioğlu, 2011; Trolliet et al., 2017; Barnes et al., 2020). A perda de espécies pode desencadear efeitos em cascata sobre outras espécies, comprometendo o funcionamento dos ecossistemas (Şekercioğlu et al., 2004; Şekercioğlu, 2006; Mariyappan et al., 2023). Por exemplo, a redução das áreas climaticamente adequadas para aves nectarívoras e suas plantas hospedeiras pode resultar em menor sobreposição na distribuição desses grupos, impactando a polinização (Remolina-Figueroa et al., 2022; Adedoja et al., 2024). Da mesma forma, a diminuição da área adequada para aves frugívoras e suas plantas associadas pode prejudicar a dispersão de sementes (Marchioro et al., 2023). Portanto, é crucial considerar a potencial perda de área adequada para essas espécies no planejamento de conservação frente às mudanças climáticas.

A vulnerabilidade das aves às mudanças climáticas pode estar associada a diversas características das espécies (Pacifici et al., 2017; Neate-Clegg et al., 2023). Por exemplo, aves florestais que se alimentam principalmente de frutos tendem a perder mais área climaticamente

adequada no futuro em comparação com espécies associadas a áreas abertas e que têm uma dieta mais variada (Miranda et al., 2019). Além disso, a massa corporal das aves pode influenciar a variação no tamanho da distribuição, sendo esperado que espécies menores sofram maiores perdas devido ao maior custo metabólico em manter a termorregulação (Smith et al., 2017). A capacidade de dispersão é outro traço ecológico importante; prevê-se uma maior perda de área adequada em cenários de não dispersão comparado a cenários de dispersão ilimitada (Prieto-Torres et al., 2020). Identificar as características associadas à maior perda de área adequada é fundamental para evitar a extinção de espécies no futuro.

Além das características individuais das espécies, padrões de diversidade são cruciais para definir estratégias de conservação eficazes para a proteção de espécies vulneráveis (Vale et al., 2018a). A combinação do número de espécies (diversidade alfa) com as mudanças na composição de espécies entre comunidades (diversidade beta) permite identificar regiões altamente diversas, tanto local quanto temporalmente, e ajuda a detectar tendências de perda ou ganho de espécies com determinadas características e/ou a substituição de espécies com diferentes atributos (Sobral et al., 2016). Por exemplo, muitas aves provavelmente perderão áreas climaticamente adequadas no futuro, resultando em uma menor riqueza de espécies (Prieto-Torres et al., 2020). Além disso, aves que dependem de recursos encontrados apenas no interior de florestas (Malanotte et al., 2019; Yatsiuk e Wesołowski, 2020) podem ser substituídas por aves generalistas que utilizam uma maior variedade de recursos, como diferentes habitats e itens alimentares, ou que são associadas a áreas abertas (Vázquez-Reyes et al., 2017). Essas alterações na estrutura das comunidades indicam localidades onde os esforços de conservação devem ser concentrados para maximizar sua efetividade diante das mudanças climáticas (Prieto-Torres et al., 2020).

Embora a diversidade taxonômica seja amplamente utilizada para avaliar os impactos das mudanças climáticas nas comunidades (Deomurari et al., 2023; de Moraes et al., 2024), é essencial considerar também o papel ecológico que as espécies desempenham (diversidade funcional) e o histórico evolutivo compartilhado por elas (diversidade filogenética) (Stewart et al., 2022; Voskamp et al., 2022). A redução da diversidade funcional pode indicar a perda de serviços ecossistêmicos importantes, como a dispersão de sementes, prejudicando o recrutamento de novas plantas. Da mesma forma, a diminuição da diversidade filogenética pode sinalizar a perda de história evolutiva com o desaparecimento de linhagens únicas (Stewart et al., 2022; Voskamp et al., 2022). Além disso, divergências entre as dimensões taxonômica, funcional e filogenética podem ocorrer, já que a perda de espécies nem sempre resulta em perda de função ou história evolutiva (Meynard et al., 2011). Portanto, é crucial

considerar todas essas dimensões para fornecer evidências biológicas sólidas sobre potenciais mudanças e apoiar estratégias de conservação mais adequadas.

O crescente interesse no impacto das mudanças climáticas sobre a biodiversidade, refletido no aumento da quantidade de publicações sobre o tema (Farooqi et al., 2022), indica a necessidade de ferramentas destinadas a análises macroecológicas. Apesar de existirem diversas ferramentas disponíveis para avaliar mudanças nas comunidades, o que inclui o cálculo de diversas métricas de diversidade (Kembel et al., 2020; Baselga et al., 2023; Dormann et al., 2023), lidar com um grande volume de dados, como é o caso de grandes extensões geográficas e/ou um grande número de espécies, é desafiador (Beck et al., 2012). Recentemente, têm surgido algumas alternativas capazes de calcular diversidade taxonômica, funcional e filogenética, bem como endemismo filogenético e redes de interação bipartidas (Mota et al., 2023; Oliveira and Heming, 2023; Alves-Ferreira et al., 2024). Essas ferramentas dispensam a transformação de dados espaciais em matrizes e tendem a exigir menor poder e tempo de processamento (Mota et al., 2023; Alves-Ferreira et al., 2024), tornando-as acessíveis a um número maior de usuários.

A Mata Atlântica brasileira é reconhecida como uma área prioritária para a conservação, destacando-se por seus altos níveis de biodiversidade e degradação (Vancine et al., 2024). Entre 2021 e 2022, foram perdidos mais de 20 mil hectares de floresta (SOS Mata Atlântica, 2023), e 97% do que resta da sua cobertura original (22,9%) concentra-se em fragmentos menores que 50 hectares (de Lima et al., 2020; Vancine et al., 2024). Ainda assim, o bioma abriga cerca de 832 espécies de aves, das quais aproximadamente 26% são endêmicas e 8% são globalmente ameaçadas (Hasui et al., 2018; Vale et al., 2018b). Muitas espécies da Mata Atlântica já são ameaçadas por diversos fatores, como a caça e o tráfico (Bernardo, 2020; Cockle and Bodrati, 2020), e as mudanças climáticas podem agravar ainda mais o risco de extinção dessas espécies. Projeções indicam que várias espécies devem perder área climaticamente adequada no futuro (Vale et al., 2018a), o que pode prejudicar a provisão de serviços ecossistêmicos importantes para a manutenção das florestas e a capacidade das plantas acompanharem as mudanças climáticas (Fricke et al., 2022; Remolina-Figueroa et al., 2022). Além disso, à medida que o bioma se torna mais seco e quente, alterações no número e na composição de espécies promovem mudanças nas comunidades, e entendê-las pode auxiliar no planejamento de conservação (Sales et al., 2020; Almazroui et al., 2021).

Diante deste contexto, no primeiro capítulo apresentamos uma visão global de como diferentes características morfológicas, ecológicas e geográficas afetam as respostas das aves em escala global às mudanças climáticas, esperando uma maior perda de área adequada para

aves com menor distribuição e tamanho, espécies florestais, especialistas e insulares. A partir do segundo capítulo, focamos no Corredor Central da Mata Atlântica, uma região prioritária para a conservação que ainda retém grande biodiversidade e cobertura florestal. No capítulo dois, avaliamos mudanças na diversidade taxonômica, funcional e filogenética de aves florestais, bem como a sobreposição de áreas altamente diversas com áreas protegidas, esperando uma perda de diversidade e a manutenção de uma maior diversidade dentro de áreas protegidas. No terceiro capítulo, identificamos as características dessas aves com potencial para aumentar sua vulnerabilidade às mudanças climáticas e onde estão concentradas, esperando maior perda de área adequada para aves com menor capacidade de dispersão, altamente especializadas e dependentes de florestas, além de maior concentração dessas aves nas regiões norte e sul. No capítulo quatro, exploramos como as mudanças climáticas afetam os padrões de diversidade alfa e beta de aves frugívoras, esperando uma diminuição da diversidade alfa e aumento da diversidade beta na porção oeste. Por fim, no último capítulo, apresentamos uma ferramenta para facilitar o cálculo de métricas de diversidade a partir de dados espacializados.

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Capítulo 1

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Amount of bird suitable areas under climate change is modulated by morphological, ecological and geographical traits

Flávio Mariano Machado Mota[1], Neander Marcel Heming[1], José Carlos Morante-Filho[1], Daniela Custódio Talora[1]

[1]Applied Ecology and Conservation Lab, Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade, Universidade Estadual de Santa Cruz, Ilhéus, Brazil

Abstract

Biodiversity is already experiencing the effects of climate change through range expansion, retraction, or relocation, potentializing negative effects of other threats. Future projections already indicate richness reduction and composition modifications of bird communities due to global warming, which may disrupt the provision of key ecological services to ecosystem maintenance. Here, we systematically review the effect of morphological, ecological, and geographical traits on the amount of future suitable area for birds worldwide. Specifically, we tested whether body mass, diet, habitat type, movement pattern, range size, and biogeographic realm affect birds' suitable area. Our search returned 75 studies that modeled the effects of climate change on 1991 bird species. Our analyses included 1661 species belonging to 128 families, representing 83% of the total, for which we were able to acquire all the six traits. The proportion of birds' suitable area was affected by range size, body mass, habitat type, and biogeographic realm, while diet and movement pattern showed lower relative importance and were not included in our final model. Contrary to expectations, the proportion of birds' suitable area was negatively related to range size, which may be explained by higher climatic stability predicted in certain areas that harbor species with restricted distribution. In contrast, we observed that birds presenting higher body mass will show an increase of the proportion of suitable area in the future. This is expected due to the high exposure of smaller birds to environmental changes and their difficulty to keep thermoregulation. Our results also indicated a low proportion of suitable area to forest-dependent birds, which is in accordance with their higher vulnerability due to specific requirements for reproduction and feeding. Finally, the

proportion of suitable area was low for birds from Oceania, which is expected since the region encompasses small islands isolated from continents, preventing their species from reaching new suitable areas. Our study highlights that different traits should be considered when assessing extinction risk of species based on future projections, helping to improve bird conservation, especially the most vulnerable to climate change.

Keywords: climate change, ecological niche models, bird traits, species distribution, suitability, systematic review

1.1. Introduction

As a result of alterations in temperature and precipitation, species distributions may shift (i.e., expansion, retraction, or relocation) to seek better climatic conditions (Bellard et al., 2012; Lenoir and Svenning, 2015). Even when a species is not directly affected by climate change, it can suffer indirectly due to its interaction with species that will lose or relocate their habitat (Thomas, 2010). In this context, several studies discuss the potential impacts of climate change on biodiversity (e.g., Pearman et al., 2011; Newbold, 2018; Hidasi-Neto et al., 2019). Several studies have reported that our planet will become warmer and drier in the next decades (e.g., Drobinski et al., 2020; Almazroui et al., 2021), which will cause an increase in the species extinction risk (Bateman et al., 2020). For instance, the number of mammal species are predicted to decrease under future scenarios, including in highly diverse regions (Hidasi-Neto et al., 2019). A similar pattern is observed for anuran and birds, whose species richness are expected to be lower in future climatic scenarios (Menéndez-Guerrero et al., 2020; Prieto-Torres et al., 2020). Additionally, climate change may lead to savannization of tropical forests (Franchito et al., 2012) and consequently the impoverishment of communities due to species replacement (i.e., extinction of specialists and expansion of generalists), as predicted for mammals (Hidasi-Neto et al., 2019; Sales et al., 2020). Because of these changes in species' suitable areas, diversity patterns (i.e., species richness and community composition) are expected to change with global warming (Mota et al., 2022), what may disrupt key ecological functions, including those provided by birds (Sekercioglu, 2006).

Avian species are among the best known organisms, they are globally distributed and sensitive to environmental modifications, making them a potential study group to evaluate climate change impacts on biodiversity (Şekercioğlu et al., 2012; Bregman et al., 2014). Additionally, birds contribute to several key ecological services, including seed dispersal, pollination, and insect control, thus providing the maintenance of natural and artificial

environments (Sekercioglu, 2006; Morante-Filho and Faria, 2017; Blount et al., 2021). However, those services may be at risk due to the redistribution of species' suitable area resulting from climate change (e.g., Nowak et al., 2019). For instance, large seeds depend on large dispersers to carry them away from the parent tree, thus, the loss of frugivores such as toucans and guans may exert evolutionary pressure towards smaller seeds (Galetti et al., 2013; Sales et al., 2021). Climate-driven extinctions and few colonization are also predicted to occur in plant-hummingbird networks from North America and lowland South America communities (Sonne et al., 2022). Furthermore, high temperature and low rainfall in future climatic scenarios are expected to decrease taxonomic, phylogenetic, and functional diversity of bird species, leading to a restructuring of species assemblages around the world (Prieto-Torres et al., 2021; Stewart et al., 2022).

Although several manuscripts have detected the pervasive effects of climate change on birds, it is still poorly understood how morphological, ecological and geographical traits can modulate this impact. For instance, birds presenting a low body mass may have high metabolic costs to keep thermoregulation, while larger ones may use metabolically more efficient mechanisms of evaporative heat loss (Smith et al., 2017). In addition, frugivorous birds from a Brazilian tropical forest are predicted to experience higher suitable area contractions compared to other trophic guilds under climate change (Miranda et al., 2019). Birds presenting restricted distributions are also predicted to be more vulnerable to global warming experiencing large suitable area contractions, while widespread species may be unaffected given that good capacity of dispersion, colonization, and maintenance of populations over large areas (Kunin and Gaston, 1997; Estrada et al., 2016; Cohen et al., 2020). Although recent studies attempt to evaluate the traits mediating birds' response to climate change, there is still no consensus. For instance, Pacifici et al. (2017) observed negative responses of birds from high altitudes, while Ortega et al. (2019) found the opposite pattern. In addition, both studies tested the effect of body mass on birds' response to climate change, but no significant relationship was found. Therefore, further investigations are needed to fully understand the impact of different traits on birds under global warming to help improve future projections and the conservation of this key species group to ecosystem functioning.

Here, we used morphological, ecological, and geographical traits compiled by Tobias et al. (2022) to evaluate whether these features influence the amount of birds' suitable area in the future. Specifically, we tested whether body mass, diet, habitat type, movement pattern, range size, and biogeographic realm affect the amount of suitable area for birds registered in the literature. We expect that the amount of birds' suitable area in future scenarios will be

positively related to range size and body mass, with species presenting restricted distributions and lower body mass losing more suitable area due to their already limited habitat and higher exposure to environmental variations, respectively. Additionally, we expect that forest dependent species, with specialized diet (e.g., frugivorous), and those from Oceania will suffer more contractions of suitable area compared to their counterparts due to specific requirements and lower habitat availability within isolated regions, respectively.

1.2. Material and Methods

We conducted a global literature search in the Web of Science (www.webofknowledge.com) and SCOPUS (www.scopus.com) on the first of March 2022, using the terms (in the study title, abstract, and keywords): 'bird*' OR 'avian' OR 'avifauna' AND 'climatic chang*' OR 'climate chang*' OR 'global warm*' OR 'climate warm*' OR 'changing climate' AND 'distribut*' OR 'suitab*' OR 'niche model*' OR 'scenario*' OR 'range shift*'. After combining the pools of results and removing duplicates, we screened the title and abstracts from the remaining articles, removing any article that did not mention future climatic scenarios and birds' range size. We then rejected studies that did not report individually changes in suitability area of species (Figure 1).

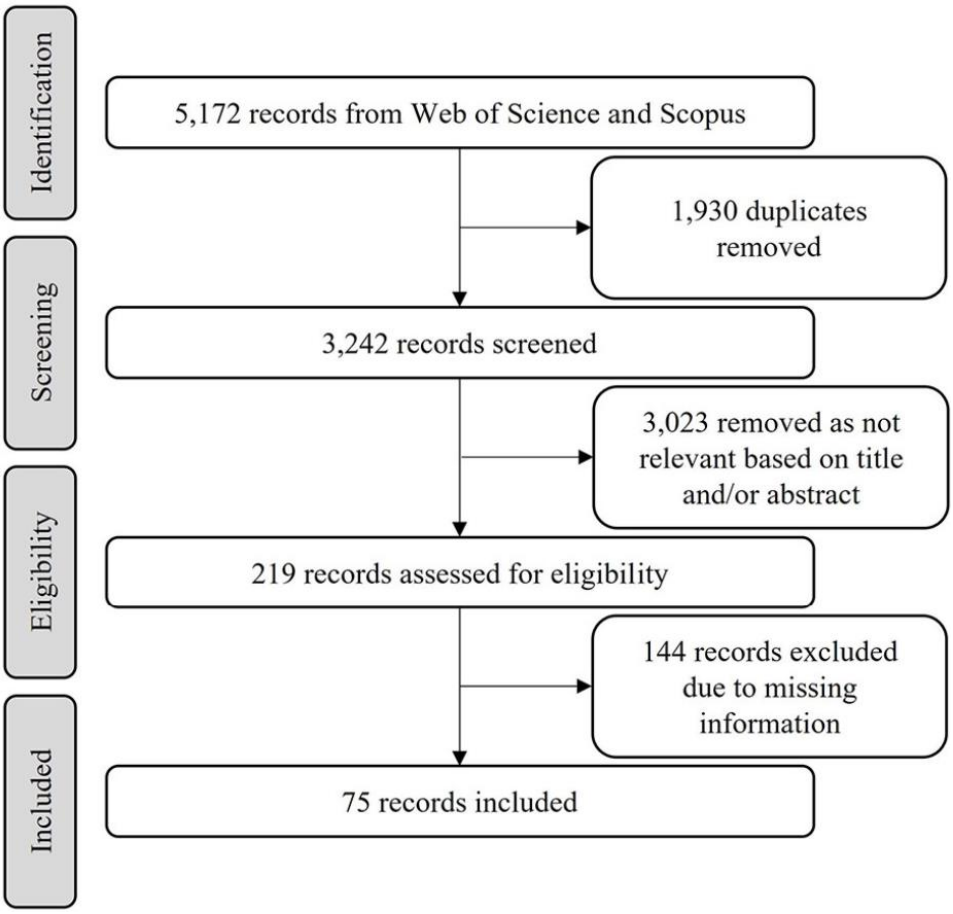

FIGURE 1 Flow diagram for the selection of articles used in our study.

Our literature search resulted in a final sample of 75 eligible studies which were reviewed. For each study, we documented the following information: bird species name, climatic suitable area in baseline scenario, and the percentage of suitable area change or climatic suitable area in future scenarios regardless of the modeling approach used (e.g., algorithm, year, and emission scenario). Because few studies evaluate dispersion capacity, we registered only the suitable area in full dispersion scenarios which were available in all eligible studies, thus maximizing the observation number. Using the literature, we obtained the following information for each bird species: body mass, habitat type, movement pattern, diet, range size, and biogeographic realm (Olson et al., 2001; Tobias et al., 2022). Traits description are given in Supplementary Table 1. We choose these traits because they have already been used in other studies and are important in predicting bird extinction risk under climate change (e.g., Simmons et al., 2004; Machado and Loyola, 2013; Ortega et al., 2019; Pacifici et al., 2017). We used the range size of the known distribution of the species when the study did not provide the climatic suitable area in the baseline scenario. Finally, we standardized all area measures to square kilometers, given that few studies reported the suitable area of species as number of pixels.

We calculated the proportion of birds' suitable area in the future for each species and study, dividing the total amount of suitable area in the future scenario by the total area in the baseline scenario. Then, we applied square root transformation to this proportion in order to normalize our response variable. Since none of the predictor variables showed correlation higher than 0.36 that could justify its removal, we proceed to model building with all the six traits. We performed generalized linear mixed models using the *glmmTMB* package (Brooks et al., 2017) to model the proportion of suitable area of all bird species as a function of habitat type, movement pattern, body mass, range size, diet, and biogeographic realm. We used species as a random factor to control for those that appear in multiple studies. Afterward, we calculated all possible models, from the null to the global model, using the 'dredge' function of the *MuMIn* package (Barton, 2022), and selected the best model based on the lowest Akaike information criterion corrected for small samples (AICc). Then, we used the best model to estimate marginal means of the traits using the packages *emmeans* (Lenth, 2022) and *ggeffects* (Lüdecke, 2018) to generate the graphics of isolated effects of each variable.

All analyses were conducted in R software (R Core Team, 2022).

1.3. Results

The 75 studies selected here modeled the future distribution of 1991 birds belonging to 129 families, with Tyrannidae as the most representative (n = 122). Most of the studies were conducted in Asia (31%) and Europe (28%), while less studies were carried out in Oceania (8%) and Africa (14%; Figure 2). We eliminated 330 species from our analysis because we could not obtain the traits for them, resulting in a final dataset with 1661 species (83% of the total).

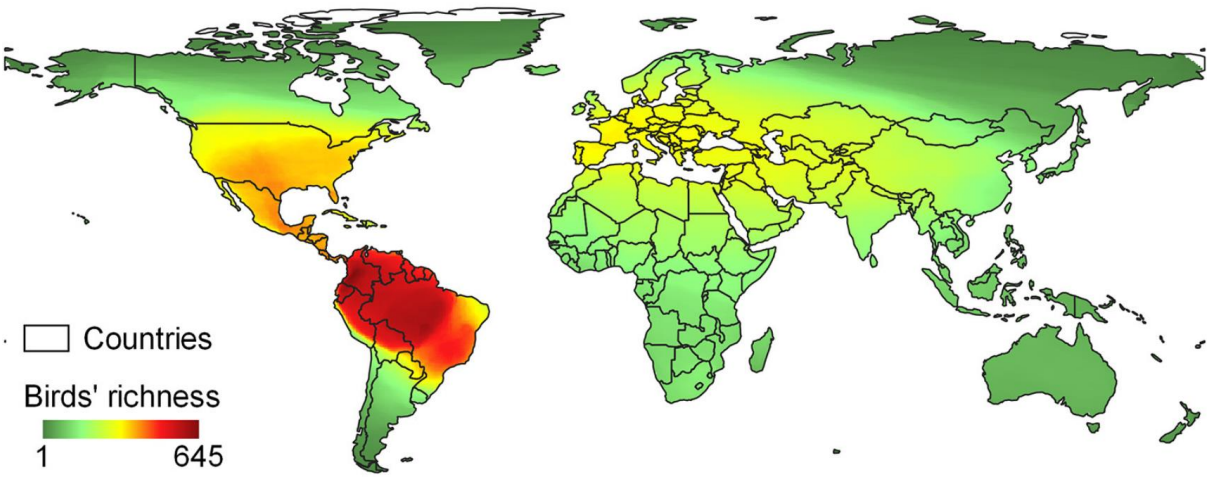

FIGURE 2 Map of birds' richness based on the distribution of the species included in our analysis among the eligible studies (n = 75).

We built a total of 64 models with AICc ranging from 8232 to 8179 and the best one included four predictor variables with relative importance higher than 0.5 (Supplementary Table 1): realm (w = 1), range size (w = 1), habitat type (w = 0.89), and body mass (w = 0.54). These variables showed significant effect on the proportion of birds' suitable area in the future.

We found a negative relationship between the proportion of birds' suitable area in the future and the baseline range size with suitable area loss increasing as the range size increases (β = -0.027, p = < 0.000; Figure 3A). The opposite pattern was observed for body mass, with the proportion of suitable area in the future increasing together with body mass (β = 0.021, p = < 0.009; Figure 3B).

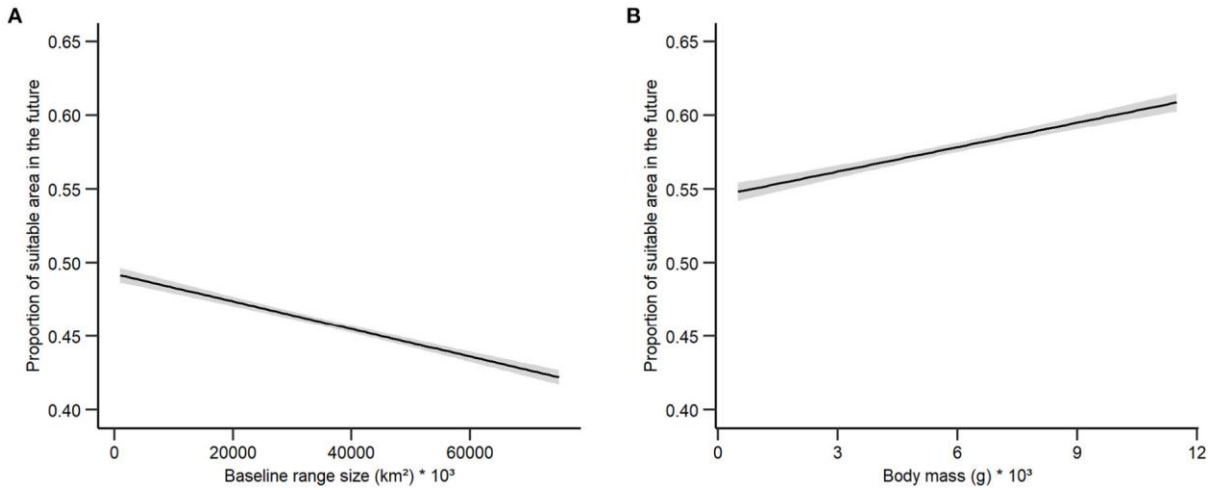

FIGURE 3 Relationship between the proportion of birds' suitable area in the future and (A) baseline range size, and (B) body mass. The gray area around the line indicates 95% confidence interval.

We found that the proportion of birds' suitable area differ among habitat type driven mostly by forest species, which present the lower average proportion of suitable area (0.73 ± 0.03), and species of woodland (0.95 ± 0.06) and shrubland (0.92 ± 0.05). Birds associated with riverine habitats showed a small gain of suitable area, indicated by values above 1, although the variation was one of the highest (1.02 ± 0.15; Figure 4A).

We found that the proportion of birds' suitable area differ among biogeographic realm driven mostly by species from Oceania, which present the lower average proportion of suitable area (0.47 ± 0.08), and species from Neartic, which present a small increase in the proportion of suitable area (1.18 ± 0.05). The Neotropical realm showed intermediate values, with a small reduction in the average proportion of suitable area (0.87 ± 0.04; Figure 4B).

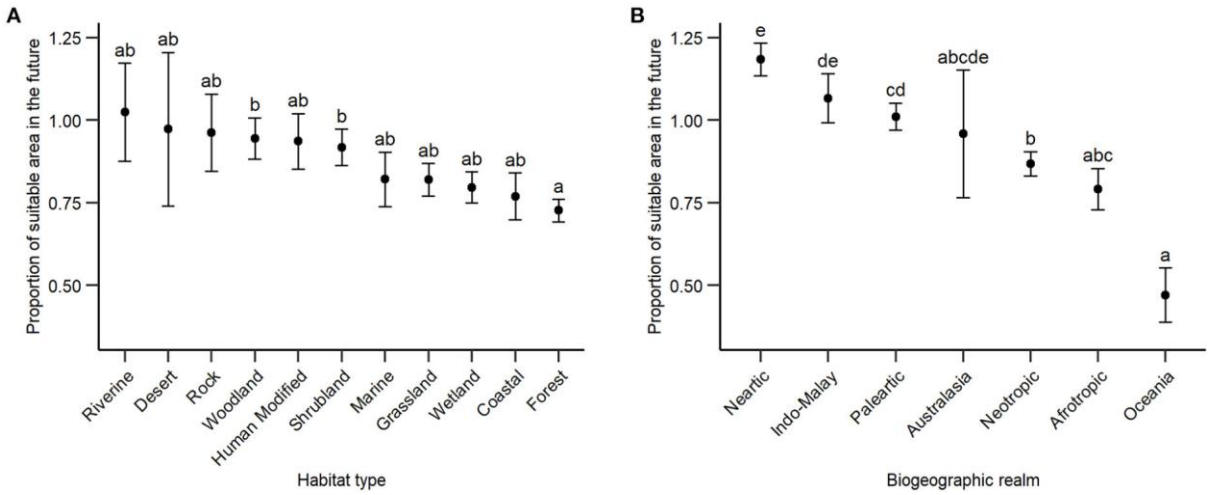

FIGURE 4 Relationship between the average (black dots) proportion of birds' suitable area and (A) habitat type, and (B) biogeographic realm. Values below 1 in y-axis represent suitable area loss. Different letters above the standard error of the mean indicate significant difference between two or more factors.

1.4. Discussion

Here, we evaluate for the first time the effect of morphological, ecological, and geographical traits on the amount of future suitable area for birds worldwide. The most important mediators of species' response to climate change were range size, body mass, habitat type, and geographic realm, while diet and movement pattern showed lower predictive power and were not included in our final model.

Unexpectedly, the proportion of birds' suitable area decreased with increasing baseline range size, indicating that species with restricted distributions may lose less suitable area compared to widely distributed species. At first glance, it may seem contradictory given that climate conditions could completely change within a small area (Clark, 1985; Wilbanks and Kates, 1999), however, large distributions can potentially lose more area. The lower impact of climate change on restricted distributed birds suggests that these species may be located in regions with more stable climate (Borges and Loyola, 2020). In fact, we observed a positive relationship between range size and climate stability, measured by the difference in the annual mean temperature of future and baseline scenarios, supporting our result. For instance, *Crax blumenbachii* had an average distribution of 18,420km² located where the annual mean temperature in the future will increase only 1ºC and is still predicted to lose 55% of its suitable area. Otherwise, *Myiothlypis mesoleuca*, another forest resident species, presented a larger average distribution (508,800km²) and suitable area loss (74%), however, the region where this species is located will experience a temperature increase of 2.36ºC. Additionally, a strong effect of stable climate was observed on endemic birds from China, resulting in higher species richness (Feng et al., 2020). Stable climate is also related to endemism hotspots that corresponds to areas with small paleoclimatic fluctuations (Harrison and Noss, 2017).

According to expectations, the proportion of birds' suitable area was positively related to body mass with smaller species predicted to suffer higher contractions in their suitable area compared to large species. This can be explained by high metabolic costs to keep thermoregulation in smaller species, while larger ones may use metabolically more efficient mechanisms of evaporative heat loss (Smith et al., 2017). For instance, the body mass of *Crax fasciolata* and *Euphonia violacea* are 2,600g and 15g, respectively, both have similar range

size and are forest frugivorous, but the smaller species are predicted to lose almost three times more suitable area than the larger one. It is corroborated by studies with birds from arid-zones that shows negative impact on fitness of smaller species and high tolerance to heat stress in larger species (du Plessis et al., 2012; Whitfield et al., 2015). Similar to our results, Mason et al. (2019) found a positive relationship between climate suitability trend and body mass for birds from the United States, which may be attributed to the presence of large bodied species.

Contractions in birds' suitable area are predicted for species associated with all habitat types, except for riverine, but higher losses are expected to forest species, corroborating our hypothesis. Forest-dependent birds require specific conditions such as several large frugivores that need of tree holes and fleshy-fruited trees for reproduction and feeding (Malanotte et al., 2019; Yatsiuk and Wesołowski, 2020), while the generalist habits of non-forest species allows species to obtain a wider range of resources in different types of habitats, including in disturbed environments (Vázquez-Reyes et al., 2022). For instance, large suitable area losses are predicted for forest dependent birds from Amazonia compared to species associated with open lands in future climate scenarios (Miranda et al., 2019). In fact, at least 29 forest birds are predicted to lose all suitable areas currently available in the next decades (Miranda et al., 2019). Similarly, forest birds in Madagascar are also expected to experience contractions in their total range areas and species such as *Oriolia bernieri* may not find suitable areas in future scenarios (Andriamasimanana and Cameron, 2013). Furthermore, it should be mentioned that even species predicted to expand their distributions are not safe, and their persistence may be limited by deforestation (Morante-Filho et al., 2021), suggesting that climate and land-use change can act synergistically and contribute to the impoverishment of birds communities (Northrup et al., 2019). For instance, although the endangered forest bird *Polyplectron katsumatae* is predicted to gain suitable area (11.8%), it has been facing habitat loss and hunting since the 1950s (IUCN, 2022).

Our findings support a larger reduction in the proportion of birds' suitable area from Oceania compared to other biogeographic realms. Oceania encompasses several small islands isolated from other continents, in addition to its particular conditions that prevent species from pursuing new suitable areas outside this region. For instance, we observed that birds from Oceania are predicted to lose an average of 80% of their suitable area, including species that will not find suitable area in the future such as *Oreomystis bairdi* and *Loxops caeruleirostris*, both forest-dependent species (Fortini et al., 2015; Paxton et al., 2016). Birds from other islands also suffer with drastic contractions in their suitable areas and common species may become rare with warming temperatures (Ko et al., 2012). In fact, the high vulnerability within islands

is known due to the specific species interactions, isolation, and low habitat availability besides holding critically endangered species already threatened by other causes not related to climate (Whittaker and Fernandez-Palacios, 2007; Kumar and Tehrany, 2017).

In our study we evidenced that the effect of climate change on the suitable areas for birds is modulated by ecological traits, especially range size, body mass, habitat type, and geographic realm. Although many studied species will experience contractions in their distributions, other birds are predicted to gain suitable area in the future, such as species from the Neartic realm and those associated with riverine habitat. However, our findings possibly underestimate range shifts since we did not include dispersion capacity of species (e.g., intermediate dispersion) and land-use change in our analysis, which we highly recommend in future studies as species may not be able to reach climatic suitable areas further apart or because these areas may become unsuitable due to habitat loss (see Ramirez-Villegas et al., 2014; Newbold, 2018; Prieto-Torres et al., 2020). Moreover, almost half of birds worldwide are already experiencing population decline due to other causes that may be worsened by climate change (Northrup et al., 2019; IUCN, 2022), and taking into account morphological, ecological, and geographical traits should help to assess species risk of extinction based on future projections (Pacifici et al., 2017). Finally, by knowing which traits make the species more vulnerable to climate change (i.e., high suitable area loss), we can maximize conservation efforts and better direct resources to prevent the impoverishment of bird communities.

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Capítulo 2

Manuscrito a ser submetido ao periódico Global Change Biology

Impact of climate change on the multiple facets of forest bird diversity in a biodiversity hotspot within the Atlantic Forest

Flávio Mariano Machado Mota[1,3], José Carlos Morante-Filho[1], Richard Glyn Davies[2], Çağan Hakkı Şekercioğlu[3,4,5], Neander Marcel Heming[1] and Daniela Custódio Talora[1]

[1]Programa de Pós-graduação em Ecologia e Conservação da Biodiversidade, Universidade Estadual de Santa Cruz, Ilheus, Bahia, Brazil

[2]School of Biological Sciences, University of East Anglia, Norwich Research Park, Norwich, UK

[3]School of Biological Sciences, University of Utah, Salt Lake City, Utah, USA

[4]Department of Molecular Biology and Genetics, Koç University, Istanbul, Türkiye

[5]KuzeyDoğa Derneği, Istasyon Mahallesi, Ismail Aytemiz Caddesi, Kars, Türkiye

Abstract

Rapid shifts in temperature and precipitation challenges species to either relocate or disappear. Despite climate change impacts on taxonomic diversity (TD) being well-known, knowledge gaps persist regarding its effects on functional (FD) and phylogenetic diversity (PD). Additionally, the ability of protected areas, primarily created to preserve species richness, to maintain FD and PD in the future remains unclear. Using ecological niche models, we assessed changes in the forest bird community in the Central Corridor of the Atlantic Forest (CCAF) in Brazil, considering multiple dimensions of diversity and the amount of overlap between highly diverse areas and protected areas under different climate scenarios (baseline and future). Our findings show that most species are projected to undergo contractions in their distributions, resulting in a reduction in TD, FD, and PD, with low-diversity areas in the western CCAF prone to greater losses compared to the coastal area that exhibits fewer or no losses. Distinct patterns emerge for FD and PD, with a replacement of functional roles shared by species in the northwesternmost portion of the CCAF and differences in phylogenetic relationships shared by species in the mideast. With climate change, the northeast protected areas will potentially harbor higher diversity dimensions, whereas the southern portion remains underrepresented.

The entire eastern portion should retain suitability for most species, which could greatly benefit from reforestation and conservation efforts. Therefore, considering multiple dimensions of diversity may help better direct limited resources toward the preservation of forest species, their ecological roles, and evolutionary heritage.

Keywords Macroecology; Species distribution; Multiple dimensions; Conservation; Beta diversity; Tropical Forest

2.1. Introduction

Climate change is advancing rapidly, surpassing historical records and drawing greater concern as high greenhouse gas emissions persist (Trisos et al., 2020). Severe impacts on biodiversity are expected, as species are unlikely to keep pace with the rapid changes in temperature and precipitation patterns (Román-Palacios and Wiens, 2020; Wormworth and Şekercioğlu, 2011). The resulting shifts in species distributions are poised to escalate the local risk of extinction, impacting multiple dimensions of diversity (Andrew et al., 2021; Olsen et al., 2022; Zhu et al., 2021). While taxonomic diversity (i.e., species diversity) remains the most used metric to assess climate change impacts on biological communities (e.g., Mota et al., 2022a), other crucial dimensions, such as functional and phylogenetic diversity, are often overlooked (Cadotte et al., 2011). Moreover, variations in responses to climate change among species and regions are likely to occur and may result in divergent patterns when comparing taxonomic, functional and phylogenetic diversity (Miranda et al., 2019; Prieto-Torres et al., 2021). This implies that functional and phylogenetic diversity could either remain more stable or undergo disproportionate changes compared to taxonomic diversity, with potentially low spatial congruence across sites (Monnet et al., 2014). Such divergences across multiple facets of diversity would have profound implications for conservation planning, including the establishment of protected areas (Martín-Regalado et al., 2022; Montaño-Centellas et al., 2023).

The creation and expansion of protected areas to safeguard biodiversity are the ultimate goal of conservationists engaged in biodiversity assessments (Castaño-Quintero et al., 2022; Vale et al., 2018). In particular, the number of species is often the sole biological criterion considered in defining new protected areas (e.g., Zhu et al., 2021), raising uncertainties about whether they harbor communities with high functional and phylogenetic diversity both currently and in the future. However, regions with high taxonomic, functional, and phylogenetic diversity have high priority in conservation planning due to their potential to

maintain functional redundancy and evolutionary history (Brum et al., 2017; Martín-Regalado et al., 2022). Such features are pivotal because they can enhance the resilience of natural systems to disturbances and support species adaptation under climate change (Biggs et al., 2020; Brum et al., 2017). Furthermore, protected areas can play a critical role by acting as refuges for wildlife in highly degraded landscapes, reducing deforestation and maintaining relatively stable temperature and precipitation over time (Gonçalves-Souza et al., 2021; Zhu et al., 2021). However, the predicted changes in species distributions could make currently protected areas unsuitable, while climatic conditions may improve in other unprotected areas (Littlefield et al., 2019).

Progress beyond identifying areas with a higher number of species to understanding the processes underlying community changes can significantly improve conservation strategies (Bergamin et al., 2017). While the number of species (i.e., alpha diversity) is useful for comparing communities in space and time that are diverse, a focus on species composition allows us to detect dissimilarities (i.e., beta diversity) between communities (e.g., Mota et al., 2022a). Furthermore, current and future communities may either become more distinct (i.e., divergent) due to changes in species richness (gain or loss) or by the replacement of one species by another, or they may remain the same (i.e., homogenous) (e.g., Hidasi-Neto et al., 2019. Additionally, changes in the distribution of other dimensions of diversity can be even more worrisome. For instance, a decrease in functional diversity in the future indicates the loss of species that play different ecological roles, threatening ecosystem function and resilience (Stewart et al., 2022). Similarly, a decrease in phylogenetic diversity is expected when entire clades or distantly related species are lost, potentially limiting the capacity of communities to adapt or persist in regions with new climatic conditions (Voskamp et al., 2022). Therefore, understanding spatiotemporal changes in communities between different climate scenarios is of utmost importance to ensure the maintenance of all three dimensions of diversity (Prieto-Torres et al., 2021).

Even though tropical forests harbor the majority of the world's bird species, most scientific research on animal biodiversity, including avian climate impacts, is conducted in temperate regions (Harris et al., 2011; Titley et al., 2017). The impacts of climate change on diversity patterns may be even more severe in deforested and fragmented regions, such as the Brazilian Atlantic Forest, with a high risk of extinction predicted for some species (Vale et al., 2018). Despite being globally known as a priority area for conservation due to its high levels of degradation, biodiversity, and endemism, this global biodiversity hotspot is still threatened by human activities (de Lima et al., 2020). Furthermore, projections already indicate that the

Atlantic Forest will become warmer and drier in the next decades (Almazroui et al., 2021), which could trigger a process of biodiversity impoverishment through the replacement of forest species by those characteristics of open vegetation, especially in the ecotonal zones (Sales et al., 2020). Additionally, changes in the distribution of species from the Atlantic Forest are expected to reduce taxonomic and functional diversity and may even increase phylogenetic diversity in case of the loss of evolutionarily similar species (Stewart et al., 2022; Voskamp et al., 2022). Yet, studies considering these three dimensions simultaneously are still scarce.

The responsiveness of birds to environmental changes makes them a valuable group to investigate the impacts of climate change on multiple facets of diversity (Bregman et al., 2014; Şekercioğlu, 2012). Changes in taxonomic diversity of birds within the Atlantic Forest are already expected in future scenarios due to spatiotemporal variation in climatically suitable areas for most species (Mota et al., 2022a). For instance, a species such as the *Pionopsitta pileata* may lose most of its current distribution in the future, while a small range expansion is projected for the *Pteroglossus bailloni*, changing the taxonomic diversity of birds in the Atlantic Forest (Mota et al., 2022a). Projections also indicate a decrease in functional diversity and phylogenetic diversity of birds in most of the Atlantic Forest region (Barbet-Massin and Jetz, 2015; Voskamp et al., 2022). This raises concerns considering how crucial birds are to ecosystem functioning. In fact, most bird species act as seed dispersers and pollinators, promoting the natural regeneration of forests, fruit production, and gene flow (Martínez and García, 2017; Sahley, 2001; Şekercioğlu, 2006; Wenny et al., 2016). Several avian species also contribute to reducing leaf damage in plants by preying on herbivores and preventing disease outbreaks through the removal of carcasses, as well as controlling other species' populations, such as rodents that may host potential pathogens (Mäntylä et al., 2011; Ogada et al., 2012; Paz Luna et al., 2020; Şekercioğlu et al., 2016). Therefore, evaluating potential changes in multiple facets of diversity under climate change is fundamental to the long-term persistence of species and their ecological roles, not only within the degraded Atlantic Forest but also in other environments.

Here, we used ecological niche models to assess future changes in forest bird communities from the Atlantic Forest, and consequences for taxonomic, functional, and phylogenetic diversity, with the aim of providing a robust ecological evidence base for future conservation planning. We also assessed the extent of overlap between areas with high taxonomic, functional, and phylogenetic diversity and the existing protected areas under different climate scenarios. Specifically, our study aimed: 1) to assess the changes in species and community composition of forest birds across taxonomic, functional, and phylogenetic

diversity between baseline and future climate scenarios, anticipating a reduction in all dimensions due to the contraction of most species distributions, with a predominance of the loss pattern over replacement (Mota et al., 2022a); and 2) to examine the representativeness of high taxonomic, functional, and phylogenetic diversity within protected areas under different climate scenarios, foreseeing a high overlap of highly diverse areas considering all dimensions as the largest protected areas are located near the coast where most forested areas are concentrated (MapBiomas, 2023; MMA, 2023). Therefore, we can better understand where and how forest bird communities may change in the future, allowing us to improve conservation efforts and prevent biodiversity loss.

2.2. Methods

Study area

The study area, known as the Central Corridor of the Atlantic Forest (CCAF), is in central-eastern Brazil, comprising the states of Espírito Santo and southern Bahia, with an approximate area of 11.7 million hectares (Figure 1). The CCAF is one of the most important regions of the Atlantic Forest hotspot, harboring high biodiversity and a considerable number of endemic species, including 1,521 plants (28%), 105 birds (51%), and 13 primates (68%) (Cordeiro, 2003; Culot et al., 2019; Werneck et al., 2011). Although the majority of the CCAF is composed of pasture and cropland agriculture (59.6%), it still contains a significant amount of forest cover (31.4%) (MapBiomas, 2023), most of which is located inside large protected areas, such as the Reserva Biológica de Sooretama in Espírito Santo state and the Parque Nacional do Pau Brasil in southern Bahia state (MMA, 2023).

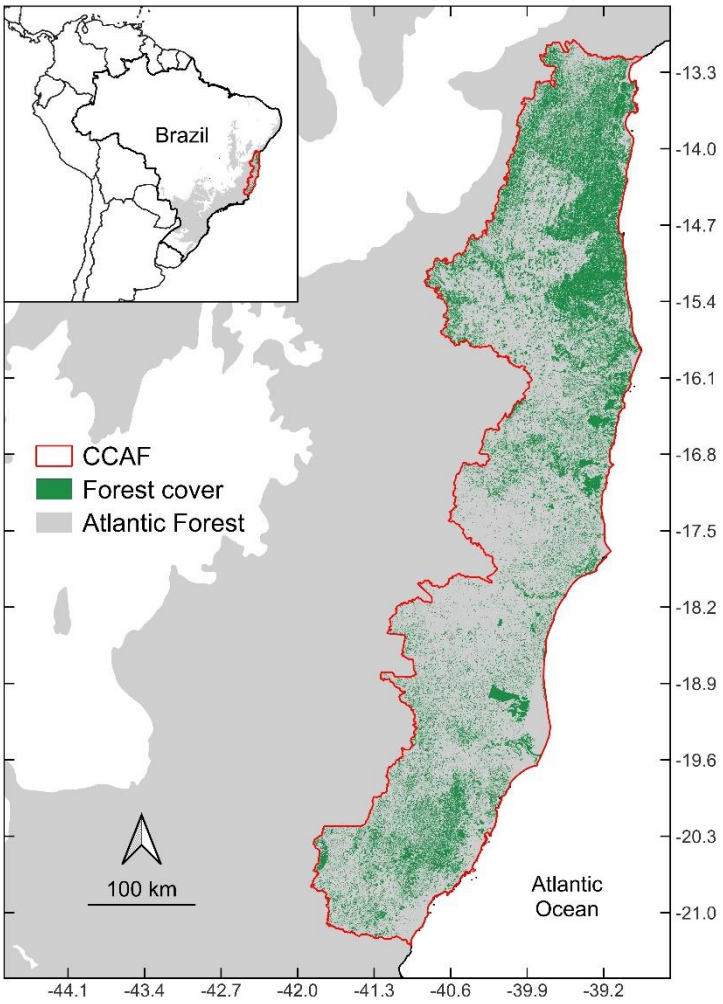

Figure 1. Location of the Central Corridor of the Atlantic Forest (CCAF) in Brazil. Grey and dark green colors indicate the boundaries of the original Atlantic Forest and remaining forest cover, respectively.

Bird data

To define the species list for data collection on occurrence records, we classified all bird species from the Brazilian Atlantic Forest (Hasui et al., 2018) according to their habitat, selecting only the resident forest species (Tobias et al., 2022) occurring within the study area. We then obtained occurrence records from the Global Biodiversity Information Facility (GBIF; www.gbif.org), which compiles data from different sources and is widely used to predict species distributions (Heberling et al., 2021), and subjected them to a quality control process to eliminate inaccurate records, such as those presenting incomplete coordinates or matching municipalities centroids (Zizka et al., 2019). Additionally, we removed occurrences that were less than 10 km apart from their nearest neighbors through the 'spThin' R package (Aiello-

Lammens et al., 2015). These procedures combined reduce potential geographical bias associated with GBIF data and are in line with the best practices for modeling species niche (Beck et al., 2014; Sillero et al., 2021). Our final dataset consisted of 292 species of forest birds (Table S1) recorded in the CCAF region.

Climate data

We obtained 19 bioclimatic variables, known to be important factors influencing biodiversity, acquired from the WorldClim platform (Fick and Hijmans, 2017) at a resolution of 2.5 arcminutes (Table 1). These variables are derived from precipitation and temperature measurements for the period of 1970–2000 (hereafter known as baseline) and are commonly used in the literature (e.g., Oliveira-Silva et al., 2022; Prieto-Torres et al., 2020). We obtained the equivalent temperature and precipitation variables for the 2050 and 2070 periods, considering three Global Climate Models (GCMs): IPSL-CM6A-LR, MIROC6, and MPI-ESM1-2-HR, and two Shared Socio-economic Pathways (SSPs): 245 and 585. The selection of these GCMs was based on their better performance with respect to frequency and persistence errors in the South America region (Cannon, 2020), while the SSPs represent optimistic and pessimistic greenhouse gas concentration scenarios, respectively (O'Neill et al., 2014). To avoid collinearity, we perform Pearson correlation analysis on all bioclimatic variables for each species and select those below the cutoff value of 0.7 (Dormann et al., 2013), using the 'ENMwizard' R package (Heming et al., 2019) (Table S2).

Ecological Niche Models (ENMs)

We used the MaxEnt algorithm to model the niches of 292 forest birds in the CCAF, which requires only occurrence data and bioclimatic variables (Phillips et al., 2006), and its better performance compared to other algorithms was demonstrated previously (Mota et al., 2022). We used the 'ENMwizard' R package to define the calibration area for each species (Heming et al., 2019) considering the total occurrences before the geographical bias procedure (above), and projected the models onto the study area only. We optimized MaxEnt parameters using the 'ENMeval' R package (Muscarella et al., 2014) and generated 70 models per species by combining ten regularization multipliers (RMs; 0.5 to 5 with intervals of 0.5) and the combinations of three feature classes (FCs; Linear, Quadratic, and Product). These two parameters are important in defining the complexity of MaxEnt models, as RMs control for model overfitting, and FCs are transformations of the original bioclimatic variables (Muscarella et al., 2014). To improve temporal and spatial transferability, we validated the

models using the block method (Roberts et al., 2017). We selected the top 10% of models based on the lowest omission rate (OR) and the highest area under the curve (AUC) (Boria et al., 2017) and projected them onto future climate scenarios (GCMs and SSPs). Then, we averaged these models to generate a single consensus model for each species and scenario. Finally, we considered the 10 percentile training presence (10ptp) threshold calculated by MaxEnt to binarize the final models (Ahmadi et al., 2020) into "suitable" or "unsuitable" areas with a 2.5 arcminutes resolution (i.e., cell size).

Taxonomic, functional and phylogenetic metrics

We used a common tree-based approach to estimate multiple dimensions of diversity of forest birds from the CCAF, enabling full comparability among taxonomic, functional, and phylogenetic diversity (Cardoso et al., 2014). To estimate taxonomic diversity, we simply counted the number of species by overlaying the ENM binary maps. To estimate functional diversity, we selected the categorical traits: (1) trophic niche (i.e., associated with the main food source), and (2) primary lifestyle (where the species spends most of its time; e.g., aerial, terrestrial, generalist), and the least correlated continuous traits (Pearson correlation < 0.7) as follows: (3) beak length and (4) beak depth, (5) wing length and (6) hand-wing index, (7) range size, and (8) body mass from the AVONET trait database (Tobias et al., 2022). Given the association between trophic niche and beak morphology with ecological functions (Pigot et al., 2020, 2016), primary lifestyle and wing morphology with dispersion capacity (Sheard et al., 2020), and range size and body mass with variations in climate suitable areas (Mota et al., 2022b), we consider these traits important for ecosystem functioning and for enabling birds to reach new climatically suitable areas. To estimate phylogenetic diversity, we acquired 1000 phylogenetic trees based on Ericson All Species backbone (Jetz et al., 2012) from Vertlife platform (www.vertlife.org; former BirdTree), then we used the 'ape' R package (Paradis and Schliep, 2019) to build a consensus tree and calculate its total branch lengths. The species *Icterus pyrrhopterus* was the only one not present in the phylogenetic trees, and its distribution models were removed from subsequent phylogenetic analysis.

Data analysis

To assess changes in taxonomic, functional, and phylogenetic diversity of forest birds we used the 'divraster' R package (Mota et al., 2023) to calculate alpha and temporal beta diversity. Given the positive relationship among taxonomic, functional, and phylogenetic diversity, we focus on exclusive patterns of each dimension. We employed multilayer binary

rasters for different climate scenarios, where each raster layer represented a species, and the stacked raster layers define the community present in each 2.5 arcminute grid cell. We calculated the percentage change in alpha diversity between scenarios by subtracting alpha in the baseline scenario from alpha in the future scenario, then dividing by alpha in the baseline scenario, multiplied by one hundred. For functional and phylogenetic diversity, the calculations are similar, but derive from a functional dendrogram of species traits and a dated phylogenetic tree, respectively. Hence, the sum of the branch lengths connecting the species within a community represents their functional and phylogenetic relationships (Faith, 1992; Petchey and Gaston, 2002). We calculated temporal beta diversity (ßtotal) using the Jaccard dissimilarity index and partitioned it into replacement (ßrepl) and richness difference (ßrich) components (see Cardoso et al., 2014). As beta diversity and its components can be expressed as 'ßtotal = ßrepl + ßrich' (Cardoso et al., 2014), the dominance of components can be expressed by the ratio 'ßrepl / ßtotal'. In this case, values close to one and zero would indicate the predominance of replacement and richness difference components, respectively (see Hidasi-Neto et al., 2019). All temporal beta diversity calculations (i.e., ßtotal and ßratio for all three dimensions) range from 0 to 1.

To access the representativeness of high taxonomic, functional, and phylogenetic diversity within protected areas of the Central Corridor of the Atlantic Forest we overlaid polygon boundaries from the World Database on Protected Areas (www.protectedplanet.net) and the National Registry of Conservation Units of Ministry of Environment (MMA, 2023) with the alpha maps for each dimension in each climate scenario. We considered diversity to be high when the alpha value for each dimension was equal to or greater than the third quantile (75%).

All analyses and graphing were conducted in R (v4.2.3; R Core Team, 2023) and QGIS (v3.28.11; QGIS, 2023).

2.3. Results

The average ecological niche models of forest bird species from the Central Corridor of the Atlantic Forest showed an intermediate to good fit. Most species (83%) presented models with Area Under the Curve (AUC) values ranging from 0.70 to 0.97, while only 17% exhibited AUC values of 0.54 to 0.69. The average Omission Rate (OR) value was 0.15, ranging from 0.02 to 0.44.

We found high values of taxonomic alpha diversity of forest birds in the northern and southeast portions of the CCAF for the baseline scenario. While most of these areas are

predicted to maintain their diversity in the future, a small increase can also be observed. However, this pattern is almost absent in the 2070 pessimistic scenario, where the losses are more consistent across the CCAF (Figure 2). In contrast, the areas with low species diversity located in the west, mostly in the midwest portion of the CCAF, are expected to lose taxonomic diversity in the future, which is particularly evident in the 2070 pessimistic scenario where the reduction may reach 50% (Figure 2e). We observed similar patterns for alpha functional and phylogenetic diversity, with current high values expected to be maintained or increase slightly in the northern and southeast portions, while current low values and high reductions are predicted in the midwest in the future (Figure 2). However, the decline in alpha functional and phylogenetic diversity was lower and concentrated in a smaller area compared to alpha taxonomic diversity, reaching a maximum of 40.8% and 27.5%, respectively, in the midwest portion of the 2070 pessimistic scenario (Figure 2j, o). Moreover, the alpha functional diversity was the only dimension where a small increase is projected in the northeast portion of the 2070 pessimistic scenario (Figure 2j). Different from alpha taxonomic and functional diversity, which showed a consistent gradient of loss westwards, alpha phylogenetic diversity showed a steep decrease in the northern portion of the CCAF (Figure 2l-o).

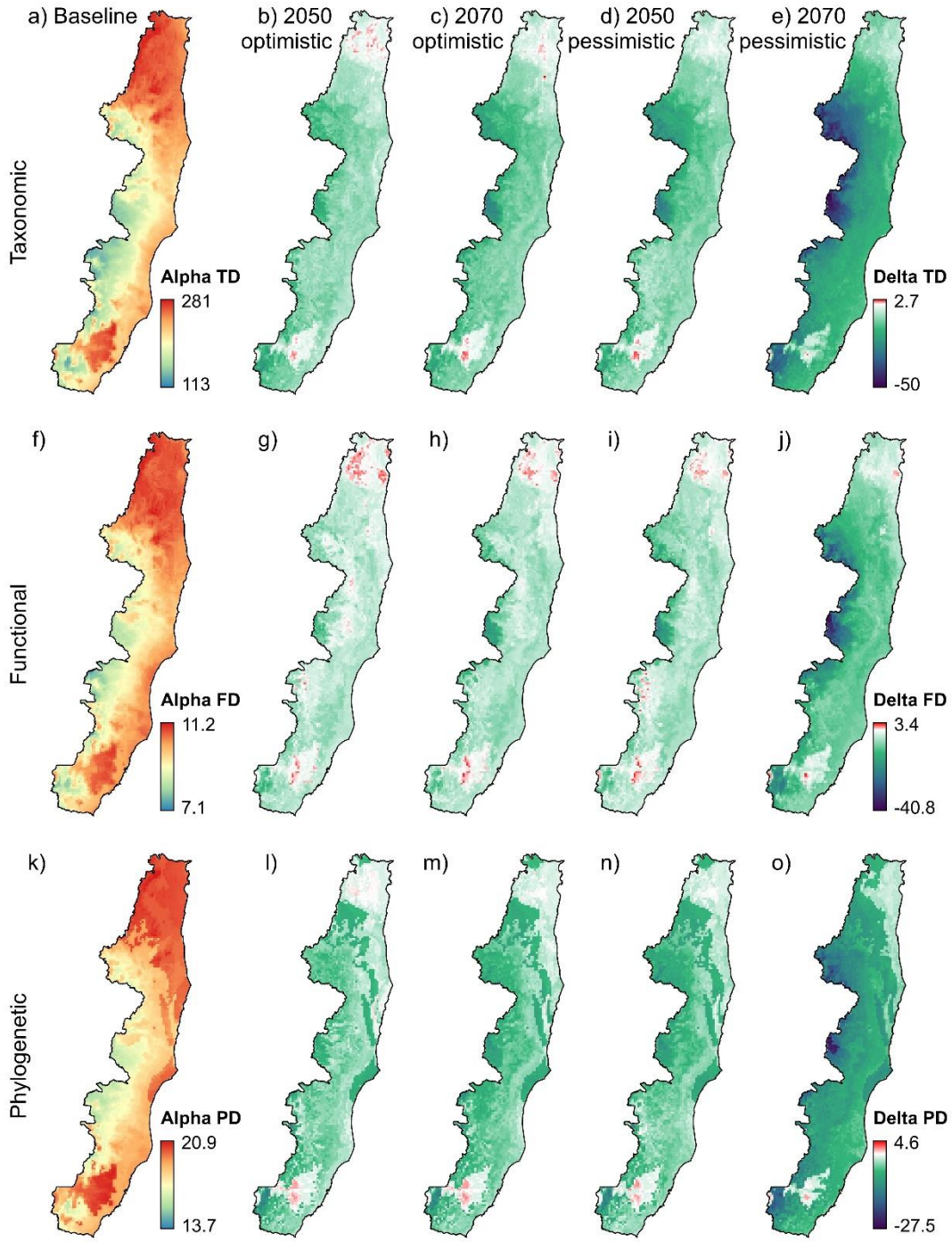

Figure 2. Taxonomic (TD), functional (FD), and phylogenetic (PD) alpha diversity of forest birds in the Central Corridor of the Atlantic Forest, and the percentage of change in alpha diversity of each dimension between the baseline and future scenarios. Dark red color in the baseline scenarios indicates high diversity, while dark blue color indicates low diversity for all dimensions (TD, FD, and PD). Red, dark green, and white colors in the future scenarios indicate an increase, a decrease, and no change in diversity, respectively, for all dimensions (TD, FD, and PD). Optimistic: SSP245. Pessimistic: SSP585.

The concordance among dimensions was lower for temporal beta results compared to alpha results. The highest values of temporal beta diversity of forest birds within the CCAF are predicted to be in the western portion across all dimensions and climate scenarios (Figure 3). For taxonomic diversity, high dissimilarity in the future community can be attributed to either the predominance of richness differences (red areas) or species replacement (blue areas) in the optimistic scenarios. However, in the pessimistic scenarios, the richness difference component dominates in the northwest portion, while the replacement component dominates in the southwest portion. For functional diversity, high dissimilarity due to the replacement of functional relationships between species in the future community is expected in the northwest portion, a pattern not observed in the other dimensions. The phylogenetic diversity also exhibits distinctive patterns, with a narrow band from north to south of high diversity due to the replacement of phylogenetic relationships shared by species in the future community (blue areas). This band is situated between areas with no change in phylogenetic diversity in the south portion. However, the band is located between differences in phylogenetic relationships shared by species (red areas) in the north portion of the CCAF. This latter pattern can also be observed in the mideast portion (Figure 3i-l). Conversely, the lowest values of temporal beta diversity are predicted for the northern, southern, and eastern portions of the CCAF, a pattern that repeats regardless of the diversity dimension and future climate scenario (white and gray areas; Figure 3).

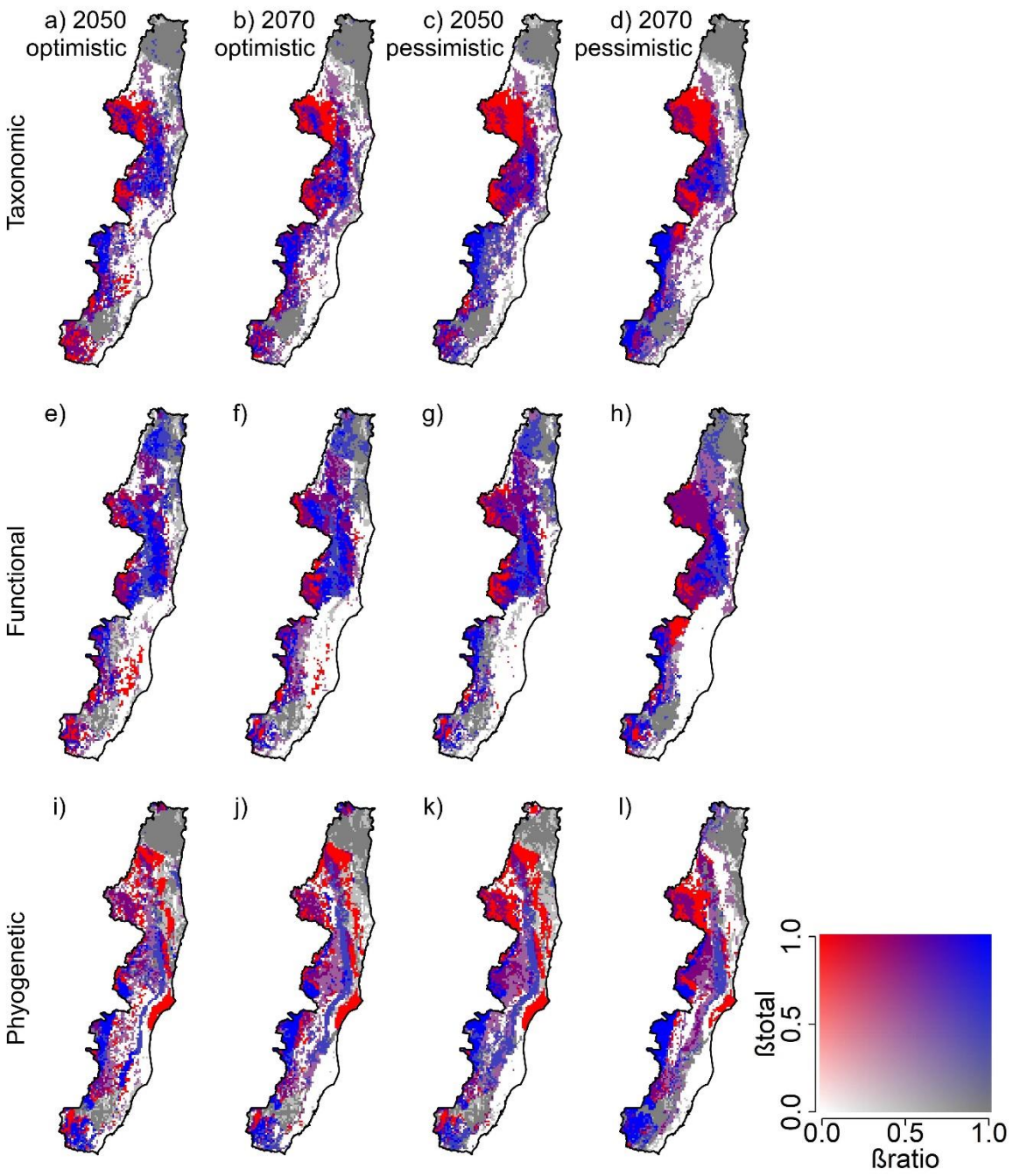

Figure 3. Temporal beta diversity of taxonomic, functional, and phylogenetic dimensions recorded within the Central Corridor of the Atlantic Forest. Red and blue colors represent high dissimilarity between future and baseline communities with the predominance of richness difference and replacement, respectively, while white and gray colors represent low dissimilarity. Optimistic: SSP245. Pessimistic: SSP585.

Our findings indicate that protected areas expected to simultaneously retain high taxonomic, functional, and phylogenetic diversity of forest birds within the CCAF are larger compared to the areas expected to retain only one or two dimensions. The high diversity of all

dimensions represented within protected areas may increase from 48.4% to 55.1-57.5%, while high taxonomic diversity decreases from 36% to 30.4-32.6% from baseline to future scenarios (Figure 4). A larger overlap between high taxonomic and high phylogenetic diversity can be observed in all scenarios (4.6-8.8%), except for the baseline where the overlapping area is larger between high taxonomic and high functional diversity (6.2%). Additionally, there are no protected areas expected to harbor only high functional or phylogenetic diversity, nor the overlap of these two in any scenario (Figure 4).

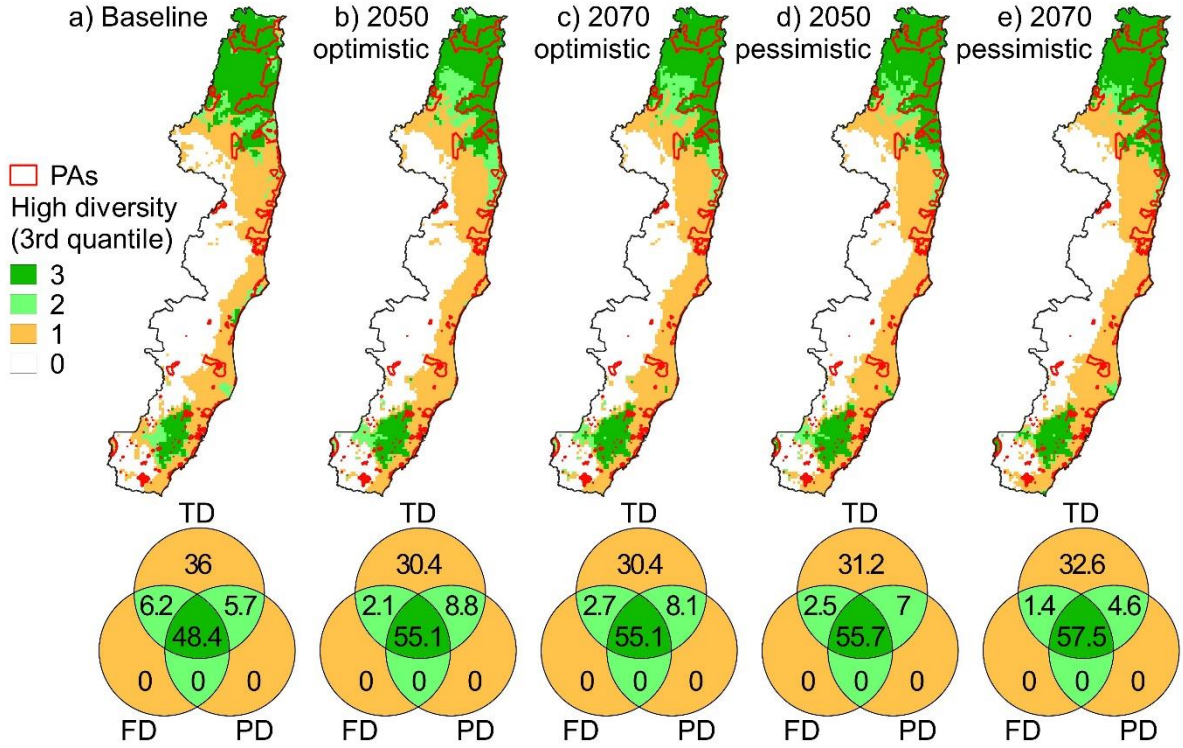

Figure 4. High multidimensional alpha diversity of forest birds observed in baseline and future scenarios within the Central Corridor of the Atlantic Forest. The red line indicates the current protected areas (PAs), and the legend shows the number of overlaying dimensions that score above the third quantile (75%). The Venn diagram at the bottom illustrates the percentage of dimensions within PAs for each scenario. For example, only 6.2% of the high taxonomic and functional dimensions are simultaneously under protection in the baseline scenario. Optimistic: SSP245. Pessimistic: SSP585.

2.4. Discussion

Our projections indicate that climate change will cause severe modifications in all diversity dimensions of forest birds across the Central Corridor of the Atlantic Forest. In fact, we observed that a decrease in alpha taxonomic, functional, and phylogenetic diversity, driven

by both replacement and richness differences, is associated with a shift in species distributions. In addition, our findings revealed that existing protected areas within the CCAF harbored high taxonomic, functional, and phylogenetic diversity of birds, and the overlay of all three dimensions increased from baseline to future scenarios, highlighting the importance of these Brazilian conservation units in safeguarding biodiversity.

The strong positive relationship between alpha taxonomic, functional, and phylogenetic diversity was already expected, as reported in other studies (e.g., Ben Saadi et al., 2022; Chapman et al., 2018; Måsviken et al., 2023). The decrease in these three dimensions in future scenarios is in agreement with previous studies that have reported losses in multiple facets of bird, mammal, and amphibian diversity facing climate change (Castaño-Quintero et al., 2022; Hidasi-Neto et al., 2019; Prieto-Torres et al., 2021). However, low congruence among the dimensions was also observed in our study in the northern portion of the CCAF, especially for the 2070 pessimistic scenario. Although alpha taxonomic diversity showed a small decline, for functional diversity, a small increase is projected in the northeastern side, suggesting that the species that will potentially disappear from this area are functionally more similar compared to the persistent ones. Despite this increase in functional diversity, the loss of redundancy in ecological roles performed by forest species is alarming, as ecosystem functioning could be compromised through the higher risk of losing a key ecological service (Zhang and Zang, 2021). In fact, most forest birds feed on invertebrates, and we observed that at least two representatives of this group (*Conopophaga lineata* and *Phylloscartes beckeri*) will not find suitable climate conditions in the northeast CCAF. This contrasting pattern between taxonomic and functional diversity has been reported for plants, where the functional group is maintained despite the depletion of its species (Thuiller et al., 2006). For phylogenetic diversity, a reduction is expected in the extreme northwest, even though taxonomic and functional diversity may remain the same or change little. This result indicates that a potential increase or stability in species richness does not necessarily compensate for the losses in phylogenetic diversity (Sobral et al., 2016), especially when the species being lost are ancient (e.g., *Touit surdus*), which contribute the most to the phylogenetic diversity calculation (Faith, 1992). Additionally, the loss of phylogenetic diversity in this region matches non-forested areas, thus supporting the importance of natural vegetation in buffering temperature rises (Frey et al., 2016).

We observed an increase in the dissimilarity of forest bird communities between baseline and future scenarios in the western portion of the CCAF, where low diversity and high losses are expected across all dimensions and scenarios. This pattern can be associated with the reductions in alpha diversity and are in line with other studies showing high community

divergence due to species loss (Mota et al., 2022a; Vasconcelos et al., 2018). On the other hand, the prevalence of the replacement component observed in the southwestern portion suggests that the projected species loss should occur at a higher rate than the arrival of new species to this region (Hidasi-Neto et al., 2019; Sobral et al., 2016). Indeed, in the southwestern portion, our projections indicate climatically suitable area for 17 species (e.g., *Neopelma aurifrons* and *Heliothryx auritus*) in the baseline that will be lost in future scenarios, while the opposite is expected for 5 species (e.g., *Veniliornis maculifrons* and *Attila spadiceus*). In the northwestern portion, the high dissimilarity in functional diversity is likely to result from the replacement of species with different traits between baseline and future scenarios, such as *Anabacerthia lichtensteini*, a smaller insectivorous bird with suitable area in the baseline but not in the future, and *Crax blumenbachii*, a larger frugivorous bird predicted to expand its distribution in the future. This result is supported by studies with other taxa, where the substitution of species increases the dissimilarity between communities (García-Navas et al., 2020; Prieto-Torres et al., 2021). Additionally, the narrow band of replacement observed in beta results for phylogenetic diversity is likely to reflect the substitution of closely related species by different ones. For instance, the *Brotogeris tirica* is projected to lose climate suitable area in this band, and the *Myrmotherula urosticta* is projected to gain area in the same location. These species belong to different families that are phylogenetically distant by ca. 30 million years, indicating a potential loss of evolutionary history, as *B. tirica* is much older than *M. urosticta* (Schmitt and Edwards, 2022). This replacement pattern in phylogenetic diversity is also observed for birds from riparian Amazonian habitats (Naka et al., 2020).

Notably, the highly diverse areas in the northern and southern portions of the CCAF are connected by a white band, indicating no change in the forest bird community between the baseline and future scenarios. This means that the climate conditions for all species occurring in this region are expected to be maintained, thus representing great potential for restoration and conservation purposes. Forest dependent species such as the *Saltator fuliginosus*, projected to lose suitable area in the central portion of the CCAF in the future, could benefit from the expansion of forested and protected areas in this region, increasing connectivity between the climate stable areas in the north and south (Littlefield et al., 2017). Given the positive effect of reforestation on biodiversity (Wang et al., 2022), this strategy may contribute to climate change mitigation and consequently reduce the loss of forest bird species in the CCAF (Han et al., 2024; Kemppinen et al., 2020).

The high taxonomic, functional, and phylogenetic diversity of forest birds within protected areas will increase in the future, as we anticipated. These highly diverse areas are

projected to concentrate in the northeastern portion of the CCAF, where the largest protected areas and highest forest cover are located, such as the Caminhos Ecológicos da Boa Esperança (-13.5433, -39.3691; 2 302 km^2) and the Lagoa Encantada e Rio Almada (-14.6395, -39.3506; 1 577 km^2) (MapBiomas, 2023; MMA, 2023). In fact, the importance of these large forest remnants near the coast to bird diversity was recently acknowledged (Tonetti et al., 2023), suggesting that these current protected areas may potentially act as refuges for species in the future. The effectiveness of protected areas in conserving bird species under climate change is supported by other studies that observed higher losses of climatically suitable areas outside than inside protected areas (Regos et al., 2019; Velásquez-Tibatá et al., 2013). However, the concentration of high diversity across multiple dimensions within protected areas in the northern portion could limit the conservation potential of the CCAF due to the restriction of species to this region with nowhere else to go (Parks et al., 2023). Indeed, in terms of number and size of protected areas, those located in the southern portion projected to retain high diversity in all dimensions correspond to only ca. 760 km^2, reinforcing the need to expand the protected area network. This would also favor other species, as the region is predicted to retain high diversity of anurans and mammals in the future (Anunciação et al., 2023; de Oliveira et al., 2024).

Our study represents the first comprehensive assessment of how climate change can affect multiple dimensions of forest bird diversity in a region of extreme conservation importance in the threatened Atlantic Forest. We observed a reduction in taxonomic, functional, and phylogenetic diversity, with greater losses anticipated under the pessimistic climate scenario projected for 2070. Although most alpha patterns for functional and phylogenetic diversity can be explained by taxonomic diversity, this should be treated with caution, especially due to distinctive patterns observed for these two dimensions in highly diverse areas in the northern region. Furthermore, changes in community composition showed much more variation among dimensions, as evidenced by temporal beta diversity results. We identified regions expected to maintain high diversity and show high dissimilarities in communities between baseline and future scenarios, evidencing either the replacement of similar species by different ones or the loss of unique species. More importantly, the climate stability in the eastern portion of the CCAF connects the highly diverse areas located in the northern and southern regions, thereby presenting a great reforestation potential to increase species persistence under climate change. Moreover, expanding the protected areas in the southern portion, which are currently underrepresented, may contribute to this goal. Therefore, we emphasize the importance of incorporating diversity patterns of multiple dimensions in

climate change studies for informing robust conservation planning in threatened environments, mitigating the risk of species loss, and safeguarding ecological services and evolutionary heritage in the future.

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Capítulo 3

Manuscrito a ser submetido ao periódico Biological Conservation

Functional traits exacerbate the vulnerability of forest birds to climate change in the Atlantic Forest

Flávio M M Mota[1,3*], Kyle D Kittelberger[3], José Carlos Morante-Filho[1], Richard G Davies[2], Çağan H Şekercioğlu[3,4,5], Neander M Heming[1] and Daniela C Talora[1]

[1]Applied Ecology and Conservation Lab, Programa de Pós-graduação em Ecologia e Conservação da Biodiversidade, Universidade Estadual de Santa Cruz, Ilheus, 45662-900, Bahia, Brazil

[2]School of Biological Sciences, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ, UK

[3]School of Biological Sciences, University of Utah, Salt Lake City, 84112, Utah, USA

[4]Department of Molecular Biology and Genetics, Koç University, 34450, Istanbul, Türkiye

[5]KuzeyDoğa Derneği, Istasyon Mahallesi, Ismail Aytemiz Caddesi, 36200 Kars, Türkiye

Abstract

Climate change is expected to promote shifts in the distribution of avian species. Understanding the traits that might influence their responses can contribute to their conservation. Using ecological niche models and ten functional traits of 292 forest bird species from the Central Corridor of the Atlantic Forest (CCAF) in Brazil, we investigate: (i) which traits correlate with larger contractions in species' current distributions, and (ii) where suitable climate conditions are projected to persist under different climate scenarios. We found that baseline suitable area, mean elevation, and forest dependency are key predictors of relative changes in suitable areas for forest birds. Species expected to experience greater losses may concentrate in the northwest and southwest portions of the CCAF. The decline in suitable area is proportionally higher for range restricted species, while highland birds face the challenge of having limited alternative habitats. Additionally, species dependent on deep forest resources are unlikely to disperse from their current locations. Importantly, vulnerable forest birds in the northern and southern

portions of the CCAF could benefit from expanding existing forested and protected areas in the region, potentially enhancing their chances to cope with climate change. Our findings provide insights into how forest bird species might respond elsewhere and the specific traits influencing these responses. Finally, we emphasize the importance of integrating species traits into climate change studies, in addition to identifying areas expected to retain suitable climate conditions for species that could be selected for future conservation planning and resource allocation.

Keywords Global warming, Neotropics, Conservation, Species distribution, Maxent, Macroecology, Ornithology

3.1. Introduction

Climate change is rapidly becoming one of the main threats to biodiversity, forcing species to shift their distributions or face extinction (Trisos et al., 2020; Mota et al., 2022b). Warmer and drier climate conditions are expected in the next decades in some parts of the world, including the north and northeast parts of South America (Almazroui et al., 2021). As a consequence, projections indicate reductions in the climatically suitable area of numerous species, thereby causing a decline in species richness across various regions worldwide (Velásquez-Tibatá et al., 2013; Miranda et al., 2019). For example, more than half of bird species from tropical forests are expected to experience contractions in their current distributions, potentially leading to local extinctions if suitable climate conditions are not found in the future (Wormworth and Şekercioğlu, 2011; Prieto-Torres et al., 2020; Mota et al., 2022a). Furthermore, the loss of species that play key roles in ecosystem functioning, such as pollination and seed dispersal, poses a significant threat under climate change (Şekercioğlu, 2006; Sales et al., 2021; Zamora-Gutierrez et al., 2021). Therefore, it is crucial to consider potential spatiotemporal changes in species distributions to avoid biodiversity loss.

Birds are a good model to evaluate the impacts of environmental changes on biodiversity (Kati and Şekercioğlu, 2006; Palacio et al., 2020). The projections indicate that many bird species will lose suitable climatic areas, and drastic contractions are expected to occur in the current distribution of different ecological groups, such as frugivorous birds. For example, recent studies in the Atlantic Forest indicated that the ranges of many frugivores, including Red-tailed Parrots (*Amazona brasiliensis*) and the Diademed Tanagers (*Stephanophorus diadematus*), are expected to contract by mid-century (Vale et al., 2018; Mota et al., 2022b). In particular, the loss of these species in some regions may have severe

consequences for ecosystem functioning, as they primarily feed on fruits and therefore potentially act as crucial seed dispersers (Şekercioğlu, 2006; Wenny et al., 2016; Trolliet et al., 2017). Birds also contribute to insect control, as the presence of some species is associated with a decrease in leaf damage that may compromise the survival of plant species (Barnes et al., 2020), and to pollination, which is important for maintaining genetic variability in plant populations (Wessinger, 2021).

Birds' response to climate change may differ among various taxa, with certain species more likely to suffer contractions in their distributions (Mota et al., 2022a). Characteristics such as range size, primary habitat, primary diet, and body mass may be important predictors of species vulnerability (Fortini et al., 2015; Smith et al., 2017; Miranda et al., 2019). For example, species with restricted distribution are expected to experience either more contraction in their ranges on a regional scale or less contraction on a global scale compared to widely distributed species (Fortini et al., 2015; Mota et al., 2022b). Additionally, forest frugivorous birds are also more prone to losing climate suitable areas compared to those species associated with open areas that feed mainly on other resources (Miranda et al., 2019). Body mass is also an important factor influencing birds' vulnerability to climate change, as smaller species may struggle to maintain thermoregulation compared to the more efficient mechanism of evaporative heat loss in larger species (Smith et al., 2017).

Other functional traits that serve as reliable indicators of birds' vulnerability to disturbances may also play a significant role in determining their response to climate change. For example, species with broad habitat and dietary breadth - indicating the number of habitats used and the variety of food types consumed, respectively - are more likely to persist in degraded environments than are more specialized species (Şekercioğlu, 2011; Callaghan et al., 2019; Kittelberger et al., 2021, 2023; Neate-Clegg et al., 2023). Therefore, such ecological traits may also mitigate the negative impacts of climate change. In addition, birds with lower hand-wing index (HWI), which is associated with dispersal ability, may be unable to reach new suitable areas (Sheard et al., 2020). Indeed, larger contractions in range size are expected for species when assuming a no-dispersal scenario compared to an unlimited scenario (de Moraes et al., 2020). Moreover, assessing the simultaneous effects of multiple traits on birds' responses to climate change can offer valuable insights into the future of avian communities and aid in conservation efforts (Kittelberger et al., 2021; Mota et al., 2022b; Neate-Clegg et al., 2023).

The Brazilian Atlantic Forest is home for 832 bird species, of which ~26% are endemic and ~8% are globally threatened (Hasui et al., 2018; Vale et al., 2018). Despite its ecological significance, much of its original vegetative cover has already been lost, leaving only 22.9%

of natural vegetation remaining, with the majority (97%) concentrated in fragments smaller than 50 hectares (de Lima et al., 2020; Vancine et al., 2024). The species' extinction risk from this biome may be even higher, as changes in temperature and precipitation patterns could lead to the replacement of forest species for those more associated with warmer and drier environments (Sales et al., 2020). Moreover, previous studies on climate change and avian species have already projected reductions in range sizes, potentially leading to impoverished bird communities in the future (Vale et al., 2018; Mota et al., 2022b; Tonetti et al., 2022). However, the functional traits mediating these changes remain to be elucidated, which could contribute to supporting conservation efforts, especially considering that responses to climate change may vary among species (Mota et al., 2022a).

In this study, we assessed how functional traits modulate the responses of Atlantic Forest birds to climate change and identified areas predicted to harbor the most vulnerable species in the future. Specifically, our aims were (i) to identify the functional traits of forest birds associated with higher contractions in species' current distributions and (ii) to identify areas with suitable climatic conditions for the most vulnerable species. We predicted that the most vulnerable forest birds would exhibit specific ecological traits, such as smaller body size (Mota et al., 2022a), high specialization (Şekercioğlu, 2011; Kittelberger et al., 2021), and low dispersal ability (Sheard et al., 2020). Also, we anticipate that such species will have restricted distributions (Mota et al., 2022b), primarily inhabiting high elevations (Sales et al., 2021) and showing a high dependency on forested habitats (Morante-Filho et al., 2021). In addition, we expected higher concentrations of vulnerable birds to be maintained in the northern and southern areas compared to lower concentrations in the mid-west areas (Mota et al., 2022b). By providing the potential distribution of forest birds under different climate scenarios, this study may assist in the conservation planning of bird communities in the region, especially for the most vulnerable species, and indicate potential trends regarding the impacts of climate change on other forest species elsewhere.

3.2. Methods

Study area

The study area encompasses the state of Espírito Santo and the southern region of Bahia, Brazil, known as the Central Corridor of the Atlantic Forest (CCAF). It is located between the coordinates 13°0'6"–21°18'36"S and 41°52'43"–37°16'40"W and covers an approximate area of 11.7 million hectares (Figure 1). The CCAF is one of the most important regions of the Atlantic Forest hotspot, harboring rich biodiversity and a significant proportion

of species endemic to this biome, including plants, birds, and primates (Cordeiro, 2003; Werneck et al., 2011; Culot et al., 2019). Despite the prevalence of agriculture, which accounts for 59.6% of the area, the CCAF still retains a substantial forest cover of 31.4% (MapBiomas, 2023).

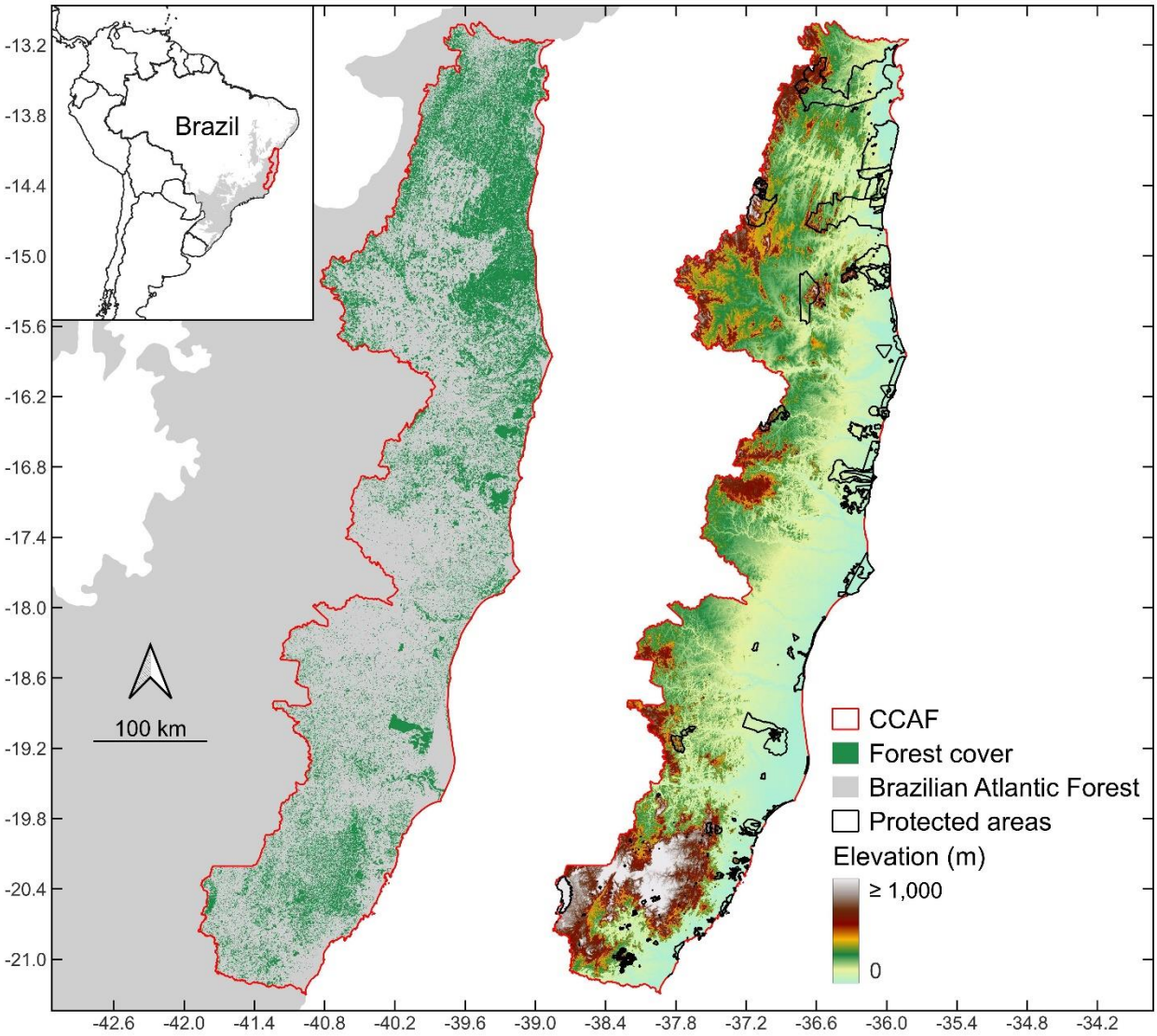

Figure 1. Location of the Central Corridor of the Atlantic Forest (CCAF) in Brazil. On the left, it shows the Atlantic Forest limits in gray and the forest cover in dark green, and on the right, it shows the protected areas and an elevational gradient.

Bird data

We selected the forest bird species that occur within the CCAF based on the literature (Hasui et al., 2018; Tobias et al., 2022). Then, we obtained occurrence records from the Global Biodiversity Information Facility (GBIF; www.gbif.org), which compiles data from different sources and is widely used to predict species distributions (Heberling et al., 2021). We

subjected the occurrences to a quality control process to eliminate inaccurate records, such as those presenting incomplete coordinates or matching municipalities centroids (Zizka et al., 2019). Additionally, to minimize geographical bias, we used the *spThin* R package (Aiello-Lammens et al., 2015) to remove occurrences that were less than 10 km apart from their nearest neighbors while retaining the highest number of records per species. Our final dataset included 292 species of forest birds registered in the CCAF region (Table S1).

For each bird species, we used several ecological traits associated with vulnerability to environmental disturbances. In particular, we obtained four measurements of bill morphology (two measures of length, width, and depth), hand-wing index (HWI), and body mass data from the AVONET database (Tobias et al., 2022). We also used information on primary diet, forest dependency, elevational range, clutch size, habitat breadth, and dietary breadth from the BirdBase database (Şekercioğlu et al., 2004, 2019; Kittelberger et al., 2021; Billerman et al., 2022). Additionally, we acquired the generation length of each species from Bird et al. (2020). We used habitat and dietary breadth to calculate an ecological specialization index (ESI; log [100/(number of habitats used × number of food types eaten)]; Şekercioğlu, 2011). We used the baseline suitable area calculated from ecological niche model results (see next sections), which represents the current suitable climatic conditions for the species, instead of the range size, which is strictly a geographical trait. We conducted a Principal Component Analysis (PCA) to summarize the four bill measurements and checked the correlation between the first two axes and all traits. We removed the first axis of the PCA and the generation length due to their high correlation with body mass (Pearson correlation > 0.6). The second axis then represents bill shape, a spectrum associated with foraging specializations that ranges from long, thin, pointy bills (e.g., Black-billed Scythebill; *Campylorhamphus falcularius*) to short, thick bills (e.g., Blue-winged Macaw; *Primolius maracana*).

Avian taxonomic classifications were based primarily on Bird Life International and its list of the world's bird species, which are reviewed and adopted by the BirdLife Taxonomic Working Group (BirdLife International, 2024) and the BirdBase database (Şekercioğlu et al., 2004, 2019; Kittelberger et al., 2021; Billerman et al., 2022). We were able to obtain traits for all species after reconciling discrepancies between sources. For instance, the species Golden-chevroned Tanager is identified as *Tangara ornata* by Bird Life International and as *Thraupis ornata* by the IOC World Bird List v13.2. Our final dataset therefore consisted of nine traits for 292 species: baseline suitable area, mean elevation, body mass, mean clutch size, HWI, bill shape, ESI, forest dependency (low, medium, and high), and primary diet (fruit, seed, invertebrate, vertebrate, and nectar) (Table S3).

Climate data

We acquired 19 bioclimatic variables from the WorldClim platform (www.worldclim.com) at a resolution of 2.5 arcminutes for the baseline and future scenarios (2050 and 2070) (Fick and Hijmans, 2017). These variables are derived from precipitation and temperature measurements and are commonly used in the literature (Prieto-Torres et al., 2020; Oliveira-Silva et al., 2022). For each species, we used the *ENMwizard* R package (Heming et al., 2019) to perform a Pearson correlation analysis considering all bioclimatic variables and selected those below the cutoff value of 0.7 to avoid collinearity (Dormann et al., 2013) (Table S2). For the future climate scenarios, we considered three Global Climate Models (GCMs): IPSL-CM6A-LR, MIROC6, and MPI-ESM1-2-HR and two Shared Socio-economic Pathways (SSPs): 245 and 585. The selection of these GCMs was based on their improved performance in reducing bias when simulating bioclimatic variables in the latest phase of the Coupled Model Intercomparison Project compared to the previous one (Cannon, 2020), while the SSPs represent optimistic and pessimistic greenhouse gas concentration scenarios, respectively (O'Neill et al., 2014).

Ecological Niche Models (ENMs)

We modeled the niches of 292 avian forest species using the MaxEnt algorithm (Phillips et al., 2006) whose better performance has been previously demonstrated (Mota et al., 2022b). We considered all occurrences of each species before the geographical bias procedure (above) to define the calibration area and projected the models onto the study area only. We used the *ENMeval* R package (Muscarella et al., 2014) to optimize MaxEnt parameters by combining ten regularization multipliers (0.5 to 5 with intervals of 0.5) and seven combinations of three feature classes (Linear, Quadratic, and Product), totaling 70 models per species. We validated the models using the block method (Roberts et al., 2017) and ranked them based on the lowest omission rate (OR) and the highest area under the curve (AUC) (Boria et al., 2017). Then, we projected the top 10% models onto the future climate scenarios (GCMs and SSPs) and averaged them to generate a single consensus model for each species and scenario (Boria et al., 2017). Finally, we transformed the final models into binary maps representing "suitable" and "unsuitable" climate areas using the ten-percentile training presence threshold calculated by MaxEnt (Ahmadi et al., 2020).

Statistical Analysis

We built linear mixed-effects models (LMMs) using the "lmer" function of the *lme4* R package (Bates et al., 2015) to test the relationship between the relative change in suitable area (i.e., [(future suitable area – baseline suitable area)/baseline suitable area]; our response variable) and our ten functional traits (predictor variables). Positive and negative values in our response variable indicate expansion and contraction of the suitable area from the baseline to the future scenario, respectively, while zero indicates no change. We accounted for avian phylogeny by including species and genus nested within taxonomic family as random effects. Additionally, we included the future scenarios as a random effect to account for pseudoreplication. We log-transformed body mass and the baseline suitable area. Then, we scaled and centered all our numerical traits to have a mean of 0 and a standard deviation of 1. We also checked for variance inflation factors (VIFs) for our predictor variables in our LMM using the "vif" function of the *car* R package (Fox and Weisberg, 2019), and all had values below 3 (Zuur et al., 2010).

From our global model comprising all nine traits, we computed every possible model by removing one trait at a time until none were left (null model) using the "dredge" function of the *MuMIn* R package (Bartoń, 2023). This resulted in a total of 512 models with Akaike information criterion corrected for small samples (AICc) values ranging from -685 to -541. We selected the model with the lowest AICc as our top model, with no competing models having a ΔAICc lower than two (Burnham and Anderson, 2002; Cade, 2015). Additionally, in our top model, for any categorical variables with more than two categories (primary diet and forest dependency), we used a likelihood ratio test to determine significance and calculated the relative change in suitable area for each category.

We considered the most vulnerable species to climate change as those expected to lose at least half of their baseline suitable area. We generated richness maps for each scenario and calculated the percentage change in richness between baseline and future scenarios using the *divraster* R package (Mota et al., 2023). The changes in climate suitable areas between the baseline and the 2050 pessimistic scenario for all species are shown in Figure S1.

All statistical analyses and graphing were conducted in R (v4.2.3; R Core Team, 2024), and the maps were made in QGIS (v3.34.6; QGIS, 2024).

3.3. Results

The 292 forest birds in the CCAF comprise 39 families, with Furnariidae and Thamnophilidae being the most representative with 28 and 26 species, respectively, while the

families Cathartidae, Galbulidae, Grallariidae, Odontophoridae, Polioptilidae, and Rallidae each presented a single species. The species expected to lose the most climate-suitable area in the future is the Ochre-breasted Foliage-gleaner (*Anabacerthia lichtensteini*; -99%), whereas the Spotted Bamboowren (*Psilorhamphus guttatus*) and Yellow-eared Woodpecker (*Veniliornis maculifrons*) are expected to expand their areas by more than twice (Table S4).

The top model revealed three functional traits significantly affecting the relative change in suitable area: baseline suitable area, mean elevation, and forest dependency. Baseline suitable area was positively associated with the relative change in suitable area (Figure 2a; 0.117 ± 0.012 se, t = 9.392, p < 0.001), with species that have small baseline suitable area being more vulnerable than widely distributed species. Conversely, mean elevation was negatively associated with the relative change in suitable area (Figure 2b; -0.066 ± 0.012 se, t = -5.509, p < 0.001), with species from higher altitudes being more vulnerable than those that occur in lowlands. Finally, forest dependency was significantly associated with the relative change in suitable area (Figure 2c; $\chi 2$ = 5.066, p = 0.024), such that species that have high forest dependency are more vulnerable than species with lower forest dependency.

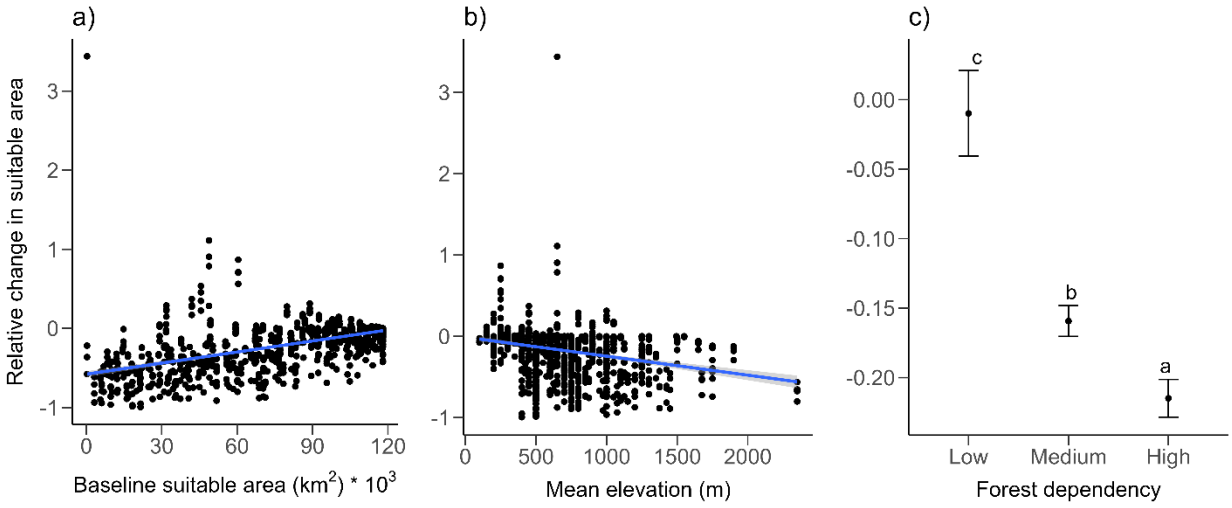

Figure 2. Relationship between the relative change in suitable area and the baseline suitable area (a), mean elevation (b), and forest dependency (c) for forest birds in the Central Corridor of the Atlantic Forest of Brazil. Positive and negative values indicate expansion and contraction of climate-suitable areas between baseline and future scenarios, respectively. Vertical bars indicate the standard error of the mean, with significant differences represented by different letters above them.

Our findings indicated that 19 forest bird species are likely to be more vulnerable to climate change within the CCAF for all scenarios evaluated: Ochre-breasted Foliage-gleaner

(*Anabacerthia lichtensteini*), Black-billed Scythebill (*Campylorhamphus falcularius*), Blue Manakin (*Chiroxiphia caudata*), Blue-naped Chlorophonia (*Chlorophonia cyanea*), Brazilian Ruby (*Clytolaema rubricauda*), Highland Elaenia (*Elaenia obscura*), Drab-breasted Bamboo-tyrant (*Hemitriccus diops*), Large-tailed Antshrike (*Mackenziaena leachii*), White-bibbed Antbird (*Myrmoderus loricatus*), Spot-winged Wood-quail (*Odontophorus capueira*), Grey-capped Tyrannulet (*Phyllomyias griseocapilla*), Greenish Tyrannulet (*Phyllomyias virescens*), Bahia Tyrannulet (*Phylloscartes beckeri*), Pileated Parrot (*Pionopsitta pileata*), Saffron Toucanet (*Pteroglossus bailloni*), Red-breasted Toucan (*Ramphastos dicolorus*), Spot-billed Toucanet (*Selenidera maculirostris*), Rusty-barred Owl (*Strix hylophila*), Gilt-edged Tanager (*Tangara cyanoventris*) (Figure 3). A higher concentration of these species is located in the northwest, southwest, and littoral portions of the CCAF, where suitable climate conditions for them are expected to be retained. Conversely, in the mid-east, we observed no to low species in the baseline scenario, coinciding with the locations expected to lose suitable area (Figure 3a). This pattern is consistent across all climate scenarios, except for the differences in the number of vulnerable species: 32 for the 2070 optimistic scenario, 41 for the 2050 pessimistic scenario, and 78 for the 2070 pessimistic scenario (Figure 3b-d).

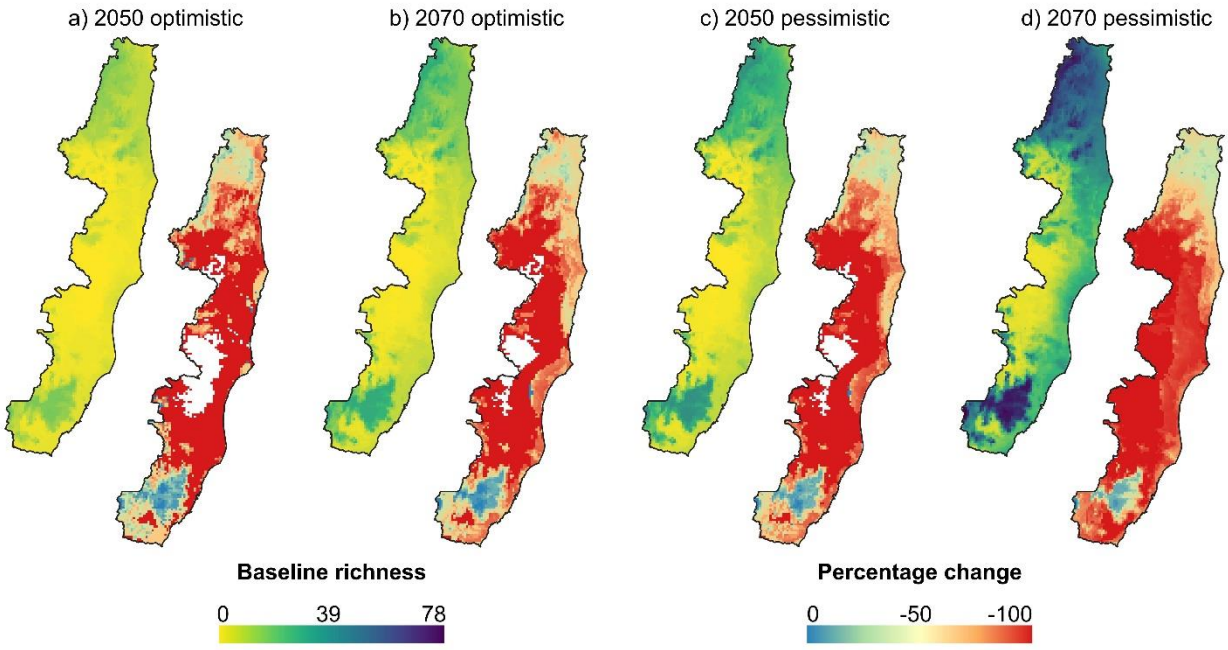

Figure 3. Baseline richness and percentage of change in richness between the baseline and future climate scenarios for the most vulnerable forest bird species in the Central Corridor of the Atlantic Forest of Brazil. Optimistic scenario: SSP245. Pessimistic scenario: SSP585.

3.4. Discussion

Alterations in the distributions of bird species due to climate change have been reported worldwide, and their traits may reveal the species more likely to suffer contractions in their baseline suitable areas, allowing us to better direct limited resources to the preservation of at-risk species. Our projections for the Central Corridor of the Atlantic Forest of Brazil indicate that avian species with restricted distributions, high dependence on forest habitats, and inhabiting regions with high elevations are expected to lose more climatically suitable areas in the future compared to their counterparts. Moreover, we identified that the northwest and southwest portions of the CCAF may concentrate most of the forest birds expected to lose more than half of their current distributions, which should be considered in conservation planning to ensure their long-term persistence in this threatened region.

According to expectations, birds currently presenting smaller distributions are predicted to lose more climate suitable area in the future, corroborating a previous study in the same region (Mota et al., 2022b). Reductions in the baseline suitable areas of these species is proportionally greater compared to the widely distributed species, as observed for Rufous-tailed Antbird (*Drymophila genei*) and Hangnest Tody-Tyrant (*Hemitriccus nidipendulus*). Both are expected to lose approximately 56% of their climate suitable area on average, but the former has a baseline suitable area 2.9 times smaller than the latter, thus likely to be more threatened by climate change (Tables S3 and S4). The opposite is also true, as the greatest expansion in climate-suitable area (3.4 times) is expected for the species Spotted Bamboowren (*Psilorhamphus guttatus*), with a baseline suitable area of 284 km², only in the 2070 optimistic scenario. In particular, the geographic range size is one of the main predictors of extinction risk, not only for climate related threats but also for habitat loss (Staude et al., 2020; Bladon et al., 2021; Manes et al., 2021). However, a recent review contradicts our result, indicating that widely distributed birds should be more vulnerable to climate change - a divergence likely resulting from the scale at which birds worldwide are considered (Mota et al., 2022a).

Similarly, birds inhabiting highlands are anticipated to be more vulnerable to climate change, experiencing a greater risk of extinction due to the contractions in their distributions, as corroborated by the disappearance of one-third of tropical birds from mountaintops (e.g., Freeman et al., 2018). In our study, species expected to gain suitable habitat in the future exhibit a mean elevation of 454 m, whereas those likely to suffer greater losses show a mean elevation of 877 m (Tables S3 and S4). Likewise, endemic birds inhabiting eastern Brazilian mountaintops within the Atlantic Forest may face potential loss of up to 94% of their current distributions (Hoffmann et al., 2020). Besides the constraints posed by the limited area at high

elevations, these species might encounter further challenges due to the upslope shifts in the distribution of their close relatives, leading to potential competition for essential resources such as food and nesting sites (Liu et al., 2023).

Greater losses of climatically suitable areas are expected for high forest dependent species in the future, corroborating our hypothesis. Forest specialist birds are likely to be the first to disappear from disturbed areas, as observed in the case of Red-headed Manakin (*Ceratopipra rubrocapilla*), which requires more than 60% landscape forest cover to persist in forest fragments (Morante-Filho et al., 2021). This is also supported by greater losses of climate suitable areas expected for forest birds compared to species associated with other habitat types (Mota et al., 2022a). The higher vulnerability of these species may be related with their limited dispersal capacity and their reliance on specific resources, such as fruits and holes for feeding and breeding found deep within forests, making it unlikely for them to cross open fields and reach new suitable areas (e.g., Spot-winged Wood-Quail [*Odontophorus capueira*]; Carroll and Kirwan, 2020). For example, we found that Scale-throated Hermit (*Phaethornis eurynome*) may lose 75% of its current distribution, while Rufous-breasted Hermit (*Glaucis hirsutus*) will lose only 4%. Despite belonging to the same family (i.e., Trochilidae), the former can be found only in forest habitat, while the latter has a higher habitat breadth including woodland, shrubland, grassland, and plantations (Hinkelmann et al., 2020b, 2020a).

We identified that the most vulnerable forest birds are concentrated in the northwest and southwest portions of the CCAF in all climate scenarios. Species such as the Rufous-brown Solitaire (*Cichlopsis leucogenys*) and the Fork-tailed Tody-tyrant (*Hemitriccus furcatus*) are expected to lose most of their baseline suitable area in the central portion of the CCAF by 2070 in the pessimistic scenario. Currently, there are large protected areas in the northern portion but smaller ones in the southern portion (UNEP-WCMC and IUCN, 2024), and their expansion could greatly contribute to the persistence of vulnerable forest birds in the future, especially those located at higher elevations (Velásquez-Tibatá et al., 2013; Malecha et al., 2023). Additionally, forest mammals are anticipated to maintain climate suitable areas in the southern CCAF, indicating that protecting this region would also benefit other taxa (de Oliveira et al., 2024).

In our study, we reveal the functional traits likely to increase the vulnerability of forest birds to climate change within the CCAF, a recognized priority area for conservation in Brazil (Vancine et al., 2024). Species with small baseline suitable areas, high forest dependency, and inhabiting highlands are predicted to be extirpated from most regions, particularly in the central portion, whereas the northwest and southwest portions may retain suitable climate conditions

for them. Given that climate suitable areas within protected areas may shift in the future and considering the potential of forested areas in mitigating temperature rises (Frey et al., 2016; Littlefield et al., 2017), the expansion of conservation areas in the region is a promising pathway. Furthermore, our findings provide insights into species distributions under different scenarios that could potentially be applied elsewhere, as large losses of suitable areas are expected for avian species from Amazonian, Mexican, and Colombian forests that could benefit from trait information (Velásquez-Tibatá et al., 2013; Miranda et al., 2019; Sierra-Morales et al., 2021). The predictions we present should help direct limited resources to prevent species loss and consequently the impoverishment of bird communities not only within the Atlantic Forest but also in other degraded environments. Finally, it is important to note that considering a non-dispersal scenario could potentially double the number of vulnerable species, making our predictions conservative (Prieto-Torres et al., 2020). Additionally, the inclusion of birds associated with open areas could provide valuable complementary information on the impacts of climate change on avifauna (Miranda et al., 2019).

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Capítulo 4

Manuscrito publicado no periódico Diversity and Distributions

Climate change is expected to restructure forest frugivorous bird communities in a biodiversity hot-point within the Atlantic Forest

Flávio Mariano Machado Mota[1], Neander Marcel Heming[1], José Carlos Morante-Filho[1], Daniela Custódio Talora[1]

[1]Applied Ecology and Conservation Lab, Programa de Pós-graduação em Ecologia e Conservação da Biodiversidade, Universidade Estadual de Santa Cruz, Ilhéus, Brazil

Abstract

Changes in climatic conditions are predicted to impact species distribution and hence alter their diversity patterns. Modifications in the composition of biological communities are expected as a result of the loss and replacement of species due to global warming. Forest frugivorous birds already suffer from habitat loss and may disappear locally due to suitable area contraction or range shifts to novel areas, disrupting seed dispersal and consequently the functioning of natural ecosystems. Here, we investigate the impacts of different climate scenarios on alpha and beta diversities of forest frugivorous birds within the Central Corridor of the Atlantic Forest (CCAF), Brazil. We used ecological niche models to project species distribution of 68 frugivorous birds for the baseline and future (2050 and 2070) scenarios. We generated binary maps of suitable areas for each species by climate scenario to calculate alpha and beta diversities. Most forest frugivorous birds were projected to lose suitable area, as a consequence of climate change, reducing alpha diversity in future scenarios and increasing temporal beta diversity, which is dominated by the nestedness component. In addition, species richness decreased from the east to the west portion of the CCAF, while differentiation of bird communities increased in the same direction, a pattern consistent across all climate scenarios evaluated. Climate change may exert drastic alterations in the composition of frugivorous bird communities in the CCAF. As forest frugivorous birds are critical to seed dispersal of forest plant species, impoverishment of their communities can drastically affect forest regeneration, diversity, and structure in the decades to come. Therefore, a better comprehension of spatio-temporal changes in diversity patterns of frugivorous birds can help us to avoid the disruption

of seed dispersal and its consequences, such as cascading effects that will trigger biodiversity loss in the CCAF.

Keywords: avian, community structure, conservation strategies, diversity patterns, future scenarios, maxent, range shift, species distribution model

4.1. Introduction

Climate change is one of the major threats to biodiversity (Bellard et al., 2012), given that alterations in temperature and precipitation can force species to seek novel areas with suitable climatic conditions, consequently changing their distribution ranges (Bellard et al., 2012; Pecl et al., 2017). However, species with restricted distributions and very sensitive to environmental disturbances might not find suitable habitats in the future, thus having a high risk of extinction (de Moraes et al., 2020). For instance, endemic and threatened species are predicted to lose at about 45% of their original distributions, and areas harbouring high species richness, such as the Brazilian Atlantic Forest hotspot, will suffer a great reduction in size (de Souza et al., 2011). Also, between 10% and 30% of vertebrate fauna are projected to be globally lost in the future (Newbold, 2018), including primates, anurans, and birds (Lima et al., 2019; Prieto-Torres et al., 2020; Vasconcelos et al., 2018). Furthermore, the loss of vertebrates that feed on fruits is predicted to decrease long-distance dispersal of seeds by 38.7% affecting tropical rainforest flora (Mokany et al., 2014). Therefore, global climate changes could significantly impact biodiversity, leading to modifications in species diversity patterns across space and time (Graham et al., 2016; Nunez et al., 2019; Timoner et al., 2020).

In particular, shifts in species distributions as a consequence of climate change might impact broad-scale patterns of species richness and composition (Lima et al., 2019). Recent studies have demonstrated richness reduction (i.e., alpha diversity) in several regions resulting on contractions in species distribution areas under climate change (e.g., Cámara-Leret et al., 2019; Hidasi-Neto et al., 2019; Kougioumoutzis et al., 2020). In this case, species composition (i.e., beta diversity) will change since the future community will become a subset of the previous one (i.e., nestedness), resulting in high values of beta diversity (Baselga, 2010; Lima et al., 2019; Ochoa-Ochoa et al., 2012; Vasconcelos et al., 2018). Additionally, even if alpha diversity remains constant, the community composition can still change as a result of the loss of sensitive species and the concomitant proliferation of habitat generalist species, leading to species turnover (Baselga, 2010; Hidasi-Neto et al., 2019; Morante-Filho et al., 2015; Spaak et al., 2017). Despite the potential scenario of species replacement in disturbed habitats, generalist

species may not fill specialists' niche, resulting in the loss of ecological functions even under the maintenance of local diversity (Galetti et al., 2013). Furthermore, species diversity patterns may also differ geographically since future changes in temperature and precipitation are heterogeneously distributed (Almazroui et al., 2021; Neilan et al., 2019).

The Brazilian Atlantic Forest is one of the top biodiversity hotspots and despite its high species endemicity it has already lost more than 80% of its original coverage (Myers et al., 2000; Ribeiro et al., 2009). In particular, the Central Corridor of the Atlantic Forest (CCAF) holds one of the highest botanic diversities globally, in addition to several exclusive species of plants, primates, and birds (Cordeiro, 2003; Martini et al., 2007; Pinto, 1994; Thomas et al., 1998; Thomaz & Monteiro, 1997). The Atlantic Forest diversity patterns have already been modified by forest loss and fragmentation (Morante-Filho et al., 2016, 2021; Püttker et al., 2020) and can be further impacted by climate change. According to the climate projections, the region is expected to become warmer and dryer (Almazroui et al., 2021) especially near the transition with the South American dry diagonal domains (i.e., Cerrado and Caatinga; Rajaud & Noblet-Ducoudré, 2017). These changes in the regional climate are projected to displace the species to coastal areas, causing richness declines towards transition regions (e.g., de Souza et al., 2011; Lima et al., 2019) or reduce species ranges, leading to generalized richness loss (Loyola et al., 2014; Lourenço-de-Moraes et al.,2019). Thus, climate change may bring severe consequences for many taxa, including forest-dependent bird communities across the CCAF.

Among taxonomic groups, birds have the potential to indicate trends regarding climate change effects on biodiversity because they are well known, globally distributed, and sensitive to environmental modifications (Bregman et al., 2014; Sekercioglu et al., 2012). Furthermore, birds provide fundamental ecological services for the functioning of natural ecosystems, including seed dispersal, pollination, and insect control (Sekercioglu, 2006). In particular, frugivorous birds disperse seeds from most tropical trees (Levey et al., 2002), performing a key role in forest regeneration and connection of habitat patches inserted in highly deforested landscapes (Caves et al., 2013; Mueller et al., 2014). For instance, long-distance dispersal benefits plants since their seeds may reach new favorable sites away from the parent plant where the competition with conspecifics is higher (Terborgh, 2012). Therefore, frugivorous birds provide an ecosystem service that is crucial for the maintenance of the forest structure and diversity, mainly in tropical regions, where up to 90% of tree species are dispersed by animals (Howe & Smallwood, 1982). Thus, understanding the effect of climate change on frugivorous bird assemblages in tropical fragmented landscapes is urgently needed. This is even more urgent in the Atlantic Forest, where the distributions of endemic birds are projected

to shrink due to climate change by 52% and some of them can almost be vanished (Vale et al., 2018). Therefore, the Atlantic Forest has a high risk of losing many of its forest- dweller frugivorous birds, compromising seed dispersal and jeopardizing its maintenance, as for other tropical forests (Bregman et al., 2016; Miranda et al., 2019; Nowak et al., 2019).

In this context, our study investigated the impacts of different climate scenarios on alpha and beta diversity of forest-dependent frugivorous birds in the CCAF. This region is a hot-point within the Atlantic Forest hotspot that harbours many endemic species of plants, primates, and birds (Cordeiro, 2003; Martini et al., 2007; Pinto, 1994; Thomas et al., 1998). Because of the projected contractions of the humid, low seasonal climate characteristic of the Atlantic Forest biome (Almazroui et al., 2021; Rajaud & NobletDucoudré, 2017), we expect contractions in most bird distribution areas in future scenarios, resulting in lower values of alpha diversity inwards and higher values of beta diversity in the middle of coastal and interior areas. In addition, the differentiation of bird communities driven by species loss and range contractions in future scenarios may result in the dominance of the nestedness component in most of the CCAF.

4.2. Methods

Study area

The Central Corridor of the Atlantic Forest comprises the state of Espírito Santo and the south of Bahia state, between 13°0′6″–21°18′36″S and 41°52′43″–37°16′40″W coordinates (Figure 1). The continental area of the CCAF has over 11.7 mi hectares and involves around 168 municipalities. Land use in this region consists mainly of pasture and agriculture that together represent 57% of the CCAF, while forest remnants represent 41% (de Santana et al., 2020). Also, the area that comprises the southernmost Bahia and the North of Espírito Santo state has extensive areas of *Eucaliptus* sp. plantations (Aguiar et al., 2003). In addition, coffee production is the main agricultural activity of Espírito Santo (Sales et al., 2013). The CCAF presents one of the highest botanic diversities worldwide and several endemic species of the Atlantic Forest are found in the region including plants, birds, and primates (Cordeiro, 2003; Martini et al., 2007; Pinto, 1994; Thomas et al., 1998; Thomaz & Monteiro, 1997).

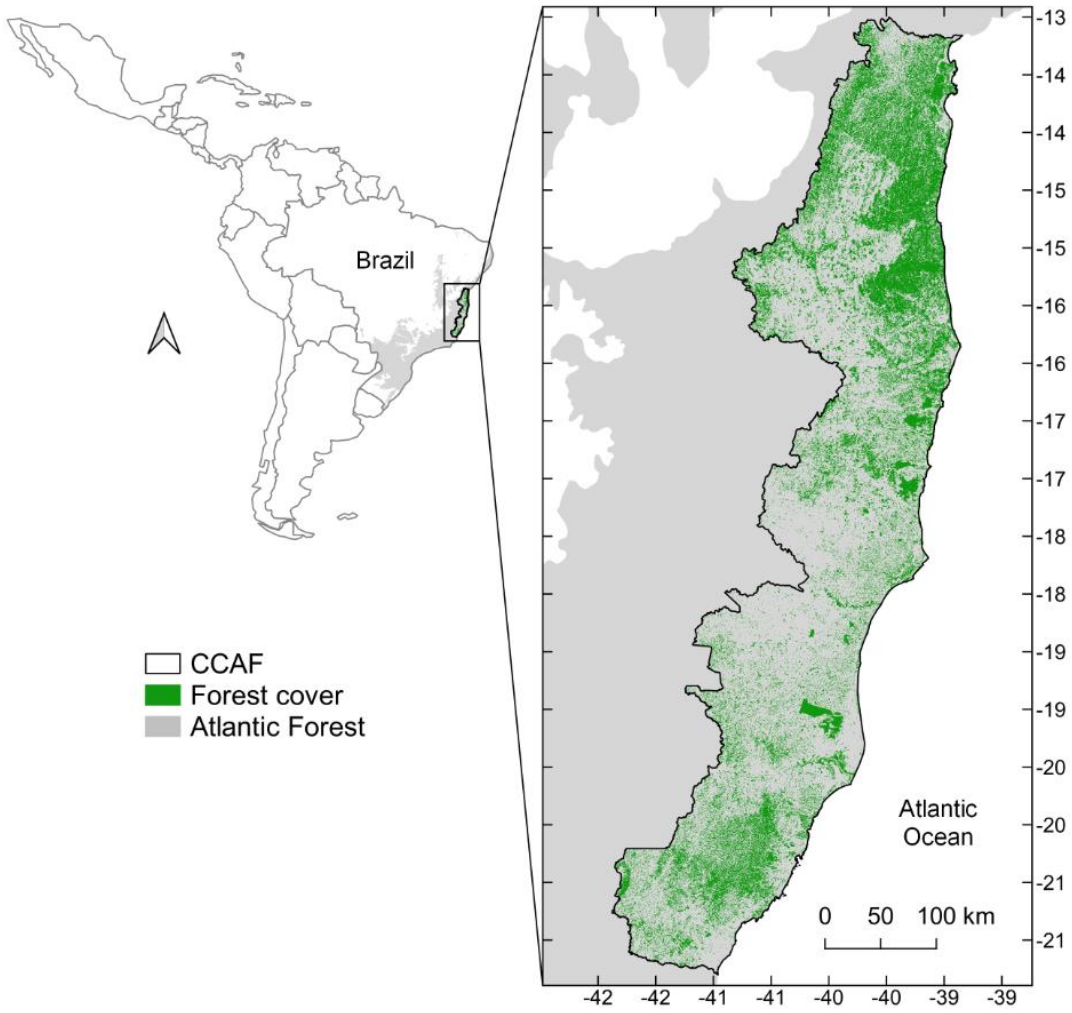

FIGURE 1 Location of the Central Corridor of the Atlantic Forest (CCAF), Brazil. Grey and dark green colors indicate the Atlantic Forest biome and remaining forest cover, respectively.

Bird data

We obtained distribution maps for all resident native bird species from BirdLife (www.birdlife.org) and overlap with the CCAF. Then, we classified the birds according to habitat specialization, as forest-dependent and non-forest dependent, based on available literature (Bregman et al., 2014; Stotz et al., 1996), and our prior knowledge about the species ecology. Afterwards, we select forest-dependent birds with at least 40% of its diet composed primarily of fruit (Wilman et al., 2014) because of the relevance of a few non-obligate frugivores as seed dispersers in the study area (Acevedo-Quintero et al., 2020; Tella et al., 2019). Therefore, forest-dependent frugivores were considered those species highly specialized on forest resources that feed mostly from fruits, including those inhabiting forest interiors. Our final species list was composed of 70 forest frugivorous birds that was carefully checked in addition to a literature review on regional studies (e.g., Cardoso et al., 2004; Cazetta et al.,

2019; Morante-Filho et al., 2015, 2016; Pizo & Tonetti, 2020; Ribeiro et al., 2009). For each of them, we obtained occurrence records from Global Biodiversity Information Facility (GBIF; www.gbif.org), VertNet (www.vertnet.org), and iDigBio (www.idigbio.org). We then checked the occurrence records to eliminate inconsistencies, such as duplicates resulting from the previous three sources, and coordinates outside the known distribution of each species.

Climate data

We downloaded 19 bioclimatic variables for the baseline and future (2050 and 2070) scenarios from the WorldClim v2.1 database (Fick & Hijmans, 2017) at a spatial resolution of 2.5 arcmin (Table 1). These variables are derived from the monthly temperature and rainfall values and are often used in ecological modeling techniques (www.worldclim. org), allowing comparisons to most of the current literature (Miranda et al., 2019; Oliveira-Silva et al., 2022; Prieto-Torres et al., 2020). For each species, we choose variables with a correlation below 0.7 through the function "select_vars" from the "ENMwizard" package (Heming et al., 2019) to avoid collinearity.

TABLE 1 Bioclimatic variables derived from temperature and precipitation data obtained from WorldClim – Global Climate Data (www.worldclim.org).

Variables	Description
Bio1	Annual mean temperature
Bio2	Mean diurnal range (mean of monthly max temp–min temp)
Bio3	Isothermality (Bio2/Bio7) (×100)
Bio4	Temperature seasonality (standard deviation ×100)
Bio5	Max temperature of warmest month
Bio6	Min temperature of coldest month
Bio7	Temperature annual range (Bio5-Bio6)
Bio8	Mean temperature of wettest quarter
Bio9	Mean temperature of driest quarter
Bio10	Mean temperature of warmest quarter
Bio11	Mean temperature of coldest quarter
Bio12	Annual precipitation
Bio13	Precipitation of wettest month
Bio14	Precipitation of driest month
Bio15	Precipitation seasonality (coefficient of variation)
Bio16	Precipitation of wettest quarter
Bio17	Precipitation of driest quarter
Bio18	Precipitation of warmest quarter
Bio19	Precipitation of coldest quarter

Ecological niche models

We modeled the ecological niche of each forest frugivorous bird species using MaxEnt (Phillips et al., 2006), whose performance is comparable with other algorithms and requires only occurrence data (Elith et al., 2006; Kaky et al., 2020). We also used the "ENMwizard" package to define the calibration area for each species by creating a minimum convex polygon around all occurrences plus a 1.5° buffer (i.e., ~165 km2). This approach was used to improve MaxEnt predictive power given that the buffer represents areas potentially accessible for the species and increases variables heterogeneity, therefore, performing more realistic niche estimations (Anderson & Raza, 2010; Barve et al., 2011). Then, we filtered the records of each species to obtain the maximum number of occurrences that were at least 10 km apart using the "spThin" package (Aiello-Lammens et al., 2015). This procedure reduces sampling bias and improves model performance (Boria et al., 2014). We modeled all forest frugivorous species with at least 10 records after the previous filtered to ensure good predictions (Wisz et al., 2008). We excluded the species *Carpornis melanocephalus* and *Touit surda* because they did not meet the previous criteria, resulting in 68 forest frugivorous birds for further analysis. We optimized MaxEnt parameters using the "ENMeval" package (Muscarella et al., 2014) to incorporate all combinations of 10 regularization multipliers (0.5–5.0 with 0.5 intervals) and three feature classes (L: linear, Q: quadratic, P: product), resulting in 70 models per species. We excluded two feature classes (Hinge and Threshold) due to their lack of biological meaning (Mertens et al., 2021). For model cross-validation, we used the "block" partitioning method that improves spatial and temporal transferability (Hijmans, 2012; Veloz, 2009) and "jackknife" for species with less than 15 records (Shcheglovitova & Anderson, 2013).

We built a consensual model for each species from the 10% top-performing MaxEnt models that were chosen based on the lowest Omission Rate (OR) and highest average Area Under the Curve (AUC) criteria, in this order (Boria et al., 2017). Then, we selected three General Circulation Models (GCM: IPSL-CM6A-LR, MIROC6, and MRI-ESM2-0) to generate the future projections based on their performance (lower frequency and persistence of errors) and geographic region (South America; see details in Cannon, 2020). Afterwards, we calculated a weighted average to combine the results of the three GCMs and projected the climate for the years 2050 and 2070, using two Shared Socioeconomic Pathways (SSPs): SSP245, considered an optimistic scenario where mitigation measures are taken to reduce greenhouse gas emissions, and SSP585, considered a pessimistic scenario where current emissions rates will be maintained in long term. Finally, we converted the final models into binary maps of "suitable" and "unsuitable" habitat using the "ten percentile training presence"

threshold calculated by MaxEnt. This threshold is indicated to presence-only data, and to minimize uncertainties related with datasets obtained from aggregated sources (i.e., GBIF, VertNet, iDigBio; Anderson et al., 2016; Raes et al., 2009).

Data analyses

We calculated alpha diversity (species richness) by summing the overlaid binary maps of species, then we transformed these maps into matrices of presence and absence of the forest frugivorous birds to each climate scenario. We used the function "beta.temp" from the "betapart" package (Baselga & Orme, 2012) to calculate the Sorensen dissimilarity index between each cell from future and baseline scenarios (βt: temporal beta diversity). In addition, we partitioned beta diversity into turnover and nestedness components (Baselga & Orme, 2012) to represent their proportion by scenario. Values close to one represent the predominance of species replacement and values close to zero indicate predominance of gain/loss of species (see Hidasi-Neto et al., 2019). Because our data were not normally distributed, we applied Friedman's non-parametric test (see Lima et al., 2019). We used alpha and beta diversity as response variables, considering the cells as blocks, to compare forest frugivorous bird communities among climate scenarios (independent variable). Finally, we compared the total suitable areas (response variable) among scenarios, considering species as blocks. We also assessed the spatial distribution of the average suitable area to compare changes between future and baseline scenarios.

All analyses were carried out in R software v4.0.5 (R Core Team, 2021) and maps of alpha and beta diversity were generated in QGIS software v3.16.16 (QGIS Development Team, 2021).

4.3. Results

Most of our ecological niche models showed good fit, presenting high Area Under the Curve (AUC) values ranging from 0.7 to 0.92. Only 11 species showed reasonably good fit models, with AUC values between 0.55 and 0.69. The average AUC value was 0.81, while the average Omission Rate (OR) value was 0.14 ranging from 0 to 0.40.

Our study detected that forest frugivorous species richness (alpha diversity) is higher in the extreme north and south portion of the Central Corridor of the Atlantic Forest (CCAF). We also observed intermediate to high bird richness in the coastline compared to the continent interior, while the midwest portion of the CCAF presented the poorest area in terms of species richness (n = 12; Figure 2a). In addition, we detected distinct species numbers among scenarios

(maxT = 122.71; p-value < .001; n = 28,890) with higher values in baseline (46 species ± 13) and lower values in 2070 pessimistic scenario (37 species ± 12). Furthermore, the CCAF is projected to lose 16 forest frugivorous birds in 2050 optimistic (Figure 2b) and 23 species in 2070 pessimistic scenarios (Figure 2d), mainly in the northwest and southwest portions of the study area. In contrast, the northeast and midwest of the CCAF may gain a maximum of 4 species in the pessimistic scenarios (Figure 2c-e).

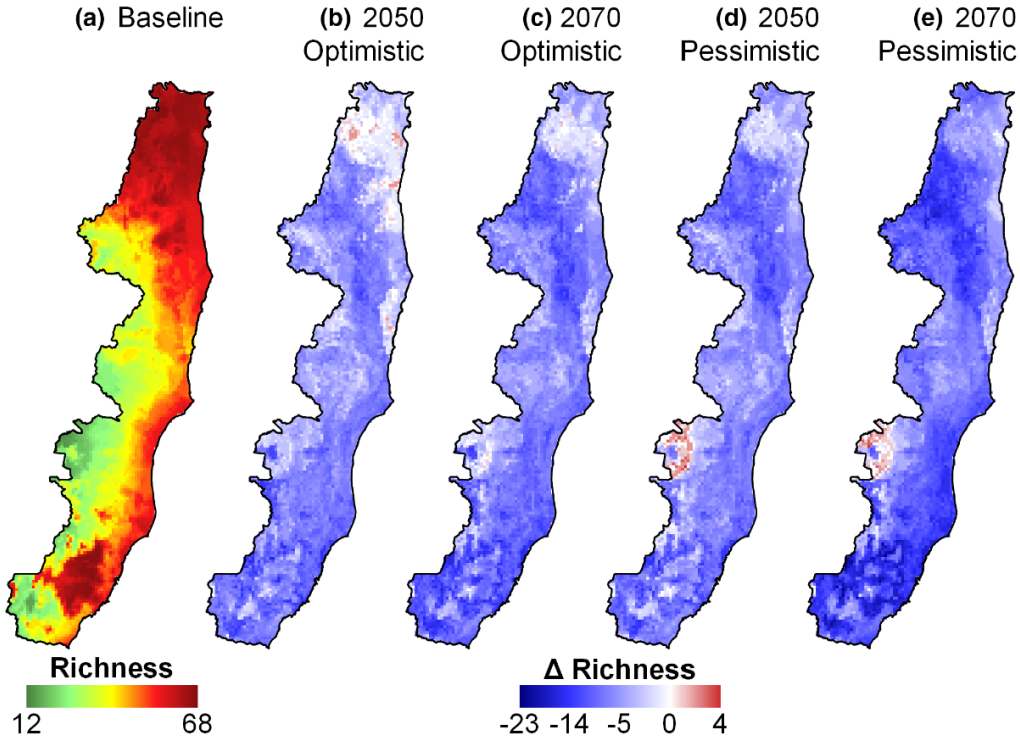

FIGURE 2 Richness (a) and differences (Δ) in richness (b–e) of forest frugivorous birds predicted in baseline and future climate scenarios in the Central Corridor of the Atlantic Forest. Positive and negative values indicate gain and loss of species from baseline to future scenarios, respectively. Optimistic scenario: SSP245. Pessimistic scenario: SSP585.

The largest changes in the composition of forest frugivorous birds (i.e., high beta diversity) were associated with the CCAF portions with lower species richness (Figure 3). We detected distinct pattern in temporal beta diversity (βt) among scenarios (maxT = 103.17; p-value < .001; n = 23,112), with higher values in 2070 pessimistic (βt = 0.65) and lower in 2050 optimistic (βt = 0.4) scenarios, both compared to the baseline. Overall, the western portion of the CCAF concentrates intermediate to high dissimilarity (i.e., high beta diversity) of forest

frugivorous birds in all climate scenarios, especially in the southwest (Figure 3 a-d), while the coastline presented low temporal beta diversity, mostly in the 2050 optimistic scenario. In fact, areas that show high values of beta diversity also show high species loss, reflecting the dominance of the nestedness component (Figure 3 e-h). Conversely, in areas located in the northern, central, and midwest portions of the CCAF which maintained or gained few species, the turnover component of beta diversity was predominant (Figure 3 e-h).

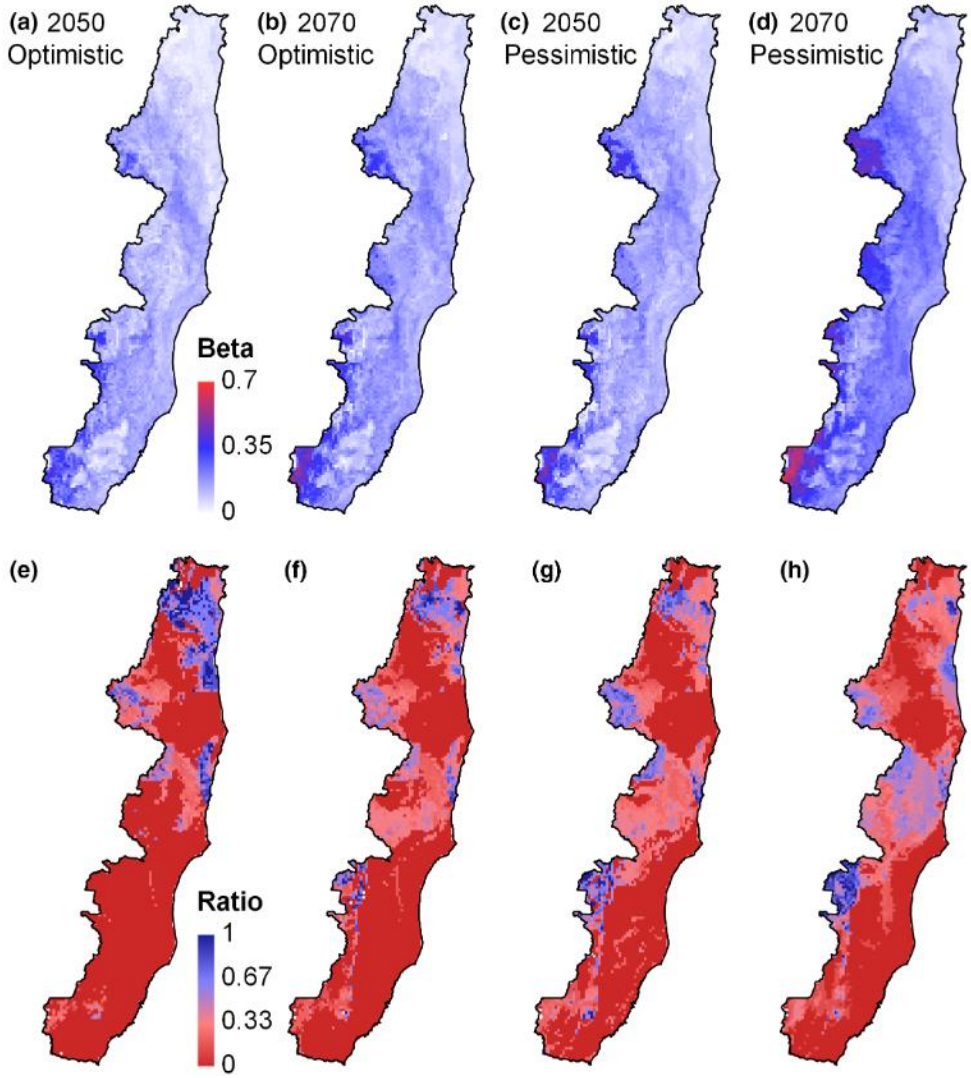

FIGURE 3 Temporal beta diversity (βt) of forest frugivorous birds calculated between baseline and future climate scenarios in the Central Corridor of the Atlantic Forest (a-d). Proportion of turnover in relation to βt (e-h), in which values close to one (blue) represent predominance of turnover, while values close to 0 (red) represent predominance of nestedness. Optimistic scenario: SSP245. Pessimistic scenario: SSP585.

We also found a spatial variation in the average suitable area of forest frugivorous birds within the CCAF. The northeast and southwest portions in the baseline scenario concentrate

species with restricted distributions, while frugivores from the midwest portion present wider suitable areas (Figure 4a). In future scenarios, species remaining in the northeast portion are predicted to be even more restricted, decreasing the average suitable area, while the disappearance of some species (e.g., *Amazona vinacea*, *Tangara cyanoventris*) restricted to the southwest portion will lead to an increase in the average suitable area (Figure 4b-e). Our study also indicated that the total suitable area is projected to decrease in future scenarios for most of the forest frugivorous birds (Table S2). In general, the total suitable area in the CCAF is predicted to decrease an average of 13,125 km2, with the 2070 pessimistic scenario holding the smallest total suitable area (16,945 km2). In particular, some species, such as *Stephanophorus diadematus* and *Pionopsitta pileata*, presented a high risk of disappearing from the CCAF, while others such as *Pipraeidea melanonota* are predicted to lose between 43.3% and 81.7% of suitable area, and *Amazona vinacea* between 68.2% and 86.9%. Only three species, *Crax blumenbachii*, *Amazona rhodocorytha*, and *Baillonius bailloni*, will gain suitable areas in all climate scenarios, while four species (i.e., *Columba speciosa*, *Cyanerpes cyaneus*, *Penelope superciliaris*, and *Psarocolius decumanus*) presented little or no variation in their suitable areas (Table S2).

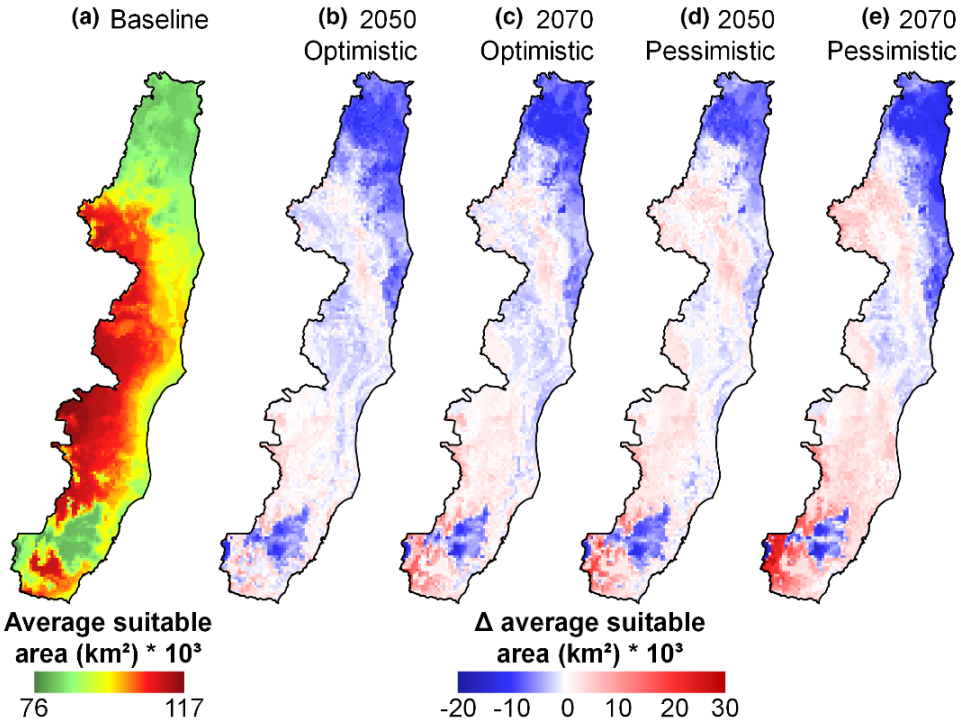

FIGURE 4 Average suitable area of forest frugivorous birds in the Central Corridor of the Atlantic Forest (CCAF). Baseline scenario (a) and the differences in average suitable area (Δ) between future and baseline scenarios (b–e). Positive and negative values indicate gain

and loss of suitable area from baseline to future scenarios, respectively. Optimistic scenario: SSP245. Pessimistic scenario: SSP585.

4.4. Discussion

Our study evidenced that climate change is projected to cause drastic alterations in the richness and composition of forest frugivorous bird communities across the Central Corridor of the Atlantic Forest, mostly due to species loss. As we expected, most modeled species will lose suitable climatic areas in future scenarios compared to the baseline one. It can cause a decrease in bird richness (lower alpha diversity) and hence an increase in the temporal dissimilarity (higher temporal beta diversity) among communities in future scenarios.

The reduction in forest frugivorous bird richness reached 34% in the 2070 pessimistic scenario compared to the baseline, which is in agreement with other studies that reported species loss varying from 29% to 47% in the worst case scenario depending on the evaluated habitat (Miranda et al., 2019; Prieto-Torres et al., 2020). On a global scale, geographic variation in species richness seems to be pronounced in frugivorous birds compared to other trophic guilds (Kissling et al., 2012). Within Atlantic Forest, other taxa are also projected to suffer species richness reduction, including primates and anurans, which can lose roughly 43% and 50% of species, respectively (Lima et al., 2019; Loyola et al., 2014). Our results also indicated a more severe loss of frugivorous species richness westwards corroborating our hypothesis. The western portion of the CCAF is projected to become warmer compared to the coastal region, which may explain the lower number of frugivorous species observed in all future climate scenarios. Furthermore, the western portion of the CCAF has lost more forest cover than the coastal region (Almazroui et al., 2021; MapBiomas, 2021). Lower forest cover reduces the probability of occurrence of forest-dependent birds in the region (Morante-Filho et al., 2021) and is likely to intensify the loss of forest-dependent birds due to climate change. Indeed, it is expected that this worst scenario will not be exclusive for frugivorous birds, thus affecting the entire bird community along the CCAF, as shown by other studies performed in the biome (e.g., Loiselle et al., 2010; Tonetti et al., 2022; Vale et al., 2018).

In highly degraded landscapes, frugivorous birds are particularly important due to their contributions to habitat regeneration via seed dispersal of many plant species (Levey et al., 2002; Mueller et al., 2014). Therefore, it is likely that a synergic effect of climate and land-use change cause even more harm on bird communities through simplification of frugivorous bird

assemblages, thus, impacting fruited-plants, driving co-extinctions of specific groups of plants and disrupting frugivorous networks (Emer et al., 2020; Northrup et al., 2019). For instance, the dispersion of large fruits depends on large frugivores, such as toucans and guans, thus, their disappearance may disrupt the maintenance of certain plants enhancing forest degradation (Dehling et al., 2021; Galetti et al., 2013). Indeed, large frugivorous birds can link forest patches in highly fragmented landscapes thus playing a structuring role in these forests (Mueller et al., 2014; Trolliet et al., 2017). Also, our study indicates that this impact might be disproportionately higher in frugivorous networks from the western portion of the CCAF, where species richness is projected to decrease in future scenarios.

In our study, we observed that the composition of frugivorous bird communities in the CCAF will suffer differentiation (i.e., high temporal beta diversity) from baseline to future scenarios, which also corroborates our hypothesis. In particular, the patterns of beta diversity were mainly determined by the nestedness component. Additionally, our findings indicated that changes in frugivorous bird composition are spatially heterogeneous, given that more distinct communities are located westwards where species richness is lower. This pattern is even more evident in the southwest portion of the 2070 pessimistic scenario, thus, the relationship between richness reduction and range contraction and/or local extinction may increase the dissimilarities of frugivorous bird communities (Ochoa-Ochoa et al., 2012). These findings agree with a previous study (Vasconcelos et al., 2018) performed in the Atlantic Forest, where it was observed an increase in nestedness component due to species loss, making future anuran communities a subset of the current ones. Conversely, we observed that the turnover component was predominant in the midwest and northeast portions of the CCAF, suggesting that part of frugivorous bird communities found in those regions will be replaced by different species in future scenarios. In fact, our findings revealed that in the northeast portion, frugivores with restricted distribution are replaced by other equally restricted, while in the midwest portion the replacement is most likely due to the arrival of widely distributed bird species (PrietoTorres et al., 2020). For instance, *S. diadematus* is projected to vanish from the northeast portion while *Iodopleura pipra* may expand its suitable area to the same location. Both species showed suitable areas lower than 20,000 km^2 in the baseline scenario. Additionally, projections from Amazon rainforest showed high suitable area reduction for forest frugivorous birds but also for forest insectivorous birds, while birds from open-areas may expand their suitable areas in the future (Miranda et al., 2019). Therefore, it is reasonable to assume that a similar pattern may be observed for forest frugivorous birds from other tropical forests.

According to our predictions, most frugivorous birds showed contraction in their distribution areas in future scenarios. In particular, our findings indicated a positive relationship between the percentage of change in birds' suitable area and the suitable area in the baseline scenario. It means that species with restricted distributions tend to be more negatively affected by climate change compared to widely distributed species. For instance, the endangered psittacid *Amazona vinacea* which presented the smallest suitable area in the baseline (10,528 km^2) is projected to contract its range an average of 75.7%, while widely distributed birds (>80,000 km^2) may expand their suitable areas up to 25% in future scenarios. Indeed, geographic range size is a trait often considered in the literature as a good predictor of birds' range shift (e.g., Avalos & Hernández, 2015; MacLean & Beissinger, 2017; Prieto-Torres et al., 2020; Bladon et al., 2021). However, despite the possibility of those species to find areas potentially suitable in the future, the ongoing conversion of the Atlantic Forest into agricultural lands (MapBiomas, 2021; Oliveira-Silva et al., 2022) is worrisome, mainly for frugivorous birds presenting certain ecological features such as game birds (e.g., guans) and species destined to illegal trade (e.g., parrots and toucans). In particular, habitat loss facilitates human access to forest fragments, increasing hunting, mostly of large birds like *Crax blumenbachii* for feeding, and some other species for trade, like *Amazona rhodocorytha* (Klemann-Júnior et al., 2008; Silveira et al., 2005). Therefore, it is highly unlikely that those species favored by climate change (e.g., via range expansion) will prosper due to other threats such as habitat loss.

We highlighted that most forest frugivorous birds will suffer contraction in their geographical range in future scenarios, including species already threatened by other causes such as habitat loss. Consequently, the projected changes in species composition towards simpler frugivorous bird communities and the dominance of the nestedness component in the beta diversity patterns may indicate a higher risk of pervasive effects on seed dispersal in future climate scenarios. This is particularly worrisome since the niche overlap between frugivorous birds and other vertebrate groups that feed on fruits is low, and thus improbable that this ecological service remains intact (Fleming, 1979; Fleming et al., 1987). Even though the loss of native frugivores could be compensated by exotic and/or generalist species (García et al., 2014), it is unlikely that their role would be as effective due to lower trait matching and dispersal potential (e.g., seed number, dispersal distance; Babweteera & Brown, 2009; Peralta et al., 2020). In fact, it has already been demonstrated a rapid reduction in seed size of a threatened Atlantic Forest palm tree (*Euterpe edulis*) in the absence of its native large-seed dispersers (toucans, cracids, and large cotingas; Galetti et al., 2013). Furthermore, we detected heterogeneous variation in temporal beta diversity across the CCAF, suggesting that a single

conservation strategy will not be effective. Given that forest frugivorous birds are highly dependent on forest cover (Morante-Filho et al., 2021), it is essential to concentrate efforts to keep the few forest remnants across the CCAF. As the coastal and inward portions of the CCAF will possess distinct climates in projected scenarios, it will be of utmost importance to improve the conservation status of forest remnants across the whole area, including strategies to connect isolated fragments allowing species to pursue their suitable habitat. Because forest frugivorous birds are critical to seed dispersal for most tropical trees (Howe & Smallwood, 1982), impoverishment of forest-dependent bird communities may have cascading effects on seed dispersal (Galetti et al., 2013), thus limiting plant recruitment and leading to biodiversity depletion within this hotspot in the future.

4.5. References

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Capítulo 5

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divraster: an R package to calculate taxonomic, functional and phylogenetic diversity from rasters

Flávio Mariano Machado Mota[1], Gabriela Alves-Ferreira[1], Daniela Custódio Talora[1] and Neander Marcel Heming[1]

[1]Applied Ecology and Conservation Lab, Programa de Pós-graduação em Ecologia e Conservação da Biodiversidade, Universidade Estadual de Santa Cruz, Ilhéus, BA, Brazil

Abstract

Diversity metrics are widely used to better understand biodiversity patterns and help with species conservation. Taxonomic diversity alone may lack valuable information on community ecology, such as the importance of species to ecosystem functioning and evolutionary history. By combining taxonomic, functional, and phylogenetic diversity, we can complement our knowledge, particularly under climate change, by improving conservation strategies and helping to maintain biodiversity while reducing costs in the decision-making process. However, the main tools used for computing these metrics may demand significant processing power because of their reliance on matrices, ultimately restricting their applicability. Here, we present *divraster*, an R package to calculate diversity metrics directly from species rasters, with the aim of reducing memory usage and processing power, especially when working with large datasets such as large areas, high resolution, or a high number of species. The main function of *divraster* can calculate changes in a given community between distinct temporal scenarios, such as present and future climate scenarios, working with taxonomic, functional, and phylogenetic diversity. It includes the partition of temporal beta diversity, making it particularly useful in ecological niche models and other macroecology studies. Additionally, divraster performs spatial calculations for both alpha and beta diversity, which are helpful in studies where time is not an issue. We also conducted a performance comparison with packages that provide similar functions and demonstrated that the divraster package outperforms them in most cases regarding memory allocation and processing time.

Keywords: biodiversity, R package, diversity patterns, macroecology, climate scenarios

5.1. Background

Taxonomic, functional, and phylogenetic diversity metrics are widely used to track the changes in biodiversity and support better conservation measures (Faith 1992, Baselga 2010, Laliberté and Legendre 2010). Currently, climate change is considered one of the main threats to biodiversity, and many studies that apply diversity metrics have been focused on the consequences of this threat. For instance, future projections of climate changes often indicate a reduction in species richness, although some species may benefit from climate change, situations that could lead to community restructuring across multiple taxa, including mammals, amphibians, and birds (Hidasi-Neto et al. 2019, Alves-Ferreira et al. 2022, Mota et al. 2022).

Taxonomic diversity is commonly used to describe variations in community structure, and the simplest way to measure it is through species richness, which can be defined as the number of species in a site (i.e. alpha diversity). It plays a crucial role in the effective assessment and conservation of biodiversity as monitoring species across different spatial scales helps define highly diverse places as priority areas (Scott et al. 1987, Weber et al. 2004, Jenkins et al. 2013, Zou et al. 2023). Besides alpha diversity, knowing species composition variation (i.e. beta diversity) is important for protecting regional diversity and can directly assist conservation planning (Socolar et al. 2016) as it represents composition changes over space and time, commonly referred to as spatial and temporal beta diversity, respectively (Legendre 2008, Anderson et al. 2011, Legendre and Gauthier 2014). Furthermore, beta diversity can be partitioned in two components representing the substitution of species from one site to another and the gain and loss of species between sites (Baselga 2010, Carvalho et al. 2012, Magurran 2021).

Alpha and beta diversity provide valuable information on community structure, and have been widely used in climate change studies (e.g. Menéndez-Guerrero et al. 2020, Mota et al. 2022). However, taxonomic diversity alone fails to capture relevant aspects of historical and ecological processes that shape species distributions, making it important to consider variations in different dimensions of diversity in conservation studies (Devictor et al. 2010, Safi et al. 2011). While the functional dimension of diversity refers to the variety of biological roles and functions performed by different species within an ecosystem (Petchey and Gaston 2006), which is related to the species features and how they interact with the environment (Tobias et al. 2022), the phylogenetic dimension takes into account the evolutionary relationships among species and the amount of time over which those relationships have developed, providing

information on the accumulated evolutionary history in a target region (Faith 1992, Moritz and Faith 1998). Together, taxonomic, functional, and phylogenetic diversity indexes encompass the most relevant information of communities and are widely used metrics in community ecology.

There are several tools that can be used to compute diversity metrics including Biodiverse (Laffan et al. 2010), SpadeR (Chao et al. 2015), PDA (Chernomor et al. 2015), EstimateS (Colwell 2013), and several packages in R (R Code Team 2023). R is a free software environment for statistical computing and graphics with the additional advantage of allowing the implementation of new features through external packages. Furthermore, R stands out in the field of ecology due to its ease of reproducibility of workflows from shared scripts and codes (Lai et al. 2019). For instance, the R package *betapart* (Baselga and Orme 2012) uses matrices to compute alpha and spatial beta diversity for taxonomic (TD), functional (FD), and phylogenetic (PD) dimensions, besides the additional feature to compute temporal beta diversity for TD only. The package *BAT* (Cardoso et al. 2015) can also compute alpha and spatial beta diversity for the three dimensions from matrices, and it has specific functions to calculate these metrics using raster objects using the raster package (Hijmans et al. 2023b). Both packages can also partition beta diversity into turnover/replacement and nestedness/richness difference components. Similarly, the package *phyloregion* calculates alpha and beta diversity and its components for both TD and PD, and also includes a function for transforming raster objects into matrices (Daru et al. 2020). Other packages such as *mFD* (Magneville et al. 2022), and *picante* (Kembel et al. 2010) can calculate beta diversity only for FD and PD, respectively, but they cannot compute replacement and richness differences components.

Most methods currently available for computing diversity metrics (taxonomic, functional, and phylogenetic) rely on matrices, which have prohibitively high RAM memory usage and processing requirements for large datasets, typical of spatial (i.e. raster) data. Nevertheless, the use of rasterized data has increased over time, alongside the growing need to analyze maps of species distributions obtained from ecological niche models (e.g. Alves-Ferreira et al. 2022, Mota et al. 2022). Thus, despite the increasing availability of data in raster format, most (if not all) packages are limited to handle matrix data, restricting the application of these metrics for many users. To address this problem, we created an R package to calculate alpha and beta diversity for taxonomic, functional, and phylogenetic dimensions using rasters as inputs. Our package can partition spatial and temporal beta diversity into species replacement and richness differences, accounting for dissimilarities between communities in

space and time.

5.2. Methods and features

The main feature of *divraster* is its ability to calculate diversity metrics directly from spatialized data (i.e. raster files) to reduce processing requirements and memory usage, thereby expanding the usability of diversity metrics to a wide range of users. *divraster* is written in the R language and environment (R Core Team 2023) and depends on the packages *terra* (Hijmans et al. 2023a) and *BAT* (Cardoso et al. 2015) to apply matrix-based calculations to multilayer SpatRaster objects.

Although the *betapart* package is more popular than *BAT* for partitioning beta diversity, we chose the latter as a dependency for two main reasons. First, the beta diversity equation used in *BAT* accounts for all richness differences, while in *betapart*, richness differences are due to nestedness (Carvalho et al. 2012). It means that *betapart* considers richness differences between communities only when the number of species shared between sites is greater than zero. Second, most studies that use rasters as a primary source of data are interested in large scale (i.e. latitudinal/biogeographical) ecological gradients. However, the beta diversity equation from *betapart* fails to detect species loss on ecological gradients, tending to underestimate species loss and overestimate replacement (see details at Carvalho et al. 2012). This happens because the replacement component from *betapart* measures the proportion of the species-poorer site that is not included within the species-richer site. However, it disregards the number of species in the richer site, even though both sites should be taken into account (Tuomisto 2010). Since the richness differences component is obtained by subtracting the replacement from total beta diversity, it may underestimate the richness differences component as well. Therefore, despite producing similar results when dealing with only one beta diversity component, *betapart* appears to struggle in mixed gradients of richness differences and replacements, especially in the poorest communities, while *BAT* shows consistency and linear responses to these gradients (see Cardoso et al. 2009, Carvalho et al. 2012).

Alpha diversity calculations also use a tree-based approach for TD, FD, and PD (Cardoso et al. 2014). FD can be calculated in several ways, and the most common metrics can be categorized as richness, divergence, and evenness. However, the latter two require species abundance data, which is often unavailable in macroecological studies. The richness metrics include Functional Attribute Diversity (FAD) (Walker et al. 1999), Modified Functional Attribute Diversity (MFAD) (Schmera et al. 2009), Functional Dendrogram (FDend) (Petchey and Gaston 2002), Generalized Functional Dendrogram (GFD) (Mouchet et al. 2008), and

Functional Richness (FRic) (Cornwell et al. 2006). FDend is among the best performing indices regarding the capacity to detect ecological processes (see Mouchet et al. 2010), is less computationally expensive, and can handle mixed types of traits (Petchey et al. 2009, Ahmed et al. 2019). Besides, FDend, the FD metric implemented in BAT and divraster, is also equivalent to the TD and PD metrics, allowing for a complete comparison among all three dimensions (TD, FD, and PD) (Cardoso et al. 2014).

In the FD calculation using FDend, a species traits matrix is converted into a distance matrix and clustered to produce a regional dendrogram (i.e. a dendrogram with all species in the raster stack) from which the total branch length is calculated. When calculating FD for each community (i.e. raster cell), the regional dendrogram is subsetted into a local dendrogram containing only the species present on the local community, and only the branch lengths connecting them are summed to represent the functional relationships of the species locally present (Petchey and Gaston 2002, 2006). Similarly, in PD, the sum of branch lengths connecting species within a community represents their shared phylogenetic relationships (Faith 1992). Alpha TD can also be visualized using a tree diagram, where each species is directly connected to the root by an edge of unit length, reflecting the number of different taxa in the community (i.e. species richness) since all taxa are at the same level (Cardoso et al. 2014). PD and FD metrics include the length of basal branches common to all species, preventing results that equals zero for single-species communities and reserving it for communities without any species (Rodrigues and Gaston 2002). Another version of FDend based on pairwise distances or recalculation of the dendrogram suggested by Podani and Schmera (2006) would introduce new issues and potentially confuse the effect of species removal on tree length, possibly leading to a FD of zero in single-species communities (Petchey and Gaston 2007). In such cases, the method would assume a greater influence on functional diversity than the species' natural history, thereby favoring the original approach where an FD of zero only occurs in empty communities (Petchey and Gaston 2007). For all these reasons we chose to calculate FD using FDend and to implement the TD, FD, and PD using *BAT* as a dependency.

divraster is the first R package to calculate temporal beta diversity and its components for taxonomic, functional, and phylogenetic diversity using raster files as inputs. It can be installed from both CRAN and GitHub repositories (Mota et al. 2023). Users are encouraged to suggest improvements and report issues at https://github.com/flaviomoc/divraster/issues.

divraster has three main functions that require multilayer SpatRaster objects (from *terra* R package) as inputs. These objects should contain binary maps of species distributions. The

function temp.beta() calculates temporal beta diversity and its components (replacement and richness differences) between two SpatRaster objects, where each raster cell represents a community and is compared to its corresponding cell from a different time (e.g. a different climate scenario). To calculate taxonomic temporal beta diversity, only two multilayer raster objects from distinct time periods are needed. To calculate functional beta diversity, a data.frame object of species traits is required, while phylogenetic calculations require a phylo object with a dated phylogenetic tree. It is crucial that the species names in all objects match for the function to work. *divraster* has a similar function called spat.beta(), which performs the same calculations as temp.beta(), but compares communities within the same SpatRaster object based on the number of neighboring cells that can be defined by the user through the argument 'd' (distance). The package includes the spat.alpha() function to calculate alpha diversity for taxonomic, functional, and phylogenetic dimensions. A schematic drawing of these functions is presented in Figure 1.

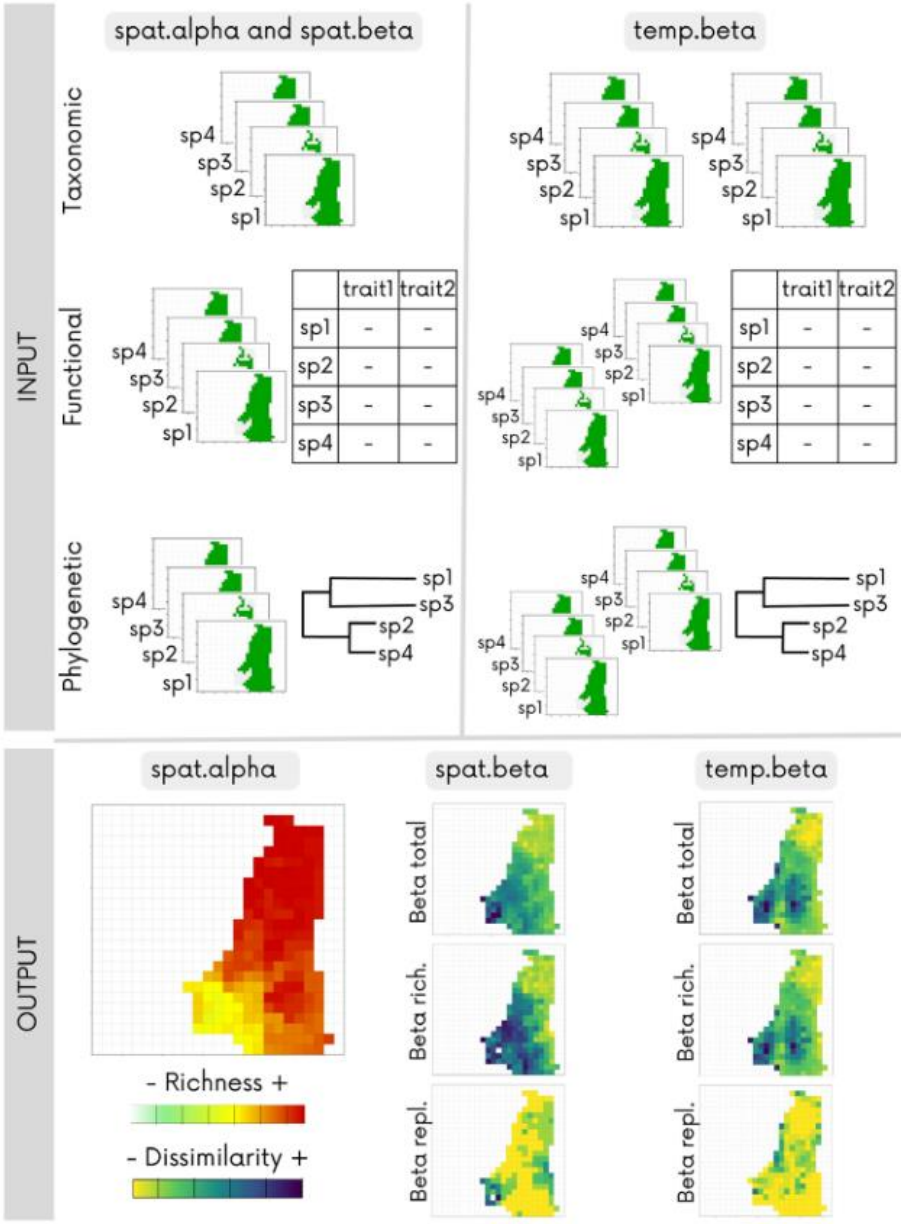

Figure 1. A schematic drawing inputs and outputs of 'divraster' functions.

Additionally, the same inputs required to calculate functional beta diversity can be used to calculate the average of all numeric traits from the data.frame across the SpatRaster layers (i.e. species) through the function spat.trait(). It is useful for evaluating spatiotemporal variation in individual traits within species communities (i.e. raster cells) and assessing their response under different climate scenarios.

divraster can calculate the standardized effect size (SES) of functional and phylogenetic alpha diversity using the package *SESraster* (Heming et al. 2023) through the function spat.rand(). SES is often used in ecological studies (e.g. Ulrich et al. 2018) to measure the magnitude of difference between observed and randomized patterns generated by null models,

expressed in standard deviation units (Gotelli and McCabe 2002, Botta-Dukát 2018). *SESraster* currently implements six of the most common community randomization methods (SIM1, SIM2, SIM3, SIM5, SIM7, and SIM9, sensu Gotelli 2000) and has other methods being implemented. The basic randomization methods are: keeping the richness constant and randomizing the position of the species within each raster cell (site, SIM3 and SIM5); keeping range size constant and randomizing the position of species presences in space (species, SIM2 and SIM7); and randomizing by both site and species simultaneously (both, SIM1).

divraster functions can automatically save the output if the user provides a path. Additionally, except for spat.beta(), all functions include the option of running calculations in parallel using a multi-core processor, which can optimize the performance when dealing with a large number of species, an extensive region, or high raster resolutions.

5.3. Example

We demonstrated the applicability of the *divraster* R package by using a modified binary dataset consisting of 68 frugivorous bird species from Mota et al. (2022), a phylogenetic tree acquired from the Vertlife platform (formerly known as BirdTree, vertlife.org), and a trait dataset from Tobias et al. (2022). The data can be accessed using the load.data() function of the *divraster* package. First, we calculated alpha diversity for the taxonomic dimension using the spat.alpha() function. As it is usually positively correlated with alpha diversity in functional and phylogenetic dimensions, the spat.rand() function uses *SESraster* package (Heming et al. 2023) to compute the standardized effect size (SES) for functional and phylogenetic alpha diversity calculations. We used a randomization method that shuffled the presences/absences within raster cells keeping species richness constant by setting the 'random' argument to "site" and ran 10 simulations defined by the 'aleats' argument. Then, we used the function spat.beta() to calculate spatial beta diversity for both scenarios. We also used the spat.trait() function to calculate the average of all numeric traits by climate scenario. Finally, we used the function temp.beta() to calculate temporal beta diversity between the reference and future scenario. All beta calculations (including replacement and richness differences components) were performed considering the three dimensions of diversity, taxonomic (TD), functional (FD), and phylogenetic (PD). All the figures resulting from this example are available in the supplementary material.

5.4. Performance comparison

We created two datasets to evaluate the performance of *divraster* in terms of memory

allocation and processing time. To this end, we compared our functions with existing ones from the *BAT* and *betapart* packages using the mark() function of the R package *bench* (Hester et al. 2021). We chose betapart because it can calculate temporal beta diversity for taxonomic diversity and it is well-known (e.g. Mota et al. 2022), while *BAT* can calculate alpha and spatial beta diversity from raster objects based on the *raster* R package (Hijmans et al. 2023b). The first SpatRaster dataset has 25 layers representing the species, 0.125º resolution, and 2º extent, totalizing 256 raster cells (hereafter known as the low-resolution dataset). The second SpatRaster dataset has the same number of layers and extent, but 0.04º resolution, totalizing 2304 raster cells (hereafter known as the high-resolution dataset). These datasets were used as inputs for *divraster* functions, and transformed into RasterStack and matrix objects to match the inputs of the functions in *BAT* and *betapart* packages.

In the low-resolution dataset, out of 32 total comparisons, *divraster* performed better in 53% (17), worse in 31% (10), and equally in 16% (5) of them (Table 1). divraster outperformed *betapart* in phylogenetic spatial beta calculation, requiring 4.3 times less memory allocation and 8.5 times less processing time. However, it underperformed in taxonomic beta diversity, requiring 7.7 times more memory allocation and being 3.5 times slower. Moreover, *divraster* outperformed *BAT's* rasterized taxonomic alpha calculation with 3.7 times less memory allocation and *BAT's* rasterized spatial beta calculation with 4.3 times less processing time. Conversely, *divraster* required 62.5 times more memory and was 3.3 times slower during functional alpha calculation compared to *BAT* non-rasterized function (matrix).

In the high-resolution dataset, out of 32 total comparisons, *divraster* performed better in 59% (19) and worse in 41% (13) of them (Table 1). Notably, in eight of these comparisons, *divraster* stood out as the only package capable of producing a result. The calculation of functional and phylogenetic spatial beta based on matrices from *BAT* and *betapart*, unfortunately, could not be finished due to memory constraints. Additionally, to the best of our knowledge, no other existing package has the capability to directly calculate temporal beta diversity and its components from rasters. We observed that *divraster* exhibited its best performance in terms of memory allocation in taxonomic temporal beta calculation with 28.5 times less memory usage compared to *betapart*, while its worst performance was in functional alpha calculation, where it was 74.2 times slower than *BAT's* non-rasterized function. Regarding processing time, *divraster's* best performance was observed during taxonomic alpha calculation, where it was 56 times faster compared to *BAT's* rasterized function. On the other hand, its worst performance was observed during taxonomic spatial beta calculation, where it was 279.5 times slower compared to *betapart's* function.

Table 1. Performance comparisons between 'divraster' functions and similar functions from 'BAT' and 'betapart' packages. Cells with 'n/a' indicate the absence of an equivalent function, and 'fail' indicates tests that were not completed due to memory constraints.

Resolution	Dimension	Diversity	Package	Memory (MB)	Time (s)
Low	Taxonomic	Alpha	divraster	1.16	0.51
Low	Taxonomic	Alpha	BAT	4.31	0.75
Low	Taxonomic	Alpha	BAT	0.25	0.50
Low	Taxonomic	Beta spatial	divraster	91.87	1.79
Low	Taxonomic	Beta spatial	BAT	42.74	5.54
Low	Taxonomic	Beta spatial	BAT	142.75	1.95
Low	Taxonomic	Beta spatial	betapart	11.99	0.51
Low	Taxonomic	Beta temporal	divraster	3.24	0.57
Low	Taxonomic	Beta temporal	betapart	9.04	0.51
Low	Functional	Alpha	divraster	119.89	1.66
Low	Functional	Alpha	BAT	116.97	5.45
Low	Functional	Alpha	BAT	1.92	0.50
Low	Functional	Beta spatial	divraster	438.54	3.78
Low	Functional	Beta spatial	BAT	879.11	16.11
Low	Functional	Beta spatial	BAT	600.77	3.97
Low	Functional	Beta spatial	betapart	421.98	252.15
Low	Functional	Beta temporal	divraster	124.23	2.93
Low	Functional	Beta temporal	n/a	n/a	n/a
Low	Phylogenetic	Alpha	divraster	70.27	0.70
Low	Phylogenetic	Alpha	BAT	70.23	0.59
Low	Phylogenetic	Alpha	BAT	1.76	0.51
Low	Phylogenetic	Beta spatial	divraster	396.62	2.53
Low	Phylogenetic	Beta spatial	BAT	539.87	6.37
Low	Phylogenetic	Beta spatial	BAT	610.27	3.59
Low	Phylogenetic	Beta spatial	betapart	1707.73	21.60
Low	Phylogenetic	Beta temporal	divraster	75.17	0.60
Low	Phylogenetic	Beta temporal	n/a	n/a	n/a
High	Taxonomic	Alpha	divraster	121.48	1.77
High	Taxonomic	Alpha	BAT	67.14	98.86
High	Taxonomic	Alpha	BAT	2.24	1.29
High	Taxonomic	Beta spatial	divraster	682.13	557.68
High	Taxonomic	Beta spatial	BAT	503.92	2119.30
High	Taxonomic	Beta spatial	BAT	11582.44	6546.07
High	Taxonomic	Beta spatial	betapart	944.59	2.00
High	Taxonomic	Beta temporal	divraster	23.06	11.55
High	Taxonomic	Beta temporal	betapart	656.87	2.42
High	Functional	Alpha	divraster	1022.88	10.45
High	Functional	Alpha	BAT	1081.02	12.83
High	Functional	Alpha	BAT	13.79	0.55
High	Functional	Beta spatial	divraster	2606.07	32.95
High	Functional	Beta spatial	BAT	8536.82	1289.13

High	Functional	Beta spatial	BAT	fail		fail	
High	Functional	Beta spatial	betapart	fail		fail	
High	Functional	Beta temporal	divraster		1064.60		16.75
High	Functional	Beta temporal	n/a	n/a		n/a	
High	Phylogenetic	Alpha	divraster		599.22		2.23
High	Phylogenetic	Alpha	BAT		660.50		5.74
High	Phylogenetic	Alpha	BAT		13.96		0.06
High	Phylogenetic	Beta spatial	divraster		2207.24		13.01
High	Phylogenetic	Beta spatial	BAT		5278.79		85.45
High	Phylogenetic	Beta spatial	BAT	fail		fail	
High	Phylogenetic	Beta spatial	betapart	fail		fail	
High	Phylogenetic	Beta temporal	divraster		641.52		2.96
High	Phylogenetic	Beta temporal	n/a	n/a		n/a	

It is important to notice that, although we rely on *BAT* as a dependency, the *divraster* functions uses SpatRaster class of objects from the *terra* package as input, which is faster compared to RasterStack objects from the *raster* package (Hijmans et al. 2023a) currently used in BAT. Regarding the *betapart* package, we have observed that it requires a minimum of six species per site to calculate beta diversity and does not provide any options to handle nodata (Baselga and Orme 2012), which limits its applicability. Although calculations based on matrices showed superior performance in some cases, we were unable to complete the tests for spatial beta functions using high-resolution datasets for functional and phylogenetic dimensions because our machine ran out of RAM memory. This supports our statement on the disadvantages of using matrices when dealing with typical large datasets of macroecological studies (e.g. Alves-Ferreira et al. 2022, Mota et al. 2022). Furthermore, the beta diversity partitioning from the *betapart* package tends to overestimate replacement and underestimate richness differences (Carvalho et al. 2012). Therefore, our package not only uses a more appropriate method to calculate beta diversity, but also demonstrates good computational performance (i.e. memory allocation and processing time).

To run the tests, we used R version 4.2.2 on a computer with the following setup: operating system = Windows 11 Pro version 22H2, processor = i5-8265U, RAM = 16GB, and SSD = 256GB.

4.5. Conclusions and future directions

We proposed an R package to compute diversity metrics based on binary maps of species distributions, such as those derived from ecological niche models that are becoming increasingly common under the threat of climate change (e.g. Alves-Ferreira et al. 2022, Mota

et al. 2022). *divraster* stands out as the first tool capable of directly calculating temporal beta diversity and its components from *rasters* for all three diversity dimensions (i.e. taxonomic, functional, and phylogenetic) without the need for transformation into matrices. Our comparisons demonstrated that *divraster* outperformed other well-known R packages, particularly in functional and phylogenetic diversity metrics that required greater processing power. Additionally, *divraster* can compute the standardized effect size (SES) for functional and phylogenetic alpha diversity, and includes the option of running calculations in parallel using a multi-core processor for most functions, which also helps to optimize the processing of large datasets. In the next versions of the *divraster* package, we plan to implement SES for beta diversity, include other randomization algorithms implemented in *SESraster*, add a function for calculating defaunation index by scenarios, and eliminate any dependencies to avoid bottlenecks. Finally, we highlight that our package is only made possible because of other available packages (e.g. *BAT*) and it is not our purpose to replace any of them, but to facilitate access to diversity metrics for macroecology researchers.

5.6. References

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Supplementary material

Table S1. List of forest bird species recorded in the Central Corridor of the Atlantic Forest, Brazil. Records correspond to the number of occurrences after geographical bias correction (spatial thinning).

Species	English Name	Order	Family	Records
Amazona amazonica	Orange-winged Amazon	Psittaciformes	Psittacidae	3506
Amazona farinosa	Southern Mealy Amazon	Psittaciformes	Psittacidae	3087
Amazona rhodocorytha	Red-browed Amazon	Psittaciformes	Psittacidae	137
Amazona vinacea	Vinaceous-breasted Amazon	Psittaciformes	Psittacidae	332
Anabacerthia lichtensteini	Ochre-breasted Foliage-gleaner	Passeriformes	Furnariidae	364
Aramides saracura	Slaty-breasted Wood-rail	Gruiformes	Rallidae	1652
Asio stygius	Stygian Owl	Strigiformes	Strigidae	625
Attila spadiceus	Bright-rumped Attila	Passeriformes	Tyrannidae	2391
Automolus leucophthalmus	White-eyed Foliage-gleaner	Passeriformes	Furnariidae	921
Batara cinerea	Giant Antshrike	Passeriformes	Thamnophilidae	619
Brotogeris tirica	Plain Parakeet	Psittaciformes	Psittacidae	785
Buteogallus lacernulatus	White-necked Hawk	Accipitriformes	Accipitridae	200
Cacicus cela	Yellow-rumped Cacique	Passeriformes	Icteridae	3746
Cacicus haemorrhous	Red-rumped Cacique	Passeriformes	Icteridae	2366
Campephilus robustus	Robust Woodpecker	Piciformes	Picidae	716
Campylorhamphus falcularius	Black-billed Scythebill	Passeriformes	Furnariidae	373
Campylorhamphus trochilirostris	Red-billed Scythebill	Passeriformes	Furnariidae	1786
Campylorhynchus turdinus	Thrush-like Wren	Passeriformes	Troglodytidae	2214
Cantorchilus longirostris	Long-billed Wren	Passeriformes	Troglodytidae	692
Capsiempis flaveola	Yellow Tyrannulet	Passeriformes	Tyrannidae	2063
Carpornis cucullata	Hooded Berryeater	Passeriformes	Cotingidae	318
Carpornis melanocephala	Black-headed Berryeater	Passeriformes	Cotingidae	104
Celeus flavescens	Blond-crested Woodpecker	Piciformes	Picidae	909
Celeus torquatus	Ringed Woodpecker	Piciformes	Picidae	795
Ceratopipra rubrocapilla	Red-headed Manakin	Passeriformes	Pipridae	682
Chaetura cinereiventris	Grey-rumped Swift	Apodiformes	Apodidae	2449
Chamaeza campanisona	Short-tailed Antthrush	Passeriformes	Formicariidae	921
Chamaeza meruloides	Cryptic Antthrush	Passeriformes	Formicariidae	166
Chiroxiphia caudata	Blue Manakin	Passeriformes	Pipridae	1469
Chiroxiphia pareola	Blue-backed Manakin	Passeriformes	Pipridae	815
Chlorestes cyanus	White-chinned Sapphire	Apodiformes	Trochilidae	1138
Chlorestes notata	Blue-chinned Emerald	Apodiformes	Trochilidae	830

Chlorophanes spiza	Green Honeycreeper	Passeriformes	Thraupidae	1728
Chlorophonia cyanea	Blue-naped Chlorophonia	Passeriformes	Fringillidae	1231
Ciccaba huhula	Black-banded Owl	Strigiformes	Strigidae	55
Ciccaba virgata	Mottled Owl	Strigiformes	Strigidae	369
Cichlocolaptes leucophrus	Large Pale-browed Treehunter	Passeriformes	Furnariidae	219
Cichlopsis leucogenys	Rufous-brown Solitaire	Passeriformes	Turdidae	62
Claravis pretiosa	Blue Ground-dove	Columbiformes	Columbidae	3662
Clytolaema rubricauda	Brazilian Ruby	Apodiformes	Trochilidae	321
Colaptes melanochloros	Green-barred Woodpecker	Piciformes	Picidae	4888
Colonia colonus	Long-tailed Tyrant	Passeriformes	Tyrannidae	2689
Conirostrum speciosum	Chestnut-vented Conebill	Passeriformes	Thraupidae	2770
Conopias trivirgatus	Three-striped Flycatcher	Passeriformes	Tyrannidae	451
Conopophaga lineata	Rufous Gnateater	Passeriformes	Conopophagidae	1271
Conopophaga melanops	Black-cheeked Gnateater	Passeriformes	Conopophagidae	345
Corythopis delalandi	Southern Antpipit	Passeriformes	Tyrannidae	766
Cotinga maculata	Banded Cotinga	Passeriformes	Cotingidae	21
Cranioleuca pallida	Pallid Spinetail	Passeriformes	Furnariidae	470
Crax blumenbachii	Red-billed Curassow	Galliformes	Cracidae	24
Crotophaga major	Greater Ani	Cuculiformes	Cuculidae	4558
Crypturellus noctivagus	Yellow-legged Tinamou	Tinamiformes	Tinamidae	190
Crypturellus obsoletus	Brown Tinamou	Tinamiformes	Tinamidae	1488
Crypturellus soui	Little Tinamou	Tinamiformes	Tinamidae	3330
Crypturellus variegatus	Variegated Tinamou	Tinamiformes	Tinamidae	930
Cyanerpes cyaneus	Red-legged Honeycreeper	Passeriformes	Thraupidae	2025
Cyanoloxia brissonii	Ultramarine Grosbeak	Passeriformes	Cardinalidae	2568
Cyclarhis gujanensis	Rufous-browed Peppershrike	Passeriformes	Vireonidae	5518
Cypseloides senex	Great Dusky Swift	Apodiformes	Apodidae	368
Dacnis cayana	Blue Dacnis	Passeriformes	Thraupidae	4164
Dacnis nigripes	Black-legged Dacnis	Passeriformes	Thraupidae	124
Dendrocincla turdina	Plain-winged Woodcreeper	Passeriformes	Furnariidae	510
Dendrocolaptes platyrostris	Planalto Woodcreeper	Passeriformes	Furnariidae	1388
Dendroplex picus	Straight-billed Woodcreeper	Passeriformes	Furnariidae	3384
Diopsittaca nobilis	Northern Red-shouldered Macaw	Psittaciformes	Psittacidae	1574
Discosura langsdorffi	Black-bellied Thorntail	Apodiformes	Trochilidae	187
Drymophila ferruginea	Ferruginous Antbird	Passeriformes	Thamnophilidae	398
Drymophila genei	Rufous-tailed Antbird	Passeriformes	Thamnophilidae	75
Drymophila ochropyga	Ochre-rumped Antbird	Passeriformes	Thamnophilidae	264
Drymophila squamata	Scaled Antbird	Passeriformes	Thamnophilidae	228
Dysithamnus mentalis	Plain Antvireo	Passeriformes	Thamnophilidae	2736

Dysithamnus plumbeus	Plumbeous Antvireo	Passeriformes	Thamnophilidae	47
Dysithamnus stictothorax	Spot-breasted Antvireo	Passeriformes	Thamnophilidae	291
Elaenia obscura	Highland Elaenia	Passeriformes	Tyrannidae	319
Eleoscytalopus indigoticus	White-breasted Tapaculo	Passeriformes	Rhinocryptidae	341
Euphonia chlorotica	Purple-throated Euphonia	Passeriformes	Fringillidae	5261
Euphonia cyanocephala	Golden-rumped Euphonia	Passeriformes	Fringillidae	1391
Euphonia pectoralis	Chestnut-bellied Euphonia	Passeriformes	Fringillidae	707
Euphonia violacea	Violaceous Euphonia	Passeriformes	Fringillidae	1949
Euphonia xanthogaster	Orange-bellied Euphonia	Passeriformes	Fringillidae	1923
Falco deiroleucus	Orange-breasted Falcon	Falconiformes	Falconidae	124
Falco rufigularis	Bat Falcon	Falconiformes	Falconidae	4692
Florisuga fusca	Black Jacobin	Apodiformes	Trochilidae	1126
Formicarius colma	Rufous-capped Antthrush	Passeriformes	Formicariidae	1042
Formicivora serrana	Serra Antwren	Passeriformes	Thamnophilidae	178
Forpus xanthopterygius	Blue-winged Parrotlet	Psittaciformes	Psittacidae	3336
Furnarius figulus	Wing-banded Hornero	Passeriformes	Furnariidae	1331
Galbula ruficauda	Rufous-tailed Jacamar	Piciformes	Galbulidae	3626
Geotrygon montana	Ruddy Quail-dove	Columbiformes	Columbidae	3127
Geotrygon violacea	Violaceous Quail-dove	Columbiformes	Columbidae	179
Glaucidium minutissimum	Least Pygmy-owl	Strigiformes	Strigidae	243
Glaucis dohrnii	Hook-billed Hermit	Apodiformes	Trochilidae	32
Glaucis hirsutus	Rufous-breasted Hermit	Apodiformes	Trochilidae	2028
Glyphorynchus spirurus	Wedge-billed Woodcreeper	Passeriformes	Furnariidae	2759
Grallaria varia	Variegated Antpitta	Passeriformes	Grallariidae	555
Habia rubica	Red-crowned Ant-tanager	Passeriformes	Cardinalidae	2381
Harpagus bidentatus	Double-toothed Kite	Accipitriformes	Accipitridae	2008
Harpia harpyja	Harpy Eagle	Accipitriformes	Accipitridae	623
Heliomaster squamosus	Stripe-breasted Starthroat	Apodiformes	Trochilidae	661
Heliothryx auritus	Black-eared Fairy	Apodiformes	Trochilidae	1080
Hemithraupis flavicollis	Yellow-backed Tanager	Passeriformes	Thraupidae	1050
Hemithraupis ruficapilla	Rufous-headed Tanager	Passeriformes	Thraupidae	764
Hemitriccus diops	Drab-breasted Bamboo-tyrant	Passeriformes	Tyrannidae	390
Hemitriccus furcatus	Fork-tailed Tody-tyrant	Passeriformes	Tyrannidae	54
Hemitriccus nidipendulus	Hangnest Tody-tyrant	Passeriformes	Tyrannidae	470
Hemitriccus striaticollis	Stripe-necked Tody-tyrant	Passeriformes	Tyrannidae	610
Herpetotheres cachinnans	Laughing Falcon	Falconiformes	Falconidae	5721
Herpsilochmus rufimarginatus	Southern Rufous-winged Antwren	Passeriformes	Thamnophilidae	741
Hylatomus lineatus	Lineated Woodpecker	Piciformes	Picidae	5028
Hylocharis sapphirina	Rufous-throated Hummingbird	Apodiformes	Trochilidae	473

Hylophilus poicilotis	Rufous-crowned Greenlet	Passeriformes	Vireonidae	713
Hylophilus thoracicus	Rio de Janeiro Greenlet	Passeriformes	Vireonidae	591
Hypoedaleus guttatus	Spot-backed Antshrike	Passeriformes	Thamnophilidae	605
Icterus pyrrhopterus	Variable Oriole	Passeriformes	Icteridae	4181
Ictinia plumbea	Plumbeous Kite	Accipitriformes	Accipitridae	5534
Ilicura militaris	Pin-tailed Manakin	Passeriformes	Pipridae	471
Iodopleura pipra	Buff-throated Purpletuft	Passeriformes	Tityridae	79
Laniisoma elegans	Elegant Mourner	Passeriformes	Tityridae	70
Laniocera hypopyrra	Cinereous Mourner	Passeriformes	Tityridae	589
Legatus leucophaius	Piratic Flycatcher	Passeriformes	Tyrannidae	3982
Lepidocolaptes squamatus	Scaled Woodcreeper	Passeriformes	Furnariidae	381
Leptodon cayanensis	Grey-headed Kite	Accipitriformes	Accipitridae	2951
Leptopogon amaurocephalus	Sepia-capped Flycatcher	Passeriformes	Tyrannidae	3281
Leptotila rufaxilla	Grey-fronted Dove	Columbiformes	Columbidae	3829
Leucochloris albicollis	White-throated Hummingbird	Apodiformes	Trochilidae	1248
Lipaugus lanioides	Cinnamon-vented Piha	Passeriformes	Cotingidae	128
Lipaugus vociferans	Screaming Piha	Passeriformes	Cotingidae	2050
Lurocalis semitorquatus	Short-tailed Nighthawk	Caprimulgiformes	Caprimulgidae	1693
Machaeropterus regulus	Kinglet Manakin	Passeriformes	Pipridae	280
Mackenziaena leachii	Large-tailed Antshrike	Passeriformes	Thamnophilidae	613
Mackenziaena severa	Tufted Antshrike	Passeriformes	Thamnophilidae	599
Malacoptila striata	Greater Crescent-chested Puffbird	Piciformes	Bucconidae	606
Manacus manacus	White-bearded Manakin	Passeriformes	Pipridae	2802
Megascops atricapilla	Black-capped Screech-owl	Strigiformes	Strigidae	246
Melanerpes flavifrons	Yellow-fronted Woodpecker	Piciformes	Picidae	683
Micrastur mintoni	Cryptic Forest-falcon	Falconiformes	Falconidae	166
Micrastur ruficollis	Barred Forest-falcon	Falconiformes	Falconidae	2417
Micrastur semitorquatus	Collared Forest-falcon	Falconiformes	Falconidae	3653
Mionectes oleagineus	Ochre-bellied Flycatcher	Passeriformes	Tyrannidae	3172
Mionectes rufiventris	Grey-hooded Flycatcher	Passeriformes	Tyrannidae	742
Monasa morphoeus	White-fronted Nunbird	Piciformes	Bucconidae	1320
Myiarchus ferox	Short-crested Flycatcher	Passeriformes	Tyrannidae	4896
Myiarchus tuberculifer	Dusky-capped Flycatcher	Passeriformes	Tyrannidae	3138
Myiobius atricaudus	Black-tailed Flycatcher	Passeriformes	Tityridae	700
Myiobius barbatus	Whiskered Flycatcher	Passeriformes	Tityridae	1385
Myiopagis caniceps	Atlantic Grey Elaenia	Passeriformes	Tyrannidae	1577
Myiornis auricularis	Eared Pygmy-tyrant	Passeriformes	Tyrannidae	909
Myiothlypis rivularis	Southern Riverbank Warbler	Passeriformes	Parulidae	588
Myrmoderus loricatus	White-bibbed Antbird	Passeriformes	Thamnophilidae	133

Myrmotherula axillaris	White-flanked Antwren	Passeriformes	Thamnophilidae	2247
Myrmotherula luctuosa	Silvery-flanked Antwren	Passeriformes	Thamnophilidae	25
Myrmotherula minor	Salvadori's Antwren	Passeriformes	Thamnophilidae	69
Myrmotherula urosticta	Band-tailed Antwren	Passeriformes	Thamnophilidae	52
Nemosia pileata	Hooded Tanager	Passeriformes	Thraupidae	2848
Neomorphus geoffroyi	Rufous-vented Ground-cuckoo	Cuculiformes	Cuculidae	141
Neopelma aurifrons	Wied's Tyrant-manakin	Passeriformes	Pipridae	33
Notharchus swainsoni	Buff-bellied Puffbird	Piciformes	Bucconidae	178
Nyctibius aethereus	Long-tailed Potoo	Caprimulgiformes	Nyctibiidae	317
Nyctibius grandis	Great Potoo	Caprimulgiformes	Nyctibiidae	1587
Nyctibius griseus	Common Potoo	Caprimulgiformes	Nyctibiidae	4212
Nyctiphrynus ocellatus	Ocellated Poorwill	Caprimulgiformes	Caprimulgidae	618
Nystalus maculatus	Spot-backed Puffbird	Piciformes	Bucconidae	1990
Odontophorus capueira	Spot-winged Wood-quail	Galliformes	Odontophoridae	524
Orchesticus abeillei	Brown Tanager	Passeriformes	Thraupidae	159
Oxyruncus cristatus	Sharpbill	Passeriformes	Tityridae	376
Pachyramphus castaneus	Chestnut-crowned Becard	Passeriformes	Tityridae	1475
Pachyramphus marginatus	Black-capped Becard	Passeriformes	Tityridae	867
Pachyramphus polychopterus	White-winged Becard	Passeriformes	Tityridae	5433
Panyptila cayennensis	Lesser Swallow-tailed Swift	Apodiformes	Apodidae	1751
Patagioenas cayennensis	Pale-vented Pigeon	Columbiformes	Columbidae	4096
Patagioenas picazuro	Picazuro Pigeon	Columbiformes	Columbidae	4922
Patagioenas plumbea	Plumbeous Pigeon	Columbiformes	Columbidae	3128
Patagioenas speciosa	Scaled Pigeon	Columbiformes	Columbidae	2704
Penelope obscura	Dusky-legged Guan	Galliformes	Cracidae	1540
Penelope superciliaris	Rusty-margined Guan	Galliformes	Cracidae	1253
Phaethornis eurynome	Scale-throated Hermit	Apodiformes	Trochilidae	719
Phaethornis idaliae	Minute Hermit	Apodiformes	Trochilidae	68
Phaethornis ruber	Reddish Hermit	Apodiformes	Trochilidae	2075
Phaethornis squalidus	Dusky-throated Hermit	Apodiformes	Trochilidae	202
Pheugopedius genibarbis	Moustached Wren	Passeriformes	Troglodytidae	1928
Philydor atricapillus	Black-capped Foliage-gleaner	Passeriformes	Furnariidae	376
Philydor rufum	Buff-fronted Foliage-gleaner	Passeriformes	Furnariidae	1273
Phyllomyias burmeisteri	Rough-legged Tyrannulet	Passeriformes	Tyrannidae	637
Phyllomyias fasciatus	Planalto Tyrannulet	Passeriformes	Tyrannidae	1285
Phyllomyias griseocapilla	Grey-capped Tyrannulet	Passeriformes	Tyrannidae	288
Phyllomyias virescens	Greenish Tyrannulet	Passeriformes	Tyrannidae	408
Phylloscartes beckeri	Bahia Tyrannulet	Passeriformes	Tyrannidae	23
Phylloscartes oustaleti	Oustalet's Tyrannulet	Passeriformes	Tyrannidae	143

Phylloscartes ventralis	Mottle-cheeked Tyrannulet	Passeriformes	Tyrannidae	1481
Piaya cayana	Common Squirrel-cuckoo	Cuculiformes	Cuculidae	5494
Piculus aurulentus	Yellow-browed Woodpecker	Piciformes	Picidae	587
Piculus flavigula	Yellow-throated Woodpecker	Piciformes	Picidae	1057
Picumnus albosquamatus	White-wedged Piculet	Piciformes	Picidae	1290
Picumnus exilis	Golden-spangled Piculet	Piciformes	Picidae	457
Pionopsitta pileata	Pileated Parrot	Psittaciformes	Psittacidae	579
Pionus maximiliani	Scaly-headed Parrot	Psittaciformes	Psittacidae	2682
Piprites chloris	Wing-barred Piprites	Passeriformes	Tyrannidae	1175
Platyrinchus leucoryphus	Russet-winged Spadebill	Passeriformes	Tyrannidae	75
Platyrinchus mystaceus	Eastern White-throated Spadebill	Passeriformes	Tyrannidae	1847
Poecilotriccus fumifrons	Smoky-fronted Tody-flycatcher	Passeriformes	Tyrannidae	274
Poecilotriccus plumbeiceps	Ochre-faced Tody-flycatcher	Passeriformes	Tyrannidae	1476
Primolius maracana	Blue-winged Macaw	Psittaciformes	Psittacidae	955
Procnias nudicollis	Bare-throated Bellbird	Passeriformes	Cotingidae	600
Psarocolius decumanus	Crested Oropendola	Passeriformes	Icteridae	3826
Pseudastur polionotus	Mantled Hawk	Accipitriformes	Accipitridae	230
Pseudopipra pipra	White-crowned Manakin	Passeriformes	Pipridae	834
Pseudoseisura cristata	Caatinga Cachalote	Passeriformes	Furnariidae	648
Psilorhamphus guttatus	Spotted Bamboowren	Passeriformes	Rhinocryptidae	226
Psittacara leucophthalmus	White-eyed Parakeet	Psittaciformes	Psittacidae	3524
Pteroglossus aracari	Black-necked Aracari	Piciformes	Ramphastidae	1204
Pteroglossus bailloni	Saffron Toucanet	Piciformes	Ramphastidae	323
Pulsatrix koeniswaldiana	Tawny-browed Owl	Strigiformes	Strigidae	434
Pulsatrix perspicillata	Spectacled Owl	Strigiformes	Strigidae	1981
Pyriglena leucoptera	White-shouldered Fire-eye	Passeriformes	Thamnophilidae	1067
Pyrrhura cruentata	Ochre-marked Parakeet	Psittaciformes	Psittacidae	75
Pyrrhura frontalis	Maroon-bellied Parakeet	Psittaciformes	Psittacidae	1589
Pyrrhura leucotis	White-eared Parakeet	Psittaciformes	Psittacidae	92
Ramphastos dicolorus	Red-breasted Toucan	Piciformes	Ramphastidae	1108
Ramphastos vitellinus	Channel-billed Toucan	Piciformes	Ramphastidae	3048
Ramphocaenus melanurus	Long-billed Gnatwren	Passeriformes	Polioptilidae	2499
Ramphodon naevius	Saw-billed Hermit	Apodiformes	Trochilidae	273
Ramphotrigon megacephalum	Large-headed Flatbill	Passeriformes	Tyrannidae	421
Rhopias gularis	Star-throated Antwren	Passeriformes	Thamnophilidae	289
Rhynchocyclus olivaceus	Eastern Olivaceous Flatbill	Passeriformes	Tyrannidae	793
Rhytipterna simplex	Greyish Mourner	Passeriformes	Tyrannidae	1410
Rupornis magnirostris	Roadside Hawk	Accipitriformes	Accipitridae	7042
Saltator fuliginosus	Black-throated Grosbeak	Passeriformes	Thraupidae	404

Saltator similis	Green-winged Saltator	Passeriformes	Thraupidae	3088
Sarcoramphus papa	King Vulture	Cathartiformes	Cathartidae	4497
Schiffornis turdina	Brown-winged Mourner	Passeriformes	Tityridae	1764
Schiffornis virescens	Greenish Schiffornis	Passeriformes	Tityridae	947
Sclerurus caudacutus	Black-tailed Leaftosser	Passeriformes	Furnariidae	325
Sclerurus mexicanus	Tawny-throated Leaftosser	Passeriformes	Furnariidae	362
Sclerurus scansor	Rufous-breasted Leaftosser	Passeriformes	Furnariidae	598
Scytalopus speluncae	Mouse-colored Tapaculo	Passeriformes	Rhinocryptidae	271
Selenidera maculirostris	Spot-billed Toucanet	Piciformes	Ramphastidae	370
Setophaga pitiayumi	Tropical Parula	Passeriformes	Parulidae	4069
Sirystes sibilator	Sibilant Sirystes	Passeriformes	Tyrannidae	1070
Sittasomus griseicapillus	Eastern Olivaceous Woodcreeper	Passeriformes	Furnariidae	3791
Spizaetus melanoleucus	Black-and-white Hawk-eagle	Accipitriformes	Accipitridae	1314
Spizaetus ornatus	Ornate Hawk-eagle	Accipitriformes	Accipitridae	1587
Spizaetus tyrannus	Black Hawk-eagle	Accipitriformes	Accipitridae	2806
Strix hylophila	Rusty-barred Owl	Strigiformes	Strigidae	316
Synallaxis cinerea	Bahia Spinetail	Passeriformes	Furnariidae	31
Synallaxis ruficapilla	Rufous-capped Spinetail	Passeriformes	Furnariidae	1334
Syndactyla rufosuperciliata	Buff-browed Foliage-gleaner	Passeriformes	Furnariidae	1429
Tangara brasiliensis	White-bellied Tanager	Passeriformes	Thraupidae	26
Tangara cayana	Burnished-buff Tanager	Passeriformes	Thraupidae	159
Tangara cyanocephala	Red-necked Tanager	Passeriformes	Thraupidae	401
Tangara cyanoptera	Azure-shouldered Tanager	Passeriformes	Thraupidae	434
Tangara cyanoventris	Gilt-edged Tanager	Passeriformes	Thraupidae	448
Tangara desmaresti	Brassy-breasted Tanager	Passeriformes	Thraupidae	353
Tangara ornata	Golden-chevroned Tanager	Passeriformes	Thraupidae	534
Tangara palmarum	Palm Tanager	Passeriformes	Thraupidae	142
Tangara sayaca	Sayaca Tanager	Passeriformes	Thraupidae	84
Tangara seledon	Green-headed Tanager	Passeriformes	Thraupidae	615
Taraba major	Great Antshrike	Passeriformes	Thamnophilidae	6118
Terenura maculata	Streak-capped Antwren	Passeriformes	Thamnophilidae	308
Tersina viridis	Swallow Tanager	Passeriformes	Thraupidae	3902
Thalurania glaucopis	Violet-capped Woodnymph	Apodiformes	Trochilidae	1311
Thamnomanes caesius	Cinereous Antshrike	Passeriformes	Thamnophilidae	1024
Thamnophilus ambiguus	Sooretama Slaty Antshrike	Passeriformes	Thamnophilidae	299
Thamnophilus caerulescens	Variable Antshrike	Passeriformes	Thamnophilidae	3913
Thamnophilus pelzelni	Planalto Slaty Antshrike	Passeriformes	Thamnophilidae	1090
Thlypopsis sordida	Orange-headed Tanager	Passeriformes	Thraupidae	1738
Thripophaga macroura	Striated Softtail	Passeriformes	Furnariidae	42

Tinamus solitarius	Solitary Tinamou	Tinamiformes	Tinamidae	366
Tityra cayana	Western Black-tailed Tityra	Passeriformes	Tityridae	2558
Tityra inquisitor	Black-crowned Tityra	Passeriformes	Tityridae	3363
Todirostrum poliocephalum	Yellow-lored Tody-flycatcher	Passeriformes	Tyrannidae	1059
Tolmomyias flaviventris	Ochre-lored Flatbill	Passeriformes	Tyrannidae	2978
Tolmomyias poliocephalus	Grey-crowned Flatbill	Passeriformes	Tyrannidae	1366
Tolmomyias sulphurescens	Yellow-olive Flatbill	Passeriformes	Tyrannidae	3936
Touit surdus	Golden-tailed Parrotlet	Psittaciformes	Psittacidae	99
Trichothraupis melanops	Black-goggled Tanager	Passeriformes	Thraupidae	1445
Triclaria malachitacea	Blue-bellied Parrot	Psittaciformes	Psittacidae	179
Trogon collaris	Collared Trogon	Trogoniformes	Trogonidae	2185
Trogon surrucura	Southern Surucua Trogon	Trogoniformes	Trogonidae	1909
Trogon viridis	Green-backed Trogon	Trogoniformes	Trogonidae	2806
Turdus albicollis	White-necked Thrush	Passeriformes	Turdidae	2667
Turdus flavipes	Yellow-legged Thrush	Passeriformes	Turdidae	944
Turdus fumigatus	Cocoa Thrush	Passeriformes	Turdidae	620
Turdus leucomelas	Pale-breasted Thrush	Passeriformes	Turdidae	3437
Veniliornis affinis	Red-stained Woodpecker	Piciformes	Picidae	1065
Veniliornis maculifrons	Yellow-eared Woodpecker	Piciformes	Picidae	268
Veniliornis passerinus	Little Woodpecker	Piciformes	Picidae	3203
Xenops minutus	White-throated Xenops	Passeriformes	Furnariidae	2967
Xenops rutilus	Streaked Xenops	Passeriformes	Furnariidae	49
Xiphocolaptes albicollis	White-throated Woodcreeper	Passeriformes	Furnariidae	617
Xipholena atropurpurea	White-winged Cotinga	Passeriformes	Cotingidae	55
Xiphorhynchus fuscus	Lesser Woodcreeper	Passeriformes	Furnariidae	1102
Xiphorhynchus guttatus	Buff-throated Woodcreeper	Passeriformes	Furnariidae	2577

Table S2. Selected bioclimatic variables (Pearson correlation < 0.7) for each forest bird species within the Central Corridor of the Atlantic Forest, Brazil, and their corresponding percentage of contribution to the niche models.

Species	bio2	bio3	bio4	bio5	bio7	bio8	bio9	bio10	bio12	bio13	bio14	bio15	bio16	bio17	bio18	bio19
Amazona amazonica	46.4	48.4		1.0						0.0	1.9	0.1			0.1	2.0
Amazona farinosa		18.6		6.2			33.2				3.6	4.5			21.6	12.3
Amazona rhodocorytha		30.2				33.8			5.1		30.9					
Amazona vinacea	1.5		33.2			28.5				0.8		6.4			28.0	1.4
Anabacerthia lichtensteini	8.0	41.2			5.6		30.0	2.9	5.1				1.8		5.4	
Aramides saracura	17.7				14.1	1.9	10.0	27.8	5.2						16.6	6.5
Asio stygius	23.0	11.0		45.0						3.8		4.3			9.6	3.2
Attila spadiceus	13.5	13.0		7.6						25.8		9.0			17.3	13.8
Automolus leucophthalmus	18.5	41.9						25.0	0.4			7.2			6.8	0.1
Batara cinerea		64.1		26.9							1.0				7.9	
Brotogeris tirica	38.9							36.8					0.9		22.8	0.5
Buteogallus lacernulatus					3.4	5.0						54.8			36.9	
Cacicus cela	39.5	5.4		13.1						0.7		33.0			4.2	4.0
Cacicus haemorrhous	15.2	33.0		20.4						2.9		19.1			8.9	0.6
Campephilus robustus	14.4				7.1			42.9	0.0	1.2					33.2	1.2
Campylorhamphus falcularius	15.9				1.2	2.1	55.5	13.4	0.6			6.3	5.1			
Campylorhamphus trochilirostris	19.9	20.9		21.6						5.4		4.5			13.5	14.3
Campylorhynchus turdinus	0.5	8.7		9.1						0.1		64.8			14.8	1.9
Cantorchilus longirostris	37.0	6.9				2.0						14.0	25.8		14.3	
Capsiempis flaveola	60.3	16.4		16.4						6.7		0.1			0.0	0.0
Carpornis cucullata	44.9				4.3	3.0		40.1	2.2	0.9					4.5	
Carpornis melanocephala		45.7			44.1	9.4							0.8			0.0
Celeus flavescens	11.8			31.2					4.2		18.4				20.3	14.1
Celeus torquatus	34.4		19.2	10.0						5.9		23.6			1.4	5.5
Ceratopipra rubrocapilla	23.9		22.7	4.1						8.0		14.4			7.9	19.0
Chaetura cinereiventris	34.6	2.7		23.9						0.7		26.5			10.3	1.3
Chamaeza campanisona	4.4	34.7		24.3						0.2		33.1			3.1	0.1
Chamaeza meruloides	12.7	29.1		35.7								9.9	12.5			
Chiroxiphia caudata	13.9	40.4		20.7						1.1	6.6				13.7	3.6
Chiroxiphia pareola	70.0	4.5		0.6						4.0		7.2			4.8	8.9
Chlorestes cyanus	42.6	38.1		1.9						0.6		7.2			7.0	2.6
Chlorestes notata	55.6		5.6	10.2						2.9		11.5			8.2	6.0
Chlorophanes spiza	35.4	4.7		23.2						5.2		16.8			11.7	3.1
Chlorophonia cyanea	18.2	6.8		49.6						1.0		17.7			5.3	1.4

Ciccaba huhula	17.1		0.5	7.7					0.1	73.4			0.9	0.2
Ciccaba virgata	2.9	8.4		8.4					13.6	33.6			20.4	12.7
Cichlocolaptes leucophrus	48.6				5.7				2.2				41.7	1.8
Cichlopsis leucogenys	22.7		2.4		53.4				0.5	8.5			8.8	3.8
Claravis pretiosa	14.7	11.5		19.2					16.5	17.9			14.8	5.3
Clytolaema rubricauda	9.8		24.8	31.9					1.4	5.2			23.6	3.4
Colaptes melanochloros	7.6	82.3		0.5						0.5			7.0	2.0
Colonia colonus	9.7	14.1		25.7					0.1	0.0			50.4	0.0
Conirostrum speciosum	9.6	63.2		6.0					0.6	3.0			14.0	3.7
Conopias trivirgatus	17.4		28.2	14.1					1.7	8.5			27.7	2.5
Conopophaga lineata	9.4				4.7		52.0	2.5		12.3			17.1	2.0
Conopophaga melanops	74.2				0.1				24.2					1.5
Corythopis delalandi	7.6	5.2			10.4		26.9	3.0		14.1			28.7	4.0
Cotinga maculata		48.9	0.0				0.0	0.1					12.7	38.3
Cranioleuca pallida					9.3	35.5		4.7		20.3			30.2	
Crax blumenbachii		46.4		44.2				2.8						6.6
Crotophaga major	65.4	19.5		10.3					0.2	2.5			2.0	0.0
Crypturellus noctivagus	24.3			1.6				21.7				17.5	35.0	
Crypturellus obsoletus	6.5	42.3		30.9					0.0	10.1			8.8	1.5
Crypturellus soui	33.5	1.8		12.9					6.8	28.3			8.2	8.4
Crypturellus variegatus	69.5	4.9		2.6					5.0	13.1			0.0	5.0
Cyanerpes cyaneus	28.1		11.9	0.9					44.7	0.7			4.7	9.0
Cyanoloxia brissonii	7.3	66.5		3.7					5.6	6.7			4.2	6.0
Cyclarhis gujanensis	26.1	42.8		10.3					3.9	5.2			7.8	3.9
Cypseloides senex	5.1				2.9		59.4	2.6		13.2			16.5	0.2
Dacnis cayana	31.7	14.6		22.4					3.0	8.2			19.1	1.0
Dacnis nigripes	39.9				4.5					8.2	35.2			20.5
Dendrocincla turdina	45.6				1.4	34.9	5.5	9.1			2.7			0.7
Dendrocolaptes platyrostris	23.2				3.5		25.4	1.2		27.0			17.8	1.9
Dendroplex picus	79.0	6.2		8.7					1.6	1.5			1.5	1.4
Diopsittaca nobilis	18.7	7.1		1.1					15.2	24.6			21.8	11.4
Discosura langsdorffi	3.1	13.6		3.6					0.5	27.6			29.1	22.4
Drymophila ferruginea					15.1		25.1		8.7	15.3			35.7	
Drymophila genei					3.7	88.0					8.3			
Drymophila ochropyga					4.6	18.1				23.7	2.2		51.3	
Drymophila squamata		57.3			21.9	0.0			1.6					19.2
Dysithamnus mentalis	8.4	17.6		34.3					0.0	8.3			30.8	0.5
Dysithamnus plumbeus	17.7	35.4	29.6			7.6			8.6				0.5	0.6
Dysithamnus stictothorax					4.3	2.4		2.0		62.9			28.4	

Elaenia obscura	7.5	1.5		59.6						0.4	4.8			13.1	13.0
Eleoscytalopus indigoticus	7.6	38.7		37.1				0.5						16.0	
Euphonia chlorotica	16.4	48.4		2.1					2.7		6.3			15.7	8.3
Euphonia cyanocephala	16.3	1.1		64.0					1.0		13.6			3.7	0.4
Euphonia pectoralis	5.5	50.5		25.3					0.0		2.1			16.1	0.4
Euphonia violacea	26.0	40.6			17.7				2.0		6.7			5.0	2.0
Euphonia xanthogaster	23.2	31.6		27.3					1.1		5.4			10.5	0.8
Falco deiroleucus		6.4		15.1						37.5	33.3			2.3	5.3
Falco rufigularis	45.9	2.4		7.0					11.1		8.3			17.6	7.6
Florisuga fusca	21.8	31.2		17.5					5.2		2.0			20.1	2.3
Formicarius colma	71.3	18.0		0.0					0.5		4.0			6.0	0.1
Formicivora serrana	2.4	46.1			31.2							20.3			
Forpus xanthopterygius	24.4	32.0		6.9					0.8		3.7			11.9	20.4
Furnarius figulus	13.4	42.6		24.2					1.1		13.3			1.1	4.4
Galbula ruficauda	17.8		40.4	0.1					0.0		27.0			14.4	0.2
Geotrygon montana	38.1	3.6		16.8					4.3		12.6			22.2	2.3
Geotrygon violacea	30.0		22.7	28.4					3.5		3.3			4.4	7.7
Glaucidium minutissimum	18.9	47.7		13.2					2.0		11.0			4.2	3.0
Glaucis dohrnii	76.2	5.2		2.3					16.3					0.0	0.1
Glaucis hirsutus	52.5	1.6		8.4					0.3		30.7			3.1	3.4
Glyphorynchus spirurus	33.3	7.3		8.9					10.3		30.3			5.7	4.1
Grallaria varia	7.2		44.5	24.5					7.8		12.5			0.1	3.4
Habia rubica	11.0	35.9		17.9					6.4		4.2			21.0	3.7
Harpagus bidentatus	35.4		13.4	6.2					22.1		7.5			7.7	7.7
Harpia harpyja	60.0	1.3		4.0					20.3		7.9			1.2	5.4
Heliomaster squamosus	15.0	5.3		31.5					2.1		20.7			17.7	7.7
Heliothryx auritus	34.8	8.5		8.8					12.3		3.9			18.0	13.7
Hemithraupis flavicollis	4.1	6.6		5.0					6.1		59.2			16.8	2.2
Hemithraupis ruficapilla	22.9	25.1			2.2		26.7	1.2			9.7			10.9	1.4
Hemitriccus diops	19.4	29.5			6.0		35.0							10.0	
Hemitriccus furcatus	6.8	29.0	16.4			18.4		5.5			21.5				2.4
Hemitriccus nidipendulus	32.2					38.0			24.6						5.1
Hemitriccus striaticollis	3.2	17.4		33.0					1.5		29.1			15.0	0.9
Herpetotheres cachinnans	23.0	23.5		4.5					8.6		19.1			21.1	0.1
Herpsilochmus rufimarginatus	17.0	58.1		17.2					0.3		1.3			5.9	0.2
Hylatomus lineatus	27.1	10.2		24.7					4.9		14.9			18.2	0.1
Hylocharis sapphirina	75.3		3.3	4.3					2.0		7.8			5.6	1.7
Hylophilus poicilotis	2.3	39.8			0.9		47.6	0.0						8.8	0.6
Hylophilus thoracicus	54.2	9.4		0.6					2.5		22.7			3.2	7.3

Hypoedaleus guttatus	8.1	31.0			2.3			23.2	0.7	1.5					18.8	14.4
Icterus pyrrhopterus	26.2	52.6		3.2						2.3				3.5	7.9	4.4
Ictinia plumbea	33.0	2.6		12.5						0.0		34.7			17.2	0.0
Ilicura militaris					15.0			37.6	0.9	0.4		5.6			40.6	
Iodopleura pipra		38.9			18.7	10.9							10.1			21.4
Laniisoma elegans	18.6		27.3	22.0						0.1		4.8			27.0	0.2
Laniocera hypopyrra	40.7	7.8		5.1						4.9		39.6			0.5	1.5
Legatus leucophaius	32.7	6.2		14.5						7.0		12.0			17.2	10.4
Lepidocolaptes squamatus	27.3				3.8			32.4	1.9	1.1		17.9			15.5	
Leptodon cayanensis	30.3	19.4		21.6						1.8		7.8			19.0	0.0
Leptopogon amaurocephalus	23.5	34.2		11.0						3.5		2.3			24.3	1.1
Leptotila rufaxilla	33.5	13.5		11.4						6.3		17.8			13.0	4.5
Leucochloris albicollis	15.5	8.9		24.3							12.8	22.0			11.8	4.7
Lipaugus lanioides	37.3					15.3						31.6	15.8			
Lipaugus vociferans	21.5	1.5		6.9						11.8		36.3			1.2	21.0
Lurocalis semitorquatus	33.3	27.1		11.7						4.6		6.5			15.9	0.8
Machaeropterus regulus	47.5		4.8			11.4				0.0		35.8			0.1	0.4
Mackenziaena leachii	10.1				15.3		17.2	28.5	1.8	2.1					9.8	15.1
Mackenziaena severa	21.1				4.5			19.1	2.7	1.4		26.6			24.6	
Malacoptila striata	19.9	43.5				5.8			2.3			4.6			22.6	1.3
Manacus manacus	50.4		4.5	17.0						0.1		0.1			15.7	12.2
Megascops atricapilla	24.3				1.9			1.4	0.6					27.9	42.4	1.4
Melanerpes flavifrons	1.9		54.6	10.6						4.3		4.3			22.5	1.8
Micrastur mintoni			18.3	6.9		3.5				6.4		32.1			7.3	25.5
Micrastur ruficollis	26.9	14.0		17.2						3.6		3.1			33.5	1.5
Micrastur semitorquatus	28.2	21.5		2.0						6.8		20.0			19.7	1.7
Mionectes oleagineus	34.7	7.2		11.5						12.1		28.8			4.7	1.0
Mionectes rufiventris	13.5	26.9			0.0			30.7	1.1	0.7					27.0	
Monasa morphoeus	3.7	2.5		0.8						0.6		41.7			26.0	24.8
Myiarchus ferox	20.2	26.7		1.7						1.3		2.6			47.5	0.0
Myiarchus tuberculifer		8.4		1.3								40.5			43.8	6.0
Myiobius atricaudus	28.0	5.6		25.5						1.4		9.9			27.2	2.4
Myiobius barbatus	33.3	28.7		3.7						13.5		4.6			14.9	1.3
Myiopagis caniceps	16.0	41.3		15.8						0.1		4.4			22.1	0.2
Myiornis auricularis	19.0					19.6				7.9				22.8	14.0	16.7
Myiothlypis rivularis	29.7	36.6		7.4						5.8		6.7			9.2	4.7
Myrmoderus loricatus		24.7	18.3		7.7			32.8	1.8						5.3	9.5
Myrmotherula axillaris	68.5	0.2		0.0						3.5		11.5			5.0	11.3
Myrmotherula luctuosa		0.5		44.2					47.5		0.2					7.6

Myrmotherula minor		47.6		31.9					2.4		9.5				8.5	0.0
Myrmotherula urosticta		7.5	7.5		73.2	2.5			9.1						0.2	0.0
Nemosia pileata	34.4	12.0		1.4						13.0		16.6			15.2	7.4
Neomorphus geoffroyi	30.7	9.3		17.2						23.4		1.6			13.2	4.5
Neopelma aurifrons	19.2	13.6				59.4				3.2					0.5	4.1
Notharchus swainsoni	26.7	45.2			7.0			6.1	7.4	1.7					5.9	
Nyctibius aethereus	8.3		0.3	0.7						0.7		48.3			40.2	1.5
Nyctibius grandis	44.3	0.9		10.4						6.9		1.3			12.9	23.3
Nyctibius griseus	28.6	9.7		9.1						3.5		17.7			27.6	3.8
Nyctiphrynus ocellatus	6.7	23.0		9.3						1.1		8.7			49.8	1.4
Nystalus maculatus	34.2	0.8		11.8					25.5		18.8				3.1	5.9
Odontophorus capueira	28.4				4.1			17.3		1.3		23.7			21.1	4.2
Orchesticus abeillei	3.6	73.1				6.5			1.5			3.6			10.7	1.0
Oxyruncus cristatus	18.8	44.1		26.6						1.1		4.4			4.9	0.1
Pachyramphus castaneus	7.9	31.4		28.9						0.3		12.5			17.4	1.6
Pachyramphus marginatus	53.2	12.5		1.4						2.5		24.5			5.1	0.7
Pachyramphus polychopterus	40.0	17.5		16.0						2.8		8.9			10.7	4.2
Panyptila cayennensis	43.9	8.3		18.7						11.2		4.5			11.7	1.6
Patagioenas cayennensis	28.5	8.0		24.6						2.4		14.9			19.0	2.7
Patagioenas picazuro	20.2	38.6		13.8							8.1				14.3	5.1
Patagioenas plumbea	20.0	6.1		30.8						0.0		20.3			22.7	0.1
Patagioenas speciosa	25.2	15.5		23.7						19.0		9.1			6.0	1.6
Penelope obscura	7.1	46.3		21.6						0.8		10.3			13.6	0.3
Penelope superciliaris	7.4			53.2					5.4		8.7				10.5	14.8
Phaethornis eurynome	26.4				5.5			29.1	1.8	2.0		9.0			24.2	2.0
Phaethornis idaliae		38.8	25.7	14.6					8.1							12.8
Phaethornis ruber	60.5	15.6		0.8						7.3		9.0			4.6	2.2
Phaethornis squalidus	8.4	65.1		14.8						0.6		2.1			8.7	0.3
Pheugopedius genibarbis	18.4	59.1		2.3						1.9		0.0			9.0	9.2
Philydor atricapillus	56.1				0.0		10.5	0.4	0.2			6.8			26.1	
Philydor rufum	6.4	31.4		31.0						0.3		8.6			21.7	0.5
Phyllomyias burmeisteri	11.1	34.6		27.9						0.4		0.6			25.2	0.2
Phyllomyias fasciatus	16.9					40.8			1.3					5.5	26.3	9.3
Phyllomyias griseocapilla					7.5	4.9						46.7	41.0			
Phyllomyias virescens	3.9	43.5		47.3							1.1				4.0	0.1
Phylloscartes beckeri		0.0	0.0	91.9	8.1					0.0						
Phylloscartes oustaleti	53.4					7.9				1.4					33.9	3.4
Phylloscartes ventralis	12.7	31.5		19.2							30.3				6.3	
Piaya cayana	30.9	4.9		16.2						4.7		7.3			32.9	3.2

Piculus aurulentus	32.9				2.3	6.1	41.2	10.0	4.5	2.5				0.7	
Piculus flavigula	77.9	11.3		0.0						1.7		3.9		3.4	1.9
Picumnus albosquamatus	11.5	7.3				2.0				17.3		18.7		30.2	13.1
Picumnus exilis	60.2		4.1	16.3						0.4		1.9		10.1	7.1
Pionopsitta pileata	4.7		38.6			11.4				2.8		8.6		30.6	3.4
Pionus maximiliani	14.0	41.3		13.6						3.5		2.7		19.1	5.8
Piprites chloris	4.1	1.4		2.3						3.4		88.6		0.1	0.2
Platyrinchus leucoryphus	48.3	48.1			1.8		0.2		0.0					1.6	
Platyrinchus mystaceus	11.3	31.6		38.1						0.0		5.9		12.9	0.3
Poecilotriccus fumifrons	34.9	31.4		5.4		20.2						0.1	6.2	1.8	
Poecilotriccus plumbeiceps	29.2	26.5		21.8								1.1		21.3	0.1
Primolius maracana	1.3	55.8		16.0						0.0		15.4		4.9	6.5
Procnias nudicollis	12.2	26.5		23.0		1.7					1.5			33.0	2.0
Psarocolius decumanus	50.2	5.5		17.2						1.6		4.3		20.9	0.5
Pseudastur polionotus	41.3			44.4									8.5		5.8
Pseudopipra pipra	48.1	0.5		6.7						0.2		41.2		0.7	2.5
Pseudoseisura cristata	32.2	16.1	1.2			0.0				34.9		3.6		10.6	1.4
Psilorhamphus guttatus	2.5	54.7		17.9		6.3			1.0					17.6	
Psittacara leucophthalmus	8.0	35.3		10.4						1.9		2.1		40.5	1.8
Pteroglossus aracari	64.8	9.4		1.4						6.4		3.9		12.0	2.1
Pteroglossus bailloni	2.0			36.5						10.1		16.5		17.7	17.3
Pulsatrix koeniswaldiana	17.4			17.1						2.8			19.4	43.3	
Pulsatrix perspicillata		46.2		5.1							8.1	1.0		27.0	12.6
Pyriglena leucoptera	8.7	44.9		28.7						0.1		0.3		14.9	2.4
Pyrrhura cruentata		36.3	3.7		1.1			3.3	0.9			52.4		2.3	
Pyrrhura frontalis	2.8	43.8		19.8						2.9		13.9		15.9	0.8
Pyrrhura leucotis	2.7	39.2		29.0						9.0		18.6		1.4	
Ramphastos dicolorus	16.0	24.0		30.2		4.1					3.5			17.0	5.2
Ramphastos vitellinus	42.0	3.5		1.1						12.9		13.8		13.6	13.2
Ramphocaenus melanurus	73.7	5.3		2.2						15.3		0.0		0.1	3.3
Ramphodon naevius					1.9	0.1				1.1		39.2		50.0	7.6
Ramphotrigon megacephalum	4.3	25.7		4.4						0.3		16.9		48.4	0.0
Rhopias gularis	31.8					2.9						36.0	29.3		
Rhynchocyclus olivaceus	62.2	13.2		4.4						0.7		17.4		1.8	0.4
Rhytipterna simplex	53.4	8.7		0.0						11.7		23.4		1.2	1.5
Rupornis magnirostris	29.6	25.1		10.9						2.2		9.0		18.9	4.2
Saltator fuliginosus	24.6							26.3		1.2		7.4		38.9	1.6
Saltator similis	15.3	43.7		15.1						0.6			14.3	8.7	2.3
Sarcoramphus papa	54.9	0.0		0.0						28.9		0.9		15.1	0.2

Schiffornis turdina	34.6	14.6		6.6						11.3		22.9			9.3	0.6
Schiffornis virescens	6.2	34.5			0.9			41.1		1.3					12.6	3.3
Sclerurus caudacutus	20.4	9.5		2.9						4.1		39.5			23.1	0.5
Sclerurus mexicanus	9.7	23.5		24.0						29.4		4.8			5.0	3.6
Sclerurus scansor	26.5				2.2			45.4	1.3			7.3	0.7		14.6	2.0
Scytalopus speluncae	34.0				11.9			38.7		10.5		4.8				
Selenidera maculirostris	11.9			5.7		4.8	48.5				1.4				22.5	5.3
Setophaga pitiayumi	16.9	27.7		21.5								11.4			19.6	2.9
Sirystes sibilator	7.7		50.5	15.1						0.3		0.1			16.4	9.9
Sittasomus griseicapillus	19.6	44.9		12.6						0.1		0.1			19.9	2.9
Spizaetus melanoleucus	54.9	6.8		8.4						0.5		5.5			22.0	1.9
Spizaetus ornatus	39.1	8.7		11.6						15.7		9.9			13.0	2.0
Spizaetus tyrannus	39.9	9.8		16.9						4.3		9.8			18.4	1.0
Strix hylophila	0.5	3.8		35.3	0.1	3.2	41.4		9.2						6.6	
Synallaxis cinerea			26.1			38.4			9.7		25.9					
Synallaxis ruficapilla	13.3				12.4			35.6	4.4			18.8			13.1	2.3
Syndactyla rufosuperciliata	25.0	21.8		11.4							23.6	6.7			8.3	3.2
Tangara brasiliensis		66.7		13.5							19.8					
Tangara cayana	9.9		24.9	5.6						5.9		22.2			5.5	26.0
Tangara cyanocephala	31.1		29.6			6.2				2.8		2.0			26.9	1.4
Tangara cyanoptera	18.9	38.2		27.7						0.1		1.0			10.3	3.8
Tangara cyanoventris					6.4	66.6				0.4		3.9			20.6	2.2
Tangara desmaresti					11.0	22.1			1.7			21.6			37.2	6.4
Tangara ornata					9.1	14.4			4.3			21.5			43.3	7.4
Tangara palmarum	45.9	5.8		23.1						21.5		0.3			0.0	3.4
Tangara sayaca	16.1			32.2	3.3				0.6			29.5			18.4	0.0
Tangara seledon	36.2			0.6			33.5				0.2	2.6			19.3	7.7
Taraba major	21.1	20.0		10.8							0.0	18.1			29.6	0.3
Terenura maculata	35.7	43.6			0.4			3.0	5.0	1.1					11.1	
Tersina viridis	27.3	1.9		24.3						2.9		3.6			39.4	0.6
Thalurania glaucopis	18.4					21.5			6.8					6.4	37.1	9.8
Thamnomanes caesius	22.9	2.1		6.7						2.1		23.8			5.0	37.4
Thamnophilus ambiguus	39.6		9.1			4.5				6.4		36.8				3.6
Thamnophilus caerulescens	7.0	66.9		10.6						1.4		1.0			12.7	0.4
Thamnophilus pelzelni	15.1	2.8				12.7			17.6			12.8			13.4	25.5
Thlypopsis sordida	13.6	32.3		7.8						1.5		4.3			31.9	8.6
Thripophaga macroura		22.2	10.0	16.7					1.4		49.8					
Tinamus solitarius		33.4		19.3	7.1					1.4		23.6			12.1	3.0
Tityra cayana	25.6	18.9		0.3						2.3		50.1			2.7	0.0

Tityra inquisitor	23.8	7.9		5.2					22.4		8.6			23.1	9.0
Todirostrum poliocephalum	10.7	27.1				13.6		1.8					6.8	34.4	5.5
Tolmomyias flaviventris	62.2	0.9		4.3					12.5		1.4			15.7	3.0
Tolmomyias poliocephalus	25.5	0.3		0.0					3.5		33.8			0.0	36.8
Tolmomyias sulphurescens	23.9	19.6		11.2					5.1		11.7			24.0	4.5
Touit surdus		8.7				3.5		38.4			12.0				37.3
Trichothraupis melanops	11.8	42.8		22.0					0.2	8.0				13.9	1.3
Triclaria malachitacea	18.6		24.8	21.9					0.8		4.0			24.2	5.8
Trogon collaris	18.4	4.3		38.1					3.9		10.4			18.0	7.0
Trogon surrucura	15.3				10.3		23.0	4.6						25.2	21.6
Trogon viridis	60.0	0.9		1.5					1.7		28.1			0.1	7.7
Turdus albicollis	13.7	19.8		17.8					4.0		33.5			10.7	0.5
Turdus flavipes	16.4	15.3		59.5					0.6		0.9			5.3	2.0
Turdus fumigatus	67.9		6.9			0.9			0.9		8.3			13.7	1.4
Turdus leucomelas	15.4	45.3		25.5					1.5		3.4			8.7	0.3
Veniliornis affinis	6.4	12.8		0.0					6.9		71.0			2.9	0.0
Veniliornis maculifrons	1.1	14.9	64.3			12.5			0.4		3.4			2.6	0.8
Veniliornis passerinus	20.9	41.7		2.2					0.0		0.0			23.7	11.5
Xenops minutus	39.9	15.9		18.7							7.4			12.2	5.9
Xenops rutilus	5.0		25.0			40.7			0.6		2.0			22.6	4.1
Xiphocolaptes albicollis	31.0				6.7		40.1	3.8	3.0					15.2	0.2
Xipholena atropurpurea		33.9	6.0		36.7	2.5					9.6	6.9		4.5	
Xiphorhynchus fuscus	5.5		34.3	24.4					1.5		1.4			32.5	0.4
Xiphorhynchus guttatus	23.6	33.0		8.4					9.5		12.2			5.4	7.8

Table S3. Functional traits of the forest bird species within the Central Corridor of the Atlantic Forest in Brazil.

Species	Baseline suitable area (km^2)	Mean elevation	Forest dependency	Primary diet	Body mass	HWI	ESI	Mean clutch size	Bill shape
Amazona amazonica	110656	300	Medium	Fruit	370.0	28.2	0.7	3.5	-1.8
Amazona farinosa	31861	800	Low	Seed	650.5	27.9	1.1	3.0	-2.1
Amazona rhodocorytha	108823	450	High	Fruit	474.3	29.9	1.5	4.0	-1.9
Amazona vinacea	40648	1100	High	Seed	254.0	31.6	1.2	3.0	-1.7
Anabacerthia lichtensteini	21564	400	High	Invertebrate	21.0	17.5	2.0	2.0	0.1
Aramides saracura	44547	500	Medium	Invertebrate	540.0	11.7	1.1	4.5	0.6
Asio stygius	117996	1500	Medium	Vertebrate	587.3	41.6	1.1	2.5	-0.2
Attila spadiceus	92549	900	Medium	Invertebrate	37.7	14.8	0.7	3.0	0.0
Automolus leucophthalmus	76653	500	High	Invertebrate	31.5	17.4	1.7	3.5	0.3
Batara cinerea	75308	1300	Medium	Invertebrate	127.5	6.6	1.1	2.5	0.2
Brotogeris tirica	67211	600	Medium	Fruit	63.0	35.1	1.1	4.0	-0.8
Buteogallus lacernulatus	96479	450	High	Vertebrate	96.0	29.6	1.7	1.0	-0.5
Cacicus cela	113707	450	Medium	Invertebrate	87.6	27.2	0.6	2.5	0.3
Cacicus haemorrhous	117996	450	Medium	Invertebrate	73.6	25.0	0.9	2.5	0.2
Campephilus robustus	19958	1100	High	Invertebrate	262.0	20.1	1.7	3.0	1.0
Campylorhamphus falcularius	35648	800	Medium	Invertebrate	39.5	14.0	1.4	2.0	3.9
Campylorhamphus trochilirostris	116130	600	Medium	Invertebrate	42.5	15.1	1.0	2.0	3.3
Campylorhynchus turdinus	115300	550	High	Invertebrate	33.5	12.9	1.4	3.5	0.6
Cantorchilus longirostris	99019	450	Medium	Invertebrate	20.5	10.6	1.2	2.5	0.7
Capsiempis flaveola	117996	750	Low	Invertebrate	8.0	12.9	0.9	2.0	-0.2
Carpornis cucullata	33633	1000	High	Fruit	76.2	19.8	1.4	1.5	-0.2
Carpornis melanocephala	70283	250	Medium	Fruit	64.2	21.1	1.2	1.0	-0.2
Celeus flavescens	108865	600	Medium	Invertebrate	137.5	16.2	0.8	3.0	0.5
Celeus torquatus	67124	300	High	Invertebrate	121.0	20.5	1.1	3.5	0.8
Ceratopipra rubrocapilla	88512	250	High	Fruit	13.5	19.7	1.4	2.0	-0.2
Chaetura cinereiventris	116169	900	Medium	Invertebrate	17.0	67.0	2.0	3.0	-0.2
Chamaeza campanisona	116880	1650	High	Invertebrate	88.0	14.2	1.2	3.0	0.1
Chamaeza meruloides	45033	850	Medium	Invertebrate	71.2	13.3	1.7	2.5	-0.1
Chiroxiphia caudata	21299	750	High	Fruit	25.6	17.6	1.2	2.0	-0.1
Chiroxiphia pareola	111468	375	High	Fruit	20.1	12.2	1.4	2.0	-0.3
Chlorestes cyanus	117996	725	Medium	Nectar	3.2	62.1	1.1	2.0	0.8
Chlorestes notata	94989	250	Low	Nectar	3.8	67.0	1.1	2.0	0.8
Chlorophanes spiza	81536	800	Medium	Fruit	18.8	24.7	0.8	2.5	0.1
Chlorophonia cyanea	71247	1200	Medium	Fruit	13.0	26.7	1.2	2.5	-0.2
Ciccaba huhula	115351	250	Medium	Invertebrate	405.3	28.0	1.4	1.5	-0.3

Ciccaba virgata	22071	1250	Medium	Invertebrate	312.0	20.8	1.1	2.0	-0.5
Cichlocolaptes leucophrus	38652	750	High	Invertebrate	50.0	19.9	2.0	3.5	0.5
Cichlopsis leucogenys	104828	950	High	Invertebrate	51.0	27.9	1.7	3.0	0.0
Claravis pretiosa	100418	650	Medium	Seed	73.8	26.7	1.1	2.0	0.2
Clytolaema rubricauda	26384	750	Medium	Nectar	7.3	63.0	1.2	2.0	1.0
Colaptes melanochloros	117668	625	Medium	Invertebrate	115.0	13.3	1.0	4.0	0.3
Colonia colonus	117996	600	Medium	Invertebrate	16.5	18.9	1.5	2.5	-0.3
Conirostrum speciosum	117996	650	Low	Invertebrate	8.5	22.1	1.1	3.0	0.0
Conopias trivirgatus	117834	150	High	Invertebrate	21.0	19.1	2.0	2.0	-0.1
Conopophaga lineata	37408	1450	Medium	Invertebrate	21.5	11.0	0.8	2.5	0.0
Conopophaga melanops	86003	400	Medium	Invertebrate	20.1	13.4	1.7	2.0	-0.1
Corythopis delalandi	14464	400	High	Invertebrate	16.0	13.4	1.7	2.5	0.1
Cotinga maculata	96206	150	High	Fruit	65.0	26.0	1.2	1.5	-0.2
Cranioleuca pallida	32650	1425	High	Invertebrate	14.5	17.0	1.7	2.5	0.2
Crax blumenbachii	60435	250	Medium	Fruit	3500.0	9.7	0.7	2.0	-1.0
Crotophaga major	109630	250	Medium	Invertebrate	184.6	23.7	0.6	3.5	-0.3
Crypturellus noctivagus	117391	150	Medium	Seed	562.0	24.1	0.9	3.5	0.4
Crypturellus obsoletus	117955	1500	High	Seed	443.4	22.4	1.4	3.5	0.4
Crypturellus soui	103083	750	Medium	Fruit	216.2	25.4	0.7	2.5	0.3
Crypturellus variegatus	92162	700	High	Seed	378.0	32.2	1.2	1.0	0.6
Cyanerpes cyaneus	117749	600	Medium	Fruit	14.7	26.0	0.9	2.5	0.4
Cyanoloxia brissonii	117621	450	Low	Seed	27.5	14.8	1.2	2.5	-0.8
Cyclarhis gujanensis	117996	1250	Medium	Invertebrate	28.5	14.8	0.9	2.5	-0.4
Cypseloides senex	83116	500	Medium	Invertebrate	83.0	61.5	1.5	1.5	-0.3
Dacnis cayana	117996	1000	Medium	Fruit	13.0	24.7	0.8	2.5	0.0
Dacnis nigripes	50120	425	Medium	Fruit	13.4	29.0	0.8	2.5	0.1
Dendrocincla turdina	86394	625	Medium	Invertebrate	38.0	19.4	1.5	2.0	0.3
Dendrocolaptes platyrostris	117975	650	Medium	Invertebrate	62.1	16.8	0.8	3.5	0.7
Dendroplex picus	105305	300	Low	Invertebrate	38.5	17.8	0.9	2.5	0.7
Diopsittaca nobilis	113143	700	Low	Seed	148.5	45.5	0.8	3.0	-2.3
Discosura langsdorffi	115984	200	High	Nectar	3.2	64.1	1.7	2.0	0.7
Drymophila ferruginea	68603	625	High	Invertebrate	10.5	7.5	1.4	2.0	0.0
Drymophila genei	18011	1675	High	Invertebrate	11.4	11.7	1.4	2.0	0.1
Drymophila ochropyga	24730	1125	High	Invertebrate	10.5	8.8	1.4	2.0	0.1
Drymophila squamata	89435	150	Medium	Invertebrate	10.8	12.0	1.5	2.0	0.1
Dysithamnus mentalis	117996	1250	Medium	Invertebrate	14.3	11.1	1.1	2.0	0.0
Dysithamnus plumbeus	117996	300	High	Invertebrate	20.5	14.6	1.7	2.0	0.1
Dysithamnus stictothorax	103918	625	Medium	Invertebrate	15.5	8.1	1.2	2.0	0.0
Elaenia obscura	60129	2350	High	Invertebrate	21.9	15.4	1.2	2.0	0.0

Eleoscytalopus indigoticus	16568	650	Medium	Invertebrate	14.8	7.6	1.5	2.0	0.1
Euphonia chlorotica	117996	600	Low	Fruit	11.2	24.2	1.2	3.5	-0.3
Euphonia cyanocephala	113931	1250	Medium	Fruit	15.5	28.9	1.1	2.5	-0.3
Euphonia pectoralis	50321	775	Medium	Fruit	15.8	21.8	1.2	3.5	-0.3
Euphonia violacea	117996	550	Medium	Fruit	14.8	27.6	1.0	4.0	-0.4
Euphonia xanthogaster	73606	1125	Medium	Fruit	12.5	22.4	1.1	4.0	-0.4
Falco deiroleucus	102612	750	High	Vertebrate	500.0	39.9	1.4	3.0	-0.9
Falco rufigularis	117655	850	High	Vertebrate	169.3	40.3	1.7	3.0	-0.8
Florisuga fusca	73948	700	Medium	Nectar	8.0	64.8	1.4	2.0	1.0
Formicarius colma	116291	250	High	Invertebrate	44.3	19.0	1.5	2.0	0.2
Formicivora serrana	31714	450	Medium	Invertebrate	11.4	9.8	1.3	1.5	0.1
Forpus xanthopterygius	117996	600	Medium	Fruit	28.0	27.8	0.9	5.5	-1.0
Furnarius figulus	114928	450	Low	Invertebrate	28.0	17.4	1.3	2.0	0.3
Galbula ruficauda	116950	450	Medium	Invertebrate	23.0	21.1	1.2	3.0	2.5
Geotrygon montana	117955	750	Medium	Seed	127.8	27.1	0.8	2.0	0.2
Geotrygon violacea	117996	825	Medium	Seed	121.5	33.3	1.2	2.0	0.3
Glaucidium minutissimum	113871	500	High	Invertebrate	48.5	21.1	1.7	3.0	-0.6
Glaucis dohrnii	59425	250	High	Nectar	6.9	46.3	1.7	2.0	1.3
Glaucis hirsutus	105801	500	Low	Nectar	6.8	59.8	0.9	2.0	1.5
Glyphorynchus spirurus	91829	600	Medium	Invertebrate	15.8	23.9	1.0	2.0	0.0
Grallaria varia	117934	700	Medium	Invertebrate	110.9	8.4	1.2	2.0	-0.1
Habia rubica	117996	600	High	Invertebrate	32.5	17.6	1.2	2.5	-0.4
Harpagus bidentatus	91872	750	Medium	Vertebrate	194.5	29.6	1.7	2.0	-0.9
Harpia harpyja	105398	400	High	Vertebrate	6350.0	47.9	2.0	2.5	-0.7
Heliomaster squamosus	56028	400	Medium	Nectar	5.8	62.2	1.4	2.0	1.6
Heliothryx auritus	111145	200	High	Nectar	5.2	66.0	1.7	2.0	0.9
Hemithraupis flavicollis	117996	500	Medium	Invertebrate	13.0	21.0	1.1	2.5	-0.2
Hemithraupis ruficapilla	47393	750	Medium	Invertebrate	12.0	20.3	1.1	2.5	0.0
Hemitriccus diops	35180	650	High	Invertebrate	11.5	11.5	1.4	2.0	0.0
Hemitriccus furcatus	95633	600	Medium	Invertebrate	9.4	10.3	1.3	2.0	-0.2
Hemitriccus nidipendulus	61576	450	Medium	Invertebrate	7.6	8.4	1.5	2.0	0.0
Hemitriccus striaticollis	116831	350	Medium	Invertebrate	9.4	10.2	1.4	2.0	0.0
Herpetotheres cachinnans	117996	750	Low	Vertebrate	652.3	18.9	1.1	1.5	-1.2
Herpsilochmus rufimarginatus	117996	550	Medium	Invertebrate	10.5	7.3	1.4	2.0	0.1
Hylatomus lineatus	117996	1050	Low	Invertebrate	200.0	21.7	0.8	3.0	0.6
Hylocharis sapphirina	115951	350	Medium	Nectar	4.2	64.2	1.2	2.0	0.8
Hylophilus poicilotis	12474	500	Medium	Invertebrate	10.5	12.6	1.2	2.5	0.0
Hylophilus thoracicus	115971	350	Medium	Invertebrate	12.5	9.6	1.0	2.5	0.0
Hypoedaleus guttatus	14794	450	High	Invertebrate	41.5	7.6	1.4	2.0	-0.2

Icterus pyrrhopterus	117996	850	Low	Invertebrate	31.9	17.3	0.8	3.5	0.1
Ictinia plumbea	117996	750	Medium	Invertebrate	253.3	41.8	1.4	1.5	-0.8
Ilicura militaris	70478	850	High	Fruit	14.6	22.6	1.4	2.5	-0.1
Iodopleura pipra	72040	500	Medium	Fruit	10.0	24.1	1.2	1.0	-0.3
Laniisoma elegans	115658	650	High	Fruit	47.4	26.0	1.4	3.0	0.1
Laniocera hypopyrra	114282	250	Medium	Invertebrate	47.0	23.5	1.2	2.0	0.0
Legatus leucophaius	117996	500	Medium	Fruit	22.5	25.5	1.1	3.0	-0.3
Lepidocolaptes squamatus	59388	800	Medium	Invertebrate	27.0	23.8	1.4	3.0	1.0
Leptodon cayanensis	117996	500	High	Invertebrate	506.8	18.8	1.1	1.5	-0.5
Leptopogon amaurocephalus	117996	650	Medium	Invertebrate	11.7	18.7	1.2	2.5	0.0
Leptotila rufaxilla	117996	275	Medium	Seed	149.0	24.5	1.1	1.5	0.3
Leucochloris albicollis	9133	500	Medium	Nectar	5.5	62.8	1.1	2.0	1.2
Lipaugus lanioides	96445	750	High	Fruit	97.5	17.0	1.7	1.0	-0.1
Lipaugus vociferans	100666	250	High	Fruit	77.8	16.9	1.2	1.0	0.0
Lurocalis semitorquatus	116954	850	Medium	Invertebrate	82.3	56.8	1.3	1.0	0.0
Machaeropterus regulus	111849	100	High	Fruit	9.5	23.7	1.4	1.0	-0.1
Mackenziaena leachii	3173	1075	Medium	Invertebrate	60.0	5.0	1.1	2.0	0.0
Mackenziaena severa	8352	700	Medium	Invertebrate	66.0	9.3	1.1	2.0	0.0
Malacoptila striata	76872	1050	Medium	Invertebrate	43.0	20.6	1.5	3.0	0.2
Manacus manacus	117754	500	Medium	Fruit	16.5	15.9	1.2	2.0	-0.2
Megascops atricapilla	75563	300	Medium	Invertebrate	140.0	25.0	1.1	2.5	-0.6
Melanerpes flavifrons	101009	900	Medium	Fruit	56.5	26.6	0.9	3.0	0.4
Micrastur mintoni	49370	300	High	Vertebrate	210.8	21.8	2.0	2.5	-0.7
Micrastur ruficollis	117996	1250	Medium	Vertebrate	212.5	21.8	1.2	4.0	-0.7
Micrastur semitorquatus	117996	450	Medium	Vertebrate	681.3	19.4	1.4	2.5	-0.8
Mionectes oleagineus	106581	600	Medium	Invertebrate	13.0	17.1	1.7	3.0	-0.1
Mionectes rufiventris	34454	500	High	Invertebrate	14.0	13.3	1.4	3.0	0.0
Monasa morphoeus	116647	150	Medium	Invertebrate	82.0	21.9	0.9	2.5	0.4
Myiarchus ferox	117996	250	Medium	Invertebrate	27.9	14.2	1.0	2.5	0.0
Myiarchus tuberculifer	29155	900	Medium	Invertebrate	20.7	18.8	0.9	3.5	0.0
Myiobius atricaudus	97831	500	Medium	Invertebrate	10.0	13.0	1.4	2.0	-0.1
Myiobius barbatus	117975	300	High	Invertebrate	9.5	16.8	1.5	2.0	-0.1
Myiopagis caniceps	117996	550	High	Invertebrate	11.8	18.7	1.1	2.0	-0.1
Myiornis auricularis	117434	650	Medium	Invertebrate	5.0	10.2	1.5	2.5	0.0
Myiothlypis rivularis	111756	500	Medium	Invertebrate	14.0	15.3	1.5	2.0	0.0
Myrmoderus loricatus	70456	1000	High	Invertebrate	15.5	9.8	1.4	2.0	0.2
Myrmotherula axillaris	98832	700	High	Invertebrate	7.8	14.8	1.5	2.0	0.1
Myrmotherula luctuosa	92422	400	High	Invertebrate	8.5	14.6	2.0	2.0	0.1
Myrmotherula minor	92571	250	High	Invertebrate	6.4	10.4	1.7	2.0	0.0

Myrmotherula urosticta	45587	250	High	Invertebrate	8.4	10.9	2.0	2.0	0.1
Nemosia pileata	117996	300	Low	Fruit	16.4	20.2	0.6	2.0	-0.1
Neomorphus geoffroyi	117975	600	Medium	Invertebrate	352.8	6.3	0.8	1.5	0.6
Neopelma aurifrons	117975	500	High	Fruit	14.0	21.3	1.1	2.0	-0.1
Notharchus swainsoni	41958	450	High	Invertebrate	73.8	29.6	1.7	2.5	-0.3
Nyctibius aethereus	112774	375	High	Invertebrate	363.5	38.0	1.7	1.0	0.2
Nyctibius grandis	79833	200	Medium	Invertebrate	490.0	44.0	0.9	1.0	0.8
Nyctibius griseus	117996	900	Medium	Invertebrate	173.5	43.8	1.4	1.0	0.3
Nyctiphrynus ocellatus	104934	675	High	Invertebrate	37.8	35.1	2.0	2.0	0.1
Nystalus maculatus	88904	1000	Low	Invertebrate	35.0	17.5	0.8	2.5	0.5
Odontophorus capueira	12240	800	High	Fruit	426.5	10.5	1.5	7.5	-0.7
Orchesticus abeillei	12032	1250	Medium	Invertebrate	31.5	19.4	1.4	2.0	-0.6
Oxyruncus cristatus	117996	750	High	Fruit	42.0	26.3	1.7	2.0	-0.1
Pachyramphus castaneus	117996	500	Medium	Invertebrate	17.3	18.3	1.1	3.5	-0.3
Pachyramphus marginatus	115690	250	High	Invertebrate	18.0	21.8	1.4	3.5	-0.3
Pachyramphus polychopterus	117996	950	Medium	Invertebrate	20.3	21.8	1.0	3.0	-0.4
Panyptila cayennensis	103446	750	Medium	Invertebrate	18.0	68.5	1.4	2.5	-0.2
Patagioenas cayennensis	117894	900	Medium	Fruit	212.8	35.1	1.0	1.5	0.3
Patagioenas picazuro	117873	550	Medium	Seed	402.0	37.6	0.8	1.5	0.3
Patagioenas plumbea	117815	1050	Medium	Fruit	201.5	34.9	1.2	1.5	0.3
Patagioenas speciosa	116272	700	Medium	Fruit	296.8	36.5	1.2	1.5	0.2
Penelope obscura	6896	1150	Medium	Fruit	1530.0	4.9	0.8	3.0	-0.3
Penelope superciliaris	116417	650	Medium	Fruit	1050.0	13.5	0.7	3.0	-0.2
Phaethornis eurynome	42504	1050	High	Nectar	4.9	60.6	1.7	2.0	2.1
Phaethornis idaliae	105346	150	High	Nectar	2.3	67.0	1.4	2.0	1.1
Phaethornis ruber	117975	450	Medium	Nectar	2.4	70.1	1.2	2.0	1.2
Phaethornis squalidus	81528	550	High	Nectar	3.0	59.8	1.7	2.0	1.2
Pheugopedius genibarbis	117996	750	Medium	Invertebrate	19.2	10.4	1.5	2.0	0.2
Philydor atricapillus	76540	525	High	Invertebrate	22.2	18.6	2.0	2.0	0.1
Philydor rufum	107156	1250	High	Invertebrate	30.5	19.8	1.7	2.5	0.2
Phyllomyias burmeisteri	104783	1300	High	Invertebrate	11.1	23.3	1.4	2.0	-0.1
Phyllomyias fasciatus	107899	650	High	Invertebrate	10.5	17.5	1.2	2.0	-0.2
Phyllomyias griseocapilla	39382	1300	Medium	Invertebrate	8.0	14.2	1.4	2.0	-0.2
Phyllomyias virescens	6131	500	High	Invertebrate	11.0	19.6	2.0	2.0	-0.1
Phylloscartes beckeri	51813	975	High	Invertebrate	8.3	16.8	2.0	2.5	0.0
Phylloscartes oustaleti	51843	700	High	Invertebrate	10.0	14.7	2.0	2.5	0.0
Phylloscartes ventralis	77095	1250	High	Invertebrate	9.0	14.9	1.2	3.0	0.0
Piaya cayana	117996	1100	Medium	Invertebrate	102.0	11.0	0.7	2.0	0.0
Piculus aurulentus	40731	1375	High	Invertebrate	45.0	20.4	1.5	3.0	0.3

Piculus flavigula	114767	250	Medium	Invertebrate	53.5	22.4	1.5	3.0	0.1
Picumnus albosquamatus	86081	1050	Medium	Invertebrate	10.0	12.5	1.5	3.0	0.0
Picumnus exilis	55321	950	Medium	Invertebrate	9.3	13.6	1.2	2.0	-0.1
Pionopsitta pileata	9690	1000	Medium	Fruit	109.0	35.8	1.7	2.0	-1.0
Pionus maximiliani	117147	750	Medium	Seed	263.0	35.2	1.1	4.0	-1.8
Piprites chloris	116554	500	High	Invertebrate	18.0	25.3	1.4	4.0	-0.2
Platyrinchus leucoryphus	67562	500	High	Invertebrate	17.0	22.4	2.0	2.0	-0.4
Platyrinchus mystaceus	117996	1300	Medium	Invertebrate	9.8	15.5	1.3	2.0	-0.4
Poecilotriccus fumifrons	117996	200	Medium	Invertebrate	6.6	12.4	1.7	2.5	0.0
Poecilotriccus plumbeiceps	108481	1750	Medium	Invertebrate	5.7	9.4	1.5	2.5	0.1
Primolius maracana	89955	500	Medium	Fruit	256.0	35.4	1.2	3.0	-2.3
Procnias nudicollis	83247	575	High	Fruit	171.5	24.0	2.0	1.5	0.0
Psarocolius decumanus	117996	500	Medium	Fruit	257.5	24.8	0.7	2.0	0.5
Pseudastur polionotus	55760	1000	High	Vertebrate	703.7	31.3	2.0	1.0	-0.7
Pseudopipra pipra	95075	800	High	Fruit	12.8	17.3	1.7	2.0	-0.2
Pseudoseisura cristata	95820	275	Medium	Invertebrate	49.5	15.7	0.5	3.5	0.4
Psilorhamphus guttatus	284	650	Medium	Invertebrate	11.6	9.0	1.4	3.0	0.2
Psittacara leucophthalmus	117996	250	Medium	Fruit	159.0	41.5	0.6	3.5	-2.1
Pteroglossus aracari	117835	300	Medium	Fruit	251.0	15.6	0.7	3.0	1.6
Pteroglossus bailloni	18350	500	High	Fruit	149.2	14.5	1.0	2.5	0.6
Pulsatrix koeniswaldiana	75284	750	Medium	Vertebrate	492.0	25.6	1.4	2.0	-0.6
Pulsatrix perspicillata	41116	500	Medium	Vertebrate	896.3	28.1	1.1	2.0	-0.5
Pyriglena leucoptera	65579	625	Medium	Invertebrate	29.5	10.3	1.1	2.0	0.1
Pyrrhura cruentata	117935	200	High	Seed	75.9	40.2	1.7	3.0	-1.6
Pyrrhura frontalis	49246	700	Medium	Seed	83.0	40.3	0.9	4.0	-1.3
Pyrrhura leucotis	117996	300	Medium	Seed	75.9	41.4	1.5	7.0	-1.2
Ramphastos dicolorus	16069	800	Medium	Fruit	332.5	14.0	0.8	3.0	1.8
Ramphastos vitellinus	117128	500	High	Fruit	362.5	13.1	0.5	3.0	2.3
Ramphocaenus melanurus	115891	750	High	Invertebrate	8.9	8.1	1.5	2.0	0.8
Ramphodon naevius	59380	250	High	Nectar	7.2	58.6	1.7	2.0	1.7
Ramphotrigon megacephalum	117996	700	Medium	Invertebrate	14.0	14.6	1.7	2.0	-0.2
Rhopias gularis	49012	750	High	Invertebrate	11.0	11.0	1.7	2.0	0.1
Rhynchocyclus olivaceus	102691	300	High	Invertebrate	21.3	15.2	1.7	2.5	-0.5
Rhytipterna simplex	115890	400	High	Invertebrate	35.5	16.8	1.7	4.0	0.0
Rupornis magnirostris	117996	1250	Low	Vertebrate	265.8	28.0	0.9	2.0	-0.6
Saltator fuliginosus	83617	600	High	Seed	44.0	14.0	1.7	3.0	-0.9
Saltator similis	111334	600	Medium	Invertebrate	45.0	15.1	0.8	2.5	-0.6
Sarcoramphus papa	117735	750	High	Vertebrate	4000.0	37.6	1.4	1.5	-0.9
Schiffornis turdina	116773	750	High	Invertebrate	30.2	15.9	1.4	2.0	-0.1

Schiffornis virescens	28775	600	High	Invertebrate	25.2	15.7	1.2	2.0	0.0
Sclerurus caudacutus	117874	250	High	Invertebrate	38.0	17.4	1.7	2.0	0.5
Sclerurus mexicanus	97192	1000	High	Invertebrate	25.1	13.0	1.7	2.0	0.7
Sclerurus scansor	46659	800	High	Invertebrate	33.0	16.0	1.7	2.5	0.6
Scytalopus speluncae	25418	1750	High	Invertebrate	13.8	10.9	1.5	2.0	0.0
Selenidera maculirostris	68778	500	High	Fruit	165.0	14.8	1.1	3.0	0.0
Setophaga pitiayumi	117996	1250	Medium	Invertebrate	7.3	20.1	1.4	3.5	0.0
Sirystes sibilator	117996	700	High	Invertebrate	31.8	19.8	1.2	4.0	-0.1
Sittasomus griseicapillus	117996	750	Medium	Invertebrate	12.9	22.0	0.7	2.5	0.2
Spizaetus melanoleucus	117996	850	Low	Vertebrate	750.0	31.1	1.4	1.0	-0.7
Spizaetus ornatus	117996	900	High	Vertebrate	1019.0	17.2	1.5	1.0	-0.7
Spizaetus tyrannus	111967	1000	Medium	Vertebrate	1035.0	17.9	1.7	2.0	-0.6
Strix hylophila	5613	500	Medium	Vertebrate	315.0	22.2	1.4	2.5	-0.7
Synallaxis cinerea	70388	875	Medium	Invertebrate	18.5	7.1	1.5	3.0	0.0
Synallaxis ruficapilla	10230	700	Medium	Invertebrate	14.0	11.6	1.5	2.5	0.2
Syndactyla rufosuperciliata	108693	1900	Medium	Invertebrate	27.5	15.0	1.4	3.0	0.2
Tangara brasiliensis	97882	250	Medium	Fruit	26.0	23.2	1.2	2.5	-0.2
Tangara cayana	109210	900	Low	Fruit	18.3	17.5	0.7	2.5	-0.3
Tangara cyanocephala	37744	500	Low	Fruit	18.5	21.3	1.1	3.0	-0.2
Tangara cyanoptera	32247	700	Medium	Fruit	43.5	25.0	1.2	2.5	-0.4
Tangara cyanoventris	29249	750	Medium	Fruit	18.0	19.1	1.4	3.0	-0.2
Tangara desmaresti	56969	1200	Medium	Fruit	20.3	20.0	0.9	2.5	-0.2
Tangara ornata	92278	875	Medium	Fruit	38.0	26.2	1.2	2.5	0.0
Tangara palmarum	117996	650	Medium	Fruit	37.5	21.9	1.0	2.0	-0.3
Tangara sayaca	117535	500	Low	Fruit	31.0	23.5	0.7	2.5	-0.4
Tangara seledon	89487	450	Medium	Fruit	18.0	22.4	1.2	3.0	-0.3
Taraba major	117996	500	Medium	Invertebrate	63.8	5.2	0.9	2.5	-0.1
Terenura maculata	68944	625	High	Invertebrate	6.5	8.2	1.7	2.0	0.2
Tersina viridis	117975	800	Medium	Fruit	30.5	29.1	1.1	3.5	-0.4
Thalurania glaucopis	98648	425	Medium	Nectar	4.8	63.1	1.2	2.0	1.0
Thamnomanes caesius	89914	300	High	Invertebrate	17.0	12.7	2.0	2.0	0.0
Thamnophilus ambiguus	117214	350	High	Invertebrate	23.4	9.7	1.7	2.0	0.0
Thamnophilus caerulescens	115094	500	Medium	Invertebrate	19.5	9.7	0.7	2.5	-0.1
Thamnophilus pelzelni	83895	600	High	Invertebrate	18.0	9.7	1.5	2.5	-0.1
Thlypopsis sordida	117996	400	Medium	Invertebrate	16.5	15.8	0.8	2.5	-0.1
Thripophaga macroura	77025	500	Medium	Invertebrate	27.7	17.9	2.0	3.0	0.2
Tinamus solitarius	67609	600	High	Seed	1531.0	13.7	1.3	6.5	0.5
Tityra cayana	117975	350	Medium	Fruit	69.5	26.1	1.0	2.5	-0.4
Tityra inquisitor	113447	600	Medium	Fruit	51.9	26.5	1.4	2.5	-0.4

Todirostrum poliocephalum	48015	650	Medium	Invertebrate	5.6	12.5	1.3	2.5	0.0
Tolmomyias flaviventris	115810	400	Low	Invertebrate	13.3	16.2	0.9	2.5	-0.3
Tolmomyias poliocephalus	96296	300	Medium	Invertebrate	11.0	14.8	2.0	2.0	-0.2
Tolmomyias sulphurescens	117996	750	Medium	Invertebrate	14.9	15.7	1.0	2.5	-0.2
Touit surdus	78414	450	High	Fruit	51.0	40.9	2.0	3.5	-1.0
Trichothraupis melanops	81622	1350	Medium	Invertebrate	22.8	19.2	1.1	3.0	-0.2
Triclaria malachitacea	30976	750	Medium	Seed	112.5	30.5	1.1	3.0	-1.4
Trogon collaris	117996	1550	High	Invertebrate	57.2	38.4	1.2	2.5	-0.5
Trogon surrucura	76474	1000	High	Invertebrate	67.2	39.2	1.4	3.0	-0.7
Trogon viridis	112339	500	Medium	Fruit	89.3	34.6	0.7	2.5	-0.6
Turdus albicollis	117996	750	Medium	Invertebrate	62.3	21.3	1.2	2.5	0.1
Turdus flavipes	99574	1000	Medium	Fruit	63.5	25.9	1.1	2.5	0.1
Turdus fumigatus	81347	550	Medium	Invertebrate	69.0	21.1	1.1	2.5	0.2
Turdus leucomelas	117996	750	Medium	Invertebrate	62.5	22.4	0.8	3.0	0.2
Veniliornis affinis	117996	700	High	Invertebrate	38.0	20.7	1.1	3.0	0.2
Veniliornis maculifrons	48805	650	Medium	Invertebrate	38.7	22.8	1.4	3.0	0.3
Veniliornis passerinus	117996	650	High	Invertebrate	30.5	15.1	0.9	3.0	0.2
Xenops minutus	113942	500	High	Invertebrate	10.6	19.2	1.7	2.0	0.0
Xenops rutilus	117996	1495	High	Invertebrate	12.5	23.5	1.7	2.5	0.0
Xiphocolaptes albicollis	58399	750	Medium	Invertebrate	120.0	14.1	0.9	3.0	1.4
Xipholena atropurpurea	63211	450	High	Fruit	61.5	21.8	1.2	1.0	0.0
Xiphorhynchus fuscus	67076	600	Medium	Invertebrate	20.3	19.6	1.5	2.5	0.8
Xiphorhynchus guttatus	86946	400	Medium	Invertebrate	60.5	15.2	1.0	2.0	1.2

Table S4. Percentage change in suitable climate area between baseline and future scenarios for forest bird species within the Central Corridor of the Atlantic Forest in Brazil.

Species	2050 optimistic	2070 optimistic	2050 pessimistic	2070 pessimistic
Amazona amazonica	1%	1%	1%	1%
Amazona farinosa	22%	15%	29%	24%
Amazona rhodocorytha	5%	6%	6%	8%
Amazona vinacea	-43%	-47%	-53%	-76%
Anabacerthia lichtensteini	-63%	-71%	-95%	-99%
Aramides saracura	-35%	-41%	-43%	-62%
Asio stygius	-2%	-7%	-8%	-34%
Attila spadiceus	11%	15%	13%	17%
Automolus leucophthalmus	-14%	-15%	-15%	-29%
Batara cinerea	-16%	-20%	-18%	-42%
Brotogeris tirica	-8%	-14%	-16%	-38%
Buteogallus lacernulatus	3%	3%	6%	6%
Cacicus cela	-1%	-2%	-1%	-5%
Cacicus haemorrhous	0%	0%	0%	-1%
Campephilus robustus	-50%	-53%	-58%	-79%
Campylorhamphus falcularius	-67%	-72%	-71%	-84%
Campylorhamphus trochilirostris	1%	1%	1%	2%
Campylorhynchus turdinus	2%	2%	2%	2%
Cantorchilus longirostris	7%	5%	9%	5%
Capsiempis flaveola	0%	0%	0%	-3%
Carpornis cucullata	-27%	-33%	-36%	-55%
Carpornis melanocephala	0%	3%	4%	-2%
Celeus flavescens	-1%	-3%	-5%	-15%
Celeus torquatus	-3%	-2%	-13%	-16%
Ceratopipra rubrocapilla	1%	0%	0%	-3%

Chaetura cinereiventris	-7%	-11%	-9%	-26%
Chamaeza campanisona	-6%	-9%	-6%	-17%
Chamaeza meruloides	-45%	-57%	-55%	-74%
Chiroxiphia caudata	-59%	-56%	-66%	-76%
Chiroxiphia pareola	-4%	-5%	-5%	-9%
Chlorestes cyanus	0%	0%	0%	0%
Chlorestes notata	-2%	-2%	-1%	-5%
Chlorophanes spiza	-9%	-13%	-15%	-29%
Chlorophonia cyanea	-54%	-69%	-68%	-87%
Ciccaba huhula	-1%	-1%	0%	-1%
Ciccaba virgata	-24%	-24%	-36%	-50%
Cichlocolaptes leucophrus	-26%	-36%	-42%	-59%
Cichlopsis leucogenys	-31%	-47%	-47%	-67%
Claravis pretiosa	10%	11%	13%	15%
Clytolaema rubricauda	-59%	-61%	-70%	-89%
Colaptes melanochloros	0%	0%	0%	0%
Colonia colonus	0%	0%	0%	-2%
Conirostrum speciosum	0%	0%	0%	0%
Conopias trivirgatus	-1%	-1%	0%	-2%
Conopophaga lineata	-45%	-52%	-66%	-89%
Conopophaga melanops	-5%	-7%	-10%	-18%
Corythopis delalandi	-25%	-27%	-30%	-55%
Cotinga maculata	-3%	4%	7%	4%
Cranioleuca pallida	-41%	-61%	-64%	-82%
Crax blumenbachii	56%	70%	71%	87%
Crotophaga major	2%	2%	3%	4%
Crypturellus noctivagus	0%	-1%	0%	-2%
Crypturellus obsoletus	-3%	-5%	-4%	-17%
Crypturellus soui	-3%	-6%	-5%	-10%

Crypturellus variegatus	0%	0%	0%	-3%
Cyanerpes cyaneus	0%	-1%	-3%	-9%
Cyanoloxia brissonii	0%	0%	0%	0%
Cyclarhis gujanensis	0%	0%	0%	0%
Cypseloides senex	-47%	-54%	-56%	-73%
Dacnis cayana	0%	-1%	-2%	-16%
Dacnis nigripes	-40%	-39%	-46%	-69%
Dendrocincla turdina	-15%	-17%	-18%	-37%
Dendrocolaptes platyrostris	-1%	-3%	-5%	-20%
Dendroplex picus	3%	3%	4%	5%
Diopsittaca nobilis	0%	-1%	-2%	-17%
Discosura langsdorffi	-5%	-7%	-4%	-8%
Drymophila ferruginea	-22%	-33%	-34%	-58%
Drymophila genei	-45%	-52%	-54%	-72%
Drymophila ochropyga	-32%	-45%	-50%	-74%
Drymophila squamata	-1%	1%	1%	-6%
Dysithamnus mentalis	0%	0%	0%	-3%
Dysithamnus plumbeus	0%	0%	0%	0%
Dysithamnus stictothorax	-22%	-35%	-37%	-58%
Elaenia obscura	-56%	-65%	-67%	-80%
Eleoscytalopus indigoticus	-36%	-33%	-57%	-88%
Euphonia chlorotica	0%	0%	0%	0%
Euphonia cyanocephala	-16%	-24%	-22%	-47%
Euphonia pectoralis	-22%	-27%	-28%	-48%
Euphonia violacea	0%	-2%	-4%	-20%
Euphonia xanthogaster	-9%	-16%	-15%	-31%
Falco deiroleucus	-1%	-6%	-4%	-12%
Falco rufigularis	0%	0%	0%	0%
Florisuga fusca	-11%	-13%	-14%	-39%

Formicarius colma	0%	0%	0%	0%
Formicivora serrana	-22%	5%	-5%	-2%
Forpus xanthopterygius	0%	0%	0%	0%
Furnarius figulus	-9%	-10%	-12%	-23%
Galbula ruficauda	0%	-1%	0%	0%
Geotrygon montana	-2%	-4%	-5%	-17%
Geotrygon violacea	-1%	0%	0%	-4%
Glaucidium minutissimum	-1%	0%	0%	-6%
Glaucis dohrnii	-1%	-1%	1%	-4%
Glaucis hirsutus	-1%	-2%	0%	-4%
Glyphorynchus spirurus	-7%	-9%	-9%	-16%
Grallaria varia	-2%	-9%	-8%	-25%
Habia rubica	0%	0%	0%	-6%
Harpagus bidentatus	-12%	-18%	-23%	-40%
Harpia harpyja	1%	1%	2%	0%
Heliomaster squamosus	-21%	-42%	-41%	-70%
Heliothryx auritus	-17%	-22%	-24%	-40%
Hemithraupis flavicollis	0%	0%	0%	-1%
Hemithraupis ruficapilla	-21%	-21%	-21%	-44%
Hemitriccus diops	-55%	-69%	-70%	-88%
Hemitriccus furcatus	-38%	-42%	-44%	-69%
Hemitriccus nidipendulus	-45%	-51%	-57%	-70%
Hemitriccus striaticollis	1%	1%	1%	1%
Herpetotheres cachinnans	0%	0%	0%	-1%
Herpsilochmus rufimarginatus	0%	0%	0%	0%
Hylatomus lineatus	0%	-1%	-2%	-10%
Hylocharis sapphirina	0%	0%	0%	0%
Hylophilus poicilotis	-44%	-50%	-56%	-78%
Hylophilus thoracicus	0%	0%	0%	-1%

Hypoedaleus guttatus	-17%	-1%	-22%	-62%
Icterus pyrrhopterus	0%	0%	0%	0%
Ictinia plumbea	0%	0%	0%	0%
Ilicura militaris	-40%	-50%	-52%	-73%
Iodopleura pipra	-29%	-33%	-34%	-54%
Laniisoma elegans	-3%	-5%	-2%	-11%
Laniocera hypopyrra	0%	0%	0%	0%
Legatus leucophaius	-3%	-9%	-10%	-42%
Lepidocolaptes squamatus	-29%	-34%	-35%	-51%
Leptodon cayanensis	0%	0%	0%	0%
Leptopogon amaurocephalus	0%	0%	0%	-1%
Leptotila rufaxilla	-1%	-4%	-5%	-23%
Leucochloris albicollis	-42%	-42%	-46%	-60%
Lipaugus lanioides	-17%	-19%	-21%	-32%
Lipaugus vociferans	4%	6%	6%	9%
Lurocalis semitorquatus	-4%	-6%	-7%	-16%
Machaeropterus regulus	-5%	-7%	-2%	-7%
Mackenziaena leachii	-61%	-71%	-82%	-94%
Mackenziaena severa	-30%	-36%	-44%	-58%
Malacoptila striata	-6%	-2%	0%	-15%
Manacus manacus	-4%	-6%	-5%	-16%
Megascops atricapilla	-1%	0%	-1%	-11%
Melanerpes flavifrons	-8%	-12%	-9%	-18%
Micrastur mintoni	4%	4%	10%	7%
Micrastur ruficollis	0%	-1%	-2%	-11%
Micrastur semitorquatus	0%	0%	0%	0%
Mionectes oleagineus	-8%	-10%	-10%	-18%
Mionectes rufiventris	-43%	-42%	-54%	-77%
Monasa morphoeus	0%	0%	0%	0%

Myiarchus ferox	0%	0%	0%	0%
Myiarchus tuberculifer	5%	2%	-10%	-16%
Myiobius atricaudus	-17%	-24%	-25%	-47%
Myiobius barbatus	0%	-1%	-2%	-7%
Myiopagis caniceps	0%	0%	0%	0%
Myiornis auricularis	-6%	-10%	-8%	-26%
Myiothlypis rivularis	-8%	-10%	-10%	-20%
Myrmoderus loricatus	-69%	-69%	-72%	-86%
Myrmotherula axillaris	0%	-1%	0%	-6%
Myrmotherula luctuosa	-4%	-2%	-5%	-12%
Myrmotherula minor	-17%	-19%	-17%	-33%
Myrmotherula urosticta	22%	35%	46%	54%
Nemosia pileata	0%	0%	0%	0%
Neomorphus geoffroyi	-1%	-3%	-3%	-11%
Neopelma aurifrons	-15%	-21%	-23%	-41%
Notharchus swainsoni	17%	29%	37%	27%
Nyctibius aethereus	0%	1%	1%	1%
Nyctibius grandis	17%	21%	20%	28%
Nyctibius griseus	0%	0%	0%	0%
Nyctiphrynus ocellatus	0%	-1%	-1%	-12%
Nystalus maculatus	19%	21%	25%	31%
Odontophorus capueira	-51%	-55%	-64%	-81%
Orchesticus abeillei	-32%	-38%	-38%	-58%
Oxyruncus cristatus	0%	0%	0%	-1%
Pachyramphus castaneus	0%	0%	0%	-5%
Pachyramphus marginatus	0%	0%	0%	0%
Pachyramphus polychopterus	0%	0%	0%	-1%
Panyptila cayennensis	-9%	-13%	-15%	-27%
Patagioenas cayennensis	-2%	-3%	-3%	-13%

Patagioenas picazuro	0%	0%	0%	-6%
Patagioenas plumbea	-2%	-5%	-4%	-18%
Patagioenas speciosa	0%	0%	-1%	-4%
Penelope obscura	-48%	-53%	-57%	-80%
Penelope superciliaris	1%	1%	1%	-1%
Phaethornis eurynome	-32%	-33%	-45%	-75%
Phaethornis idaliae	11%	11%	11%	12%
Phaethornis ruber	0%	0%	0%	-1%
Phaethornis squalidus	-16%	-17%	-16%	-33%
Pheugopedius genibarbis	0%	0%	0%	0%
Philydor atricapillus	-12%	-16%	-17%	-45%
Philydor rufum	-14%	-18%	-16%	-36%
Phyllomyias burmeisteri	-13%	-16%	-15%	-32%
Phyllomyias fasciatus	-24%	-34%	-35%	-59%
Phyllomyias griseocapilla	-53%	-58%	-59%	-71%
Phyllomyias virescens	-70%	-72%	-79%	-94%
Phylloscartes beckeri	-55%	-73%	-72%	-91%
Phylloscartes oustaleti	-38%	-48%	-52%	-68%
Phylloscartes ventralis	-28%	-33%	-32%	-57%
Piaya cayana	0%	0%	0%	-2%
Piculus aurulentus	-43%	-61%	-63%	-88%
Piculus flavigula	0%	0%	0%	-2%
Picumnus albosquamatus	18%	15%	15%	-1%
Picumnus exilis	-17%	-21%	-23%	-32%
Pionopsitta pileata	-75%	-73%	-86%	-96%
Pionus maximiliani	0%	0%	0%	-6%
Piprites chloris	-2%	-3%	-2%	-4%
Platyrinchus leucoryphus	0%	3%	3%	-2%
Platyrinchus mystaceus	0%	0%	0%	-4%

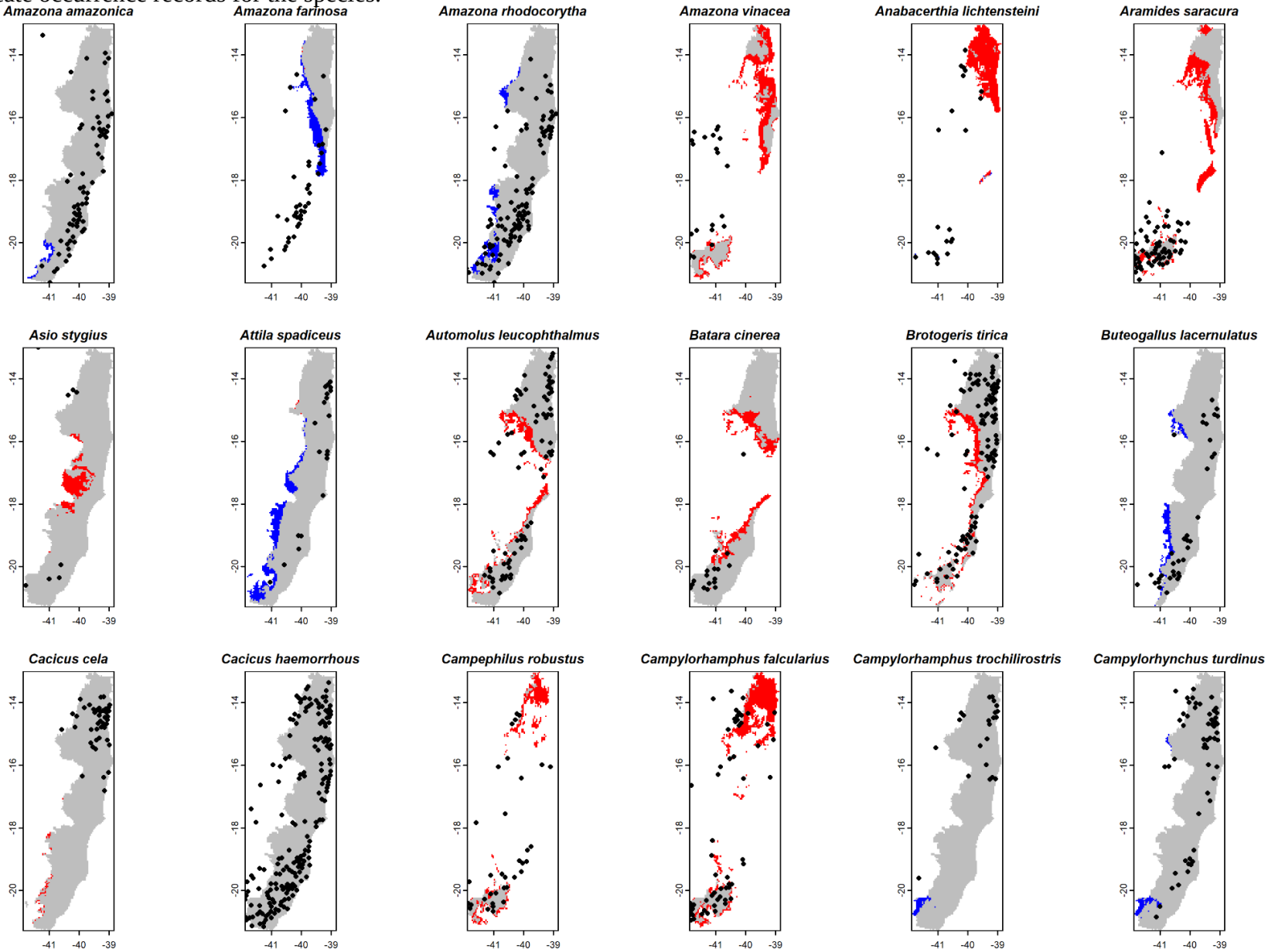
Poecilotriccus fumifrons	-10%	-13%	-16%	-32%
Poecilotriccus plumbeiceps	-12%	-14%	-13%	-29%
Primolius maracana	-8%	-7%	-9%	-22%
Procnias nudicollis	-20%	-23%	-25%	-49%
Psarocolius decumanus	0%	0%	0%	-5%
Pseudastur polionotus	-38%	-44%	-46%	-64%
Pseudopipra pipra	-6%	-8%	-5%	-10%
Pseudoseisura cristata	1%	-6%	2%	-3%
Psilorhamphus guttatus	-36%	345%	-22%	-58%
Psittacara leucophthalmus	0%	0%	0%	0%
Pteroglossus aracari	-1%	-1%	-1%	-2%
Pteroglossus bailloni	-83%	-68%	-97%	-99%
Pulsatrix koeniswaldiana	-22%	-33%	-39%	-61%
Pulsatrix perspicillata	-24%	-44%	-43%	-65%
Pyriglena leucoptera	-32%	-36%	-37%	-66%
Pyrrhura cruentata	0%	0%	0%	0%
Pyrrhura frontalis	-10%	-14%	-13%	-42%
Pyrrhura leucotis	0%	0%	0%	0%
Ramphastos dicolorus	-72%	-74%	-81%	-89%
Ramphastos vitellinus	-4%	-7%	-9%	-17%
Ramphocaenus melanurus	0%	0%	0%	-3%
Ramphodon naevius	1%	5%	-6%	-30%
Ramphotrigon megacephalum	0%	0%	0%	0%
Rhopias gularis	-36%	-41%	-45%	-62%
Rhynchocyclus olivaceus	-5%	-7%	-6%	-14%
Rhytipterna simplex	0%	0%	0%	-1%
Rupornis magnirostris	0%	0%	0%	0%
Saltator fuliginosus	-35%	-47%	-48%	-66%
Saltator similis	-8%	-10%	-10%	-28%

Sarcoramphus papa	0%	0%	0%	-2%
Schiffornis turdina	-1%	0%	0%	-1%
Schiffornis virescens	-34%	-33%	-49%	-72%
Sclerurus caudacutus	-1%	-1%	-1%	-2%
Sclerurus mexicanus	-16%	-18%	-22%	-36%
Sclerurus scansor	-39%	-49%	-56%	-81%
Scytalopus speluncae	-40%	-44%	-52%	-74%
Selenidera maculirostris	-62%	-72%	-75%	-88%
Setophaga pitiayumi	0%	0%	0%	0%
Sirystes sibilator	0%	0%	0%	0%
Sittasomus griseicapillus	0%	0%	0%	0%
Spizaetus melanoleucus	0%	0%	0%	0%
Spizaetus ornatus	-1%	-3%	-3%	-11%
Spizaetus tyrannus	-7%	-10%	-13%	-29%
Strix hylophila	-55%	-60%	-64%	-90%
Synallaxis cinerea	-37%	-52%	-54%	-76%
Synallaxis ruficapilla	-42%	-52%	-62%	-80%
Syndactyla rufosuperciliata	-12%	-15%	-18%	-29%
Tangara brasiliensis	2%	8%	11%	9%
Tangara cayana	-16%	-19%	-25%	-32%
Tangara cyanocephala	-13%	-19%	-15%	-35%
Tangara cyanoptera	-25%	-26%	-34%	-69%
Tangara cyanoventris	-59%	-66%	-69%	-86%
Tangara desmaresti	-36%	-47%	-52%	-74%
Tangara ornata	-23%	-33%	-35%	-56%
Tangara palmarum	0%	-1%	-1%	-8%
Tangara sayaca	-1%	-1%	-1%	-3%
Tangara seledon	-16%	-22%	-24%	-60%
Taraba major	0%	0%	0%	0%

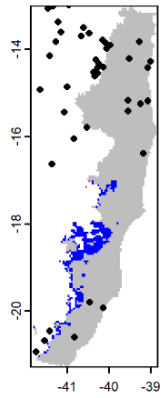
Terenura maculata	-4%	-2%	-2%	-14%
Tersina viridis	-4%	-11%	-12%	-41%
Thalurania glaucopis	-5%	-12%	-15%	-34%
Thamnomanes caesius	-2%	-2%	0%	0%
Thamnophilus ambiguus	-1%	-4%	-9%	-25%
Thamnophilus caerulescens	-7%	-9%	-7%	-27%
Thamnophilus pelzelni	7%	1%	2%	-19%
Thlypopsis sordida	0%	0%	0%	0%
Thripophaga macroura	-26%	-24%	-30%	-49%
Tinamus solitarius	-19%	-21%	-22%	-42%
Tityra cayana	0%	0%	0%	-1%
Tityra inquisitor	2%	2%	2%	3%
Todirostrum poliocephalum	-19%	-19%	-22%	-49%
Tolmomyias flaviventris	0%	0%	1%	1%
Tolmomyias poliocephalus	-2%	-3%	-2%	-6%
Tolmomyias sulphurescens	0%	0%	0%	0%
Touit surdus	-46%	-50%	-56%	-70%
Trichothraupis melanops	-22%	-25%	-26%	-52%
Triclaria malachitacea	-22%	-24%	-42%	-80%
Trogon collaris	0%	0%	0%	-1%
Trogon surrucura	-35%	-37%	-40%	-66%
Trogon viridis	0%	0%	1%	0%
Turdus albicollis	0%	-3%	-2%	-11%
Turdus flavipes	-17%	-26%	-25%	-52%
Turdus fumigatus	-6%	-8%	-7%	-12%
Turdus leucomelas	0%	0%	0%	0%
Veniliornis affinis	0%	0%	0%	0%
Veniliornis maculifrons	28%	79%	91%	111%
Veniliornis passerinus	0%	0%	0%	0%

Xenops minutus	-3%	-5%	-5%	-16%
Xenops rutilus	0%	0%	0%	0%
Xiphocolaptes albicollis	-35%	-43%	-49%	-76%
Xipholena atropurpurea	-25%	-26%	-29%	-42%
Xiphorhynchus fuscus	-34%	-44%	-43%	-67%
Xiphorhynchus guttatus	10%	8%	6%	11%

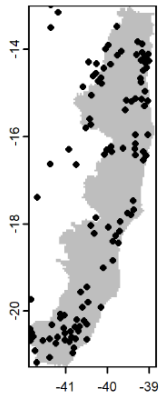
Figure S1. Change in climate suitable areas for forest birds in the Central Corridor of the Atlantic Forest, Brazil, between the baseline and the 2050 pessimistic (SSP585) scenario. Blue, red, gray, and white colors indicate gain, loss, no change, and unsuitability, respectively. Black dots indicate occurrence records for the species.



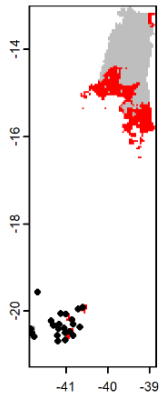
Cantorchilus longirostris



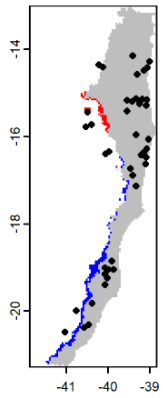
Capsiempis flaveola



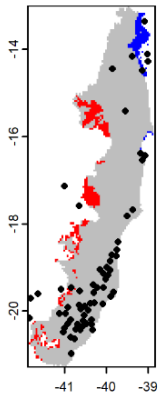
Carpornis cucullata



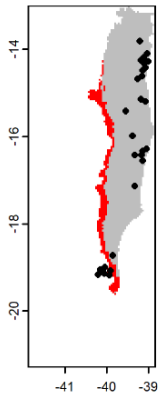
Carpornis melanocephala



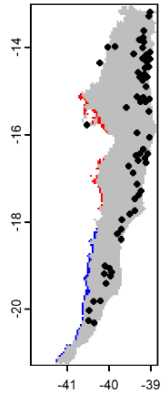
Celeus flavescens



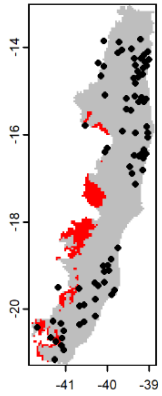
Celeus torquatus



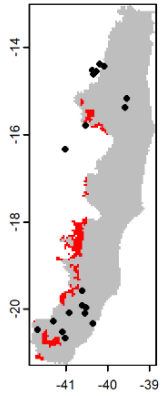
Ceratopipra rubrocapilla



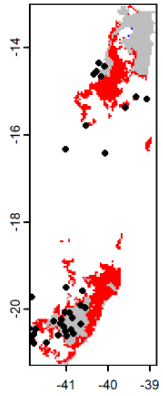
Chaetura cinereiventris



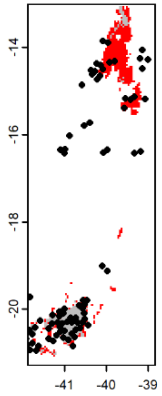
Chamaeza campanisona



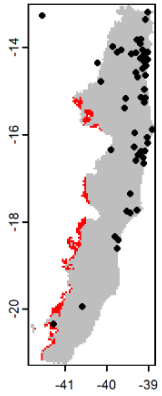
Chamaeza meruloides



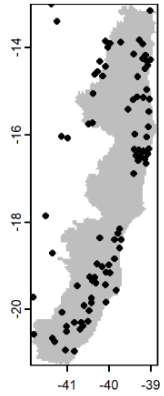
Chiroxiphia caudata



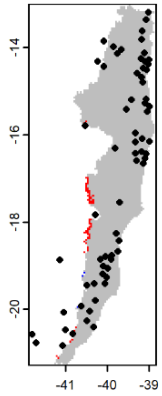
Chiroxiphia pareola



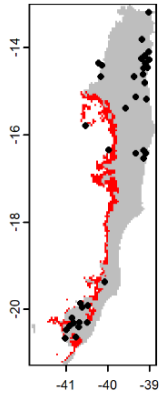
Chlorestes cyanus



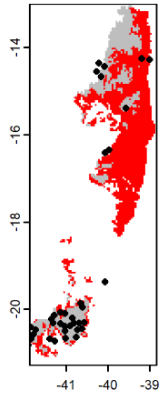
Chlorestes notata



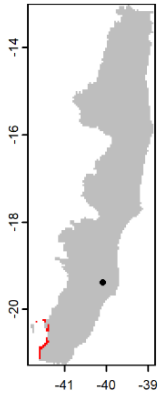
Chlorophanes spiza



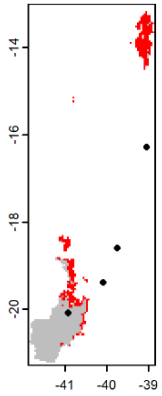
Chlorophonia cyanea



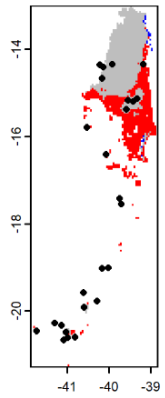
Ciccaba huhula



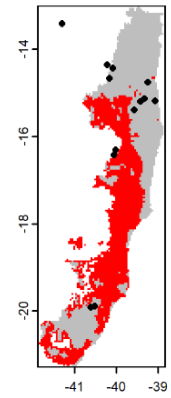
Ciccaba virgata



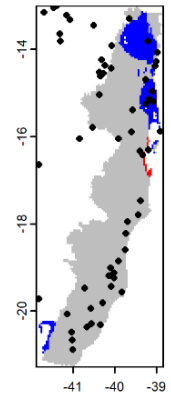
Cichlocolaptes leucophrus



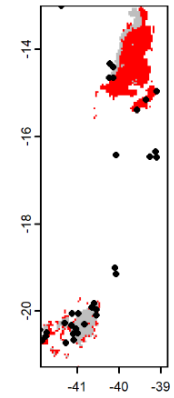
Cichlopsis leucogenys



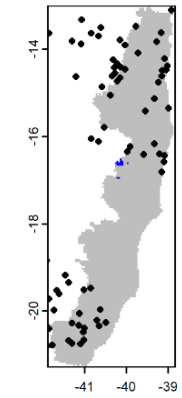
Claravis pretiosa



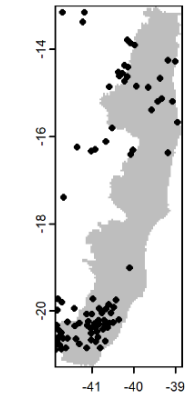
Clytolaema rubricauda



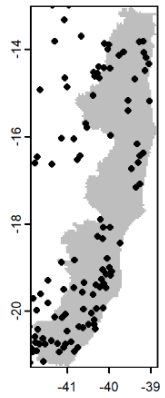
Colaptes melanochloros



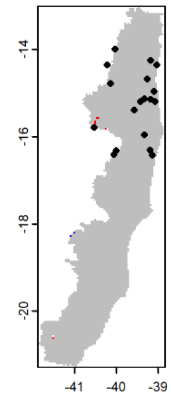
Colonia colonus



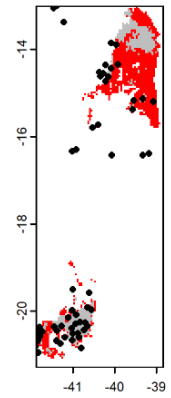
Conirostrum speciosum



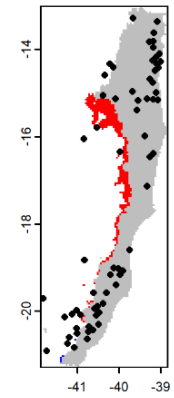
Conopias trivirgatus



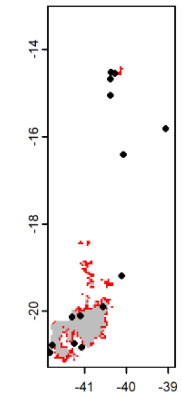
Conopophaga lineata



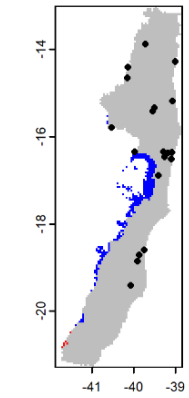
Conopophaga melanops



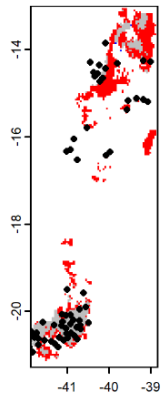
Corythopis delalandi



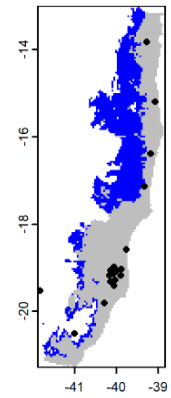
Cotinga maculata



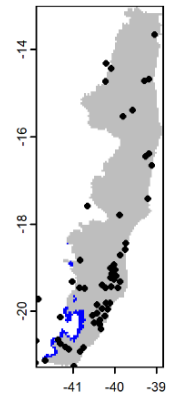
Cranioleuca pallida



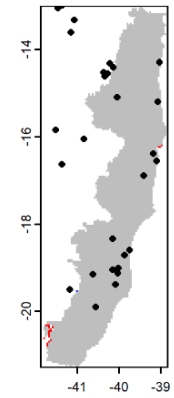
Crax blumenbachii



Crotophaga major



Crypturellus noctivagus



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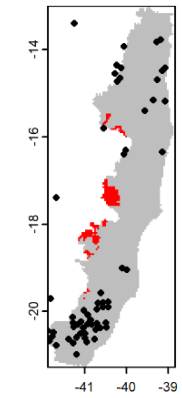
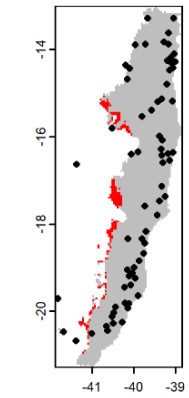
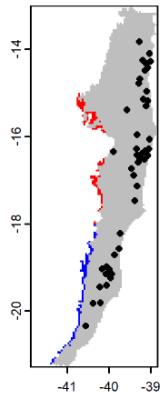


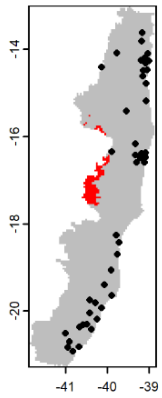
Crypturellus soui



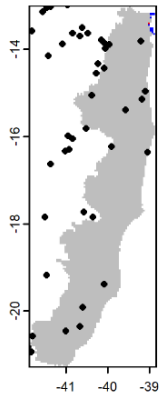
Crypturellus variegatus



Cyanerpes cyaneus



Cyanoloxia brissonii



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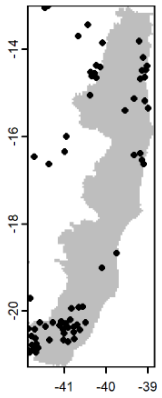

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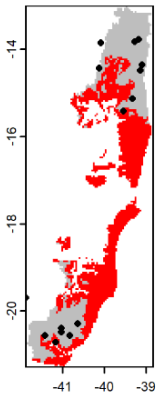
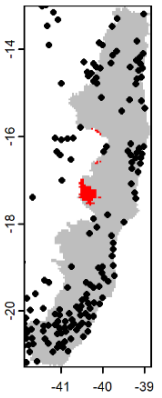


Dacnis cayana



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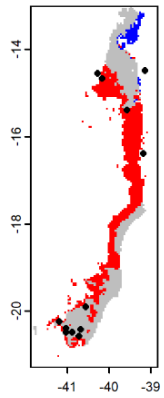
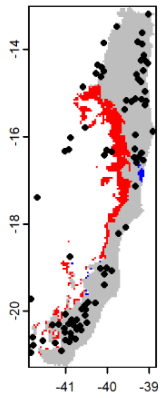


Dendrocincla turdina



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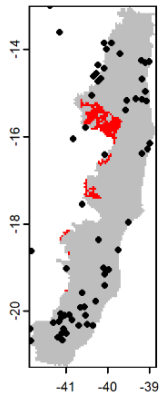

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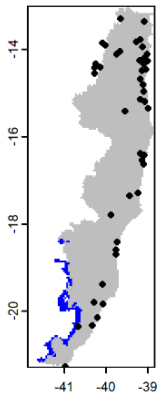
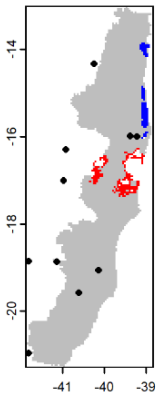
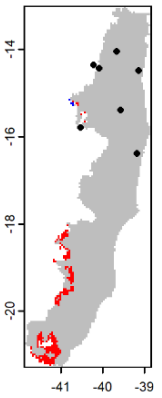


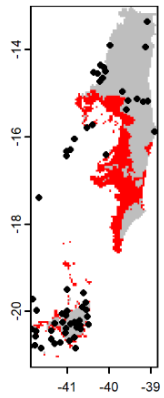
Diopsittaca nobilis



Discosura langsdorffi



Drymophila ferruginea



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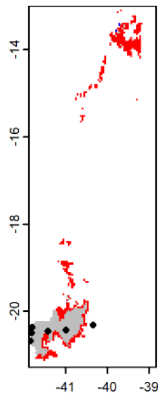

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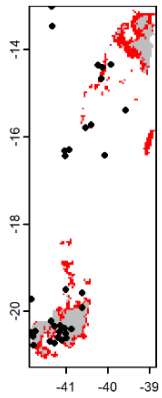
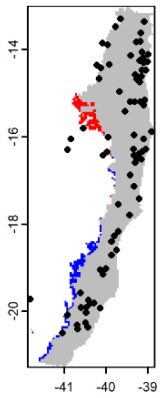
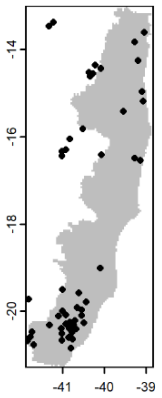


Drymophila squamata



Dysithamnus mentalis



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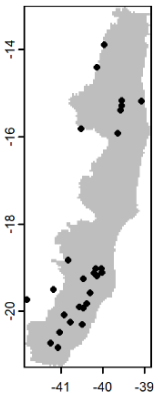

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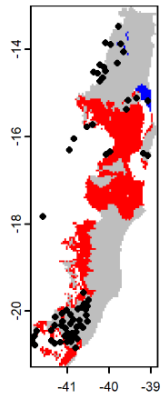
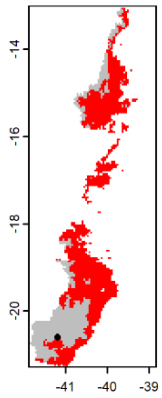


Elaenia obscura



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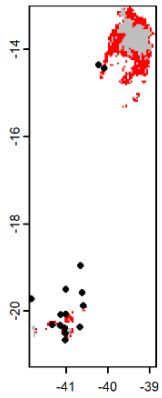
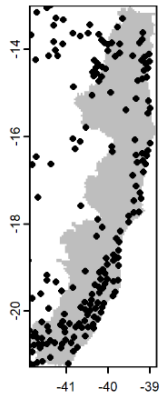


Euphonia chlorotica



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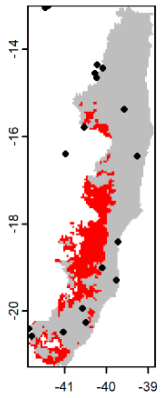

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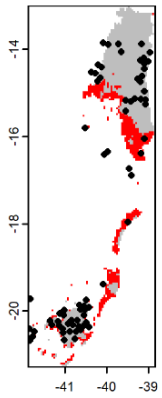
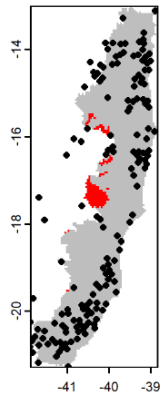
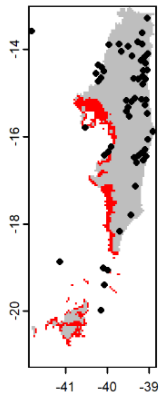


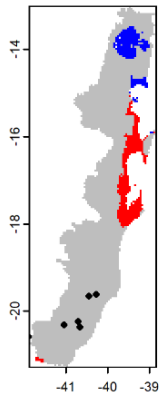
Euphonia violacea



Euphonia xanthogaster



Falco deiroleucus



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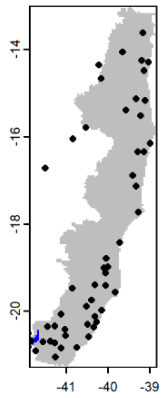

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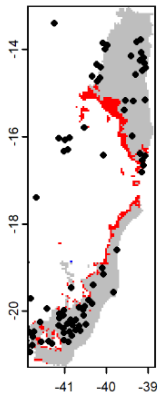

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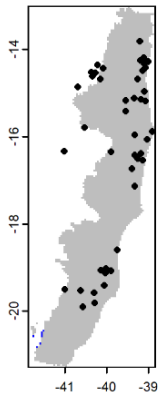

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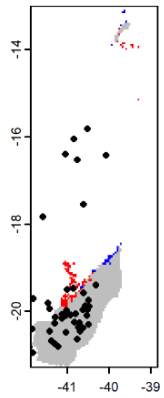

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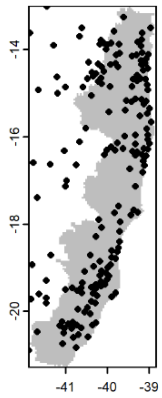
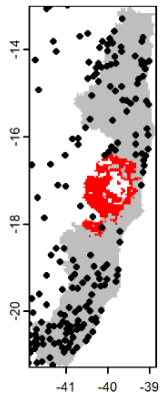


Furnarius figulus



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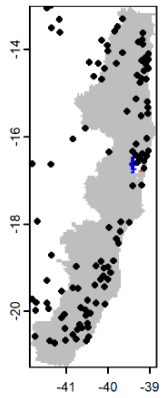

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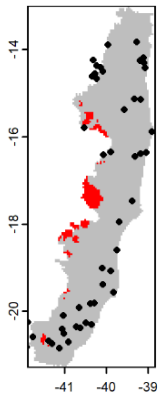

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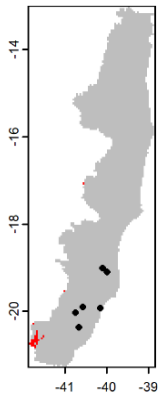

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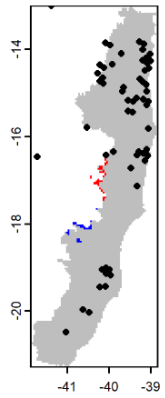
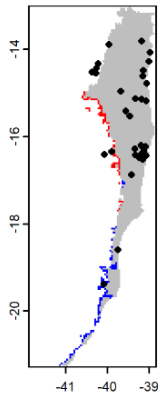


Glaucis dohrnii



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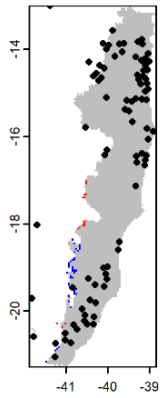
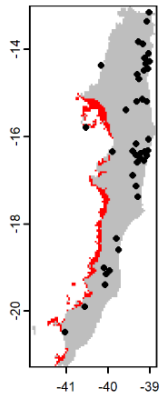


Glyphorynchus spirurus



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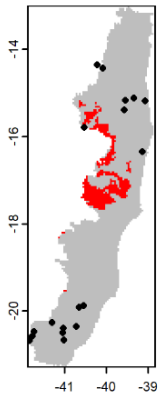
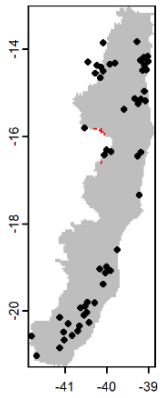
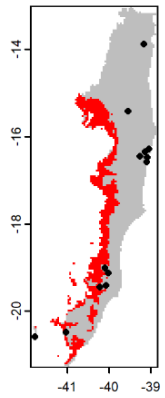


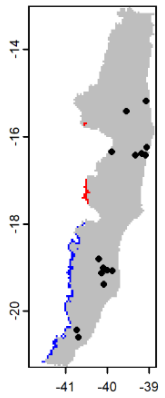
Habia rubica



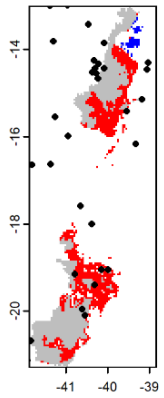
Harpagus bidentatus



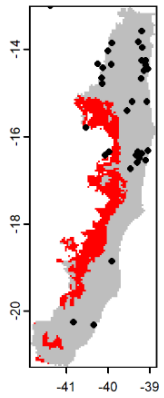
Harpia harpyja



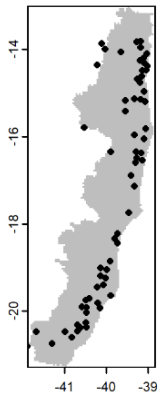
Heliomaster squamosus



Heliothryx auritus



Hemithraupis flavicollis



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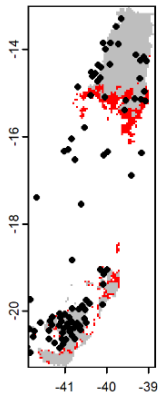
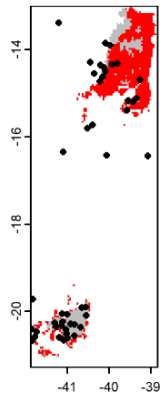


Hemitriccus diops



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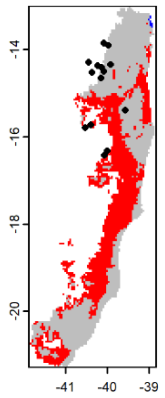

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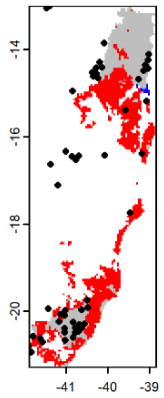
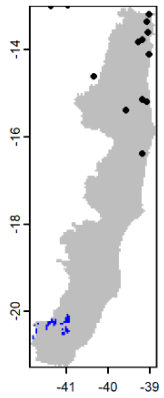
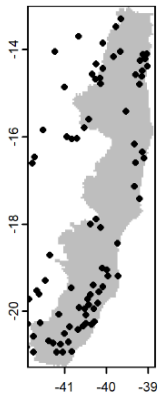


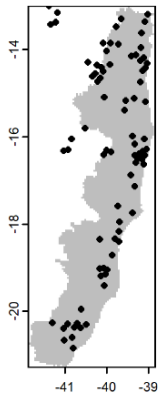
Hemitriccus striaticollis



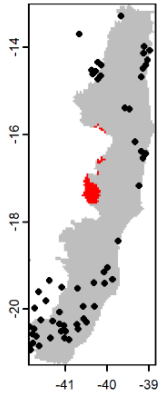
Herpetotheres cachinnans



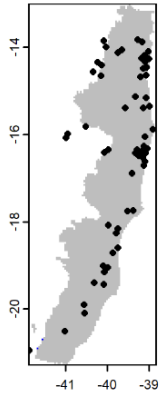
Herpsilochmus rufimarginatus



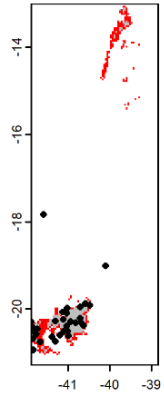
Hylatomus lineatus



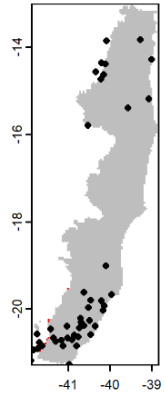
Hylocharis sapphirina



Hylophilus poicilotis



Hylophilus thoracicus



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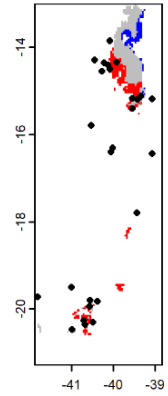
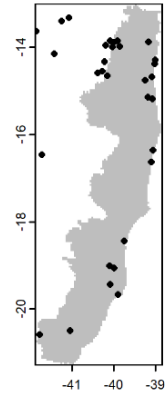
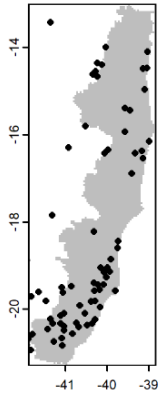


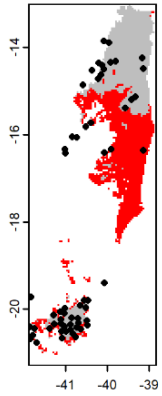
Icterus pyrrhopterus



Ictinia plumbea



Ilicura militaris



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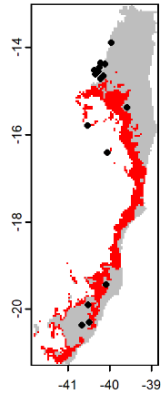
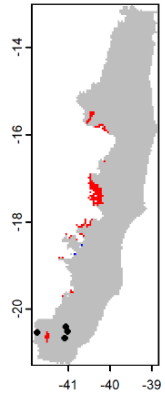


Laniisoma elegans



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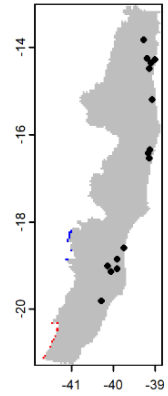
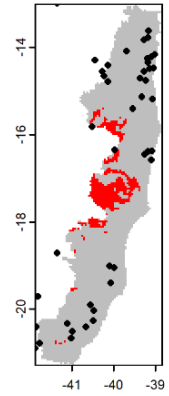
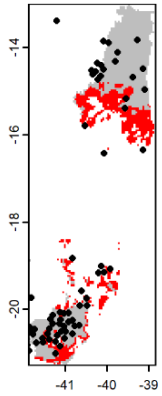


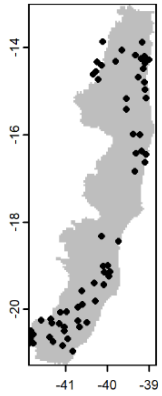
Legatus leucophaius



Lepidocolaptes squamatus



Leptodon cayanensis



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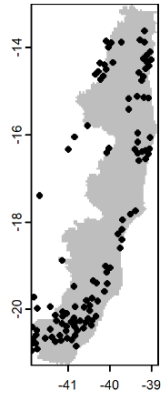

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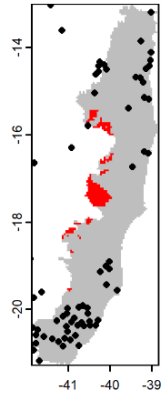
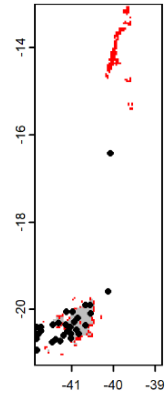
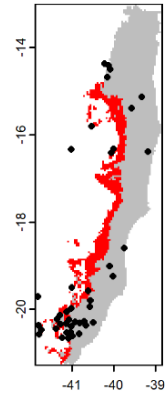


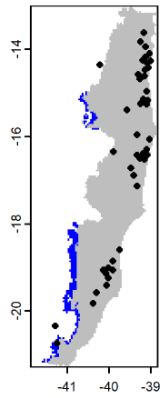
Leucochloris albicollis



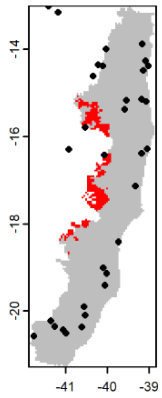
Lipaugus lanioides



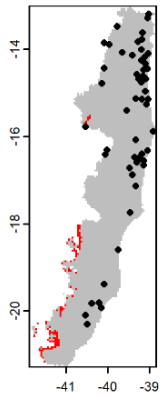
Lipaugus vociferans



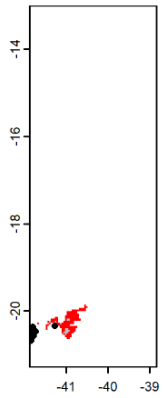
Lurocalis semitorquatus



Machaeropterus regulus



Mackenziaena leachii



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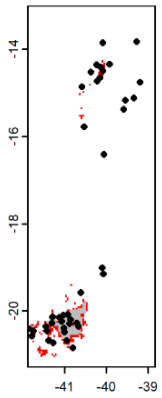
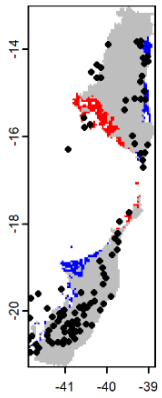
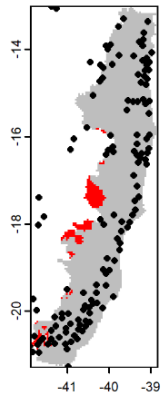


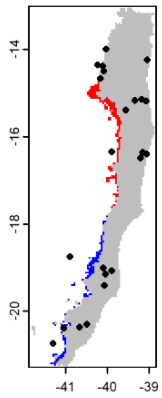
Malacoptila striata



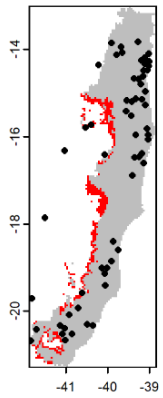
Manacus manacus



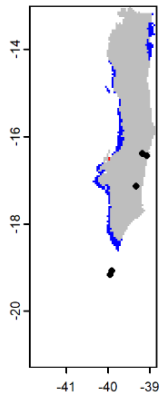
Megascops atricapilla



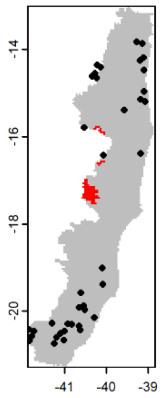
Melanerpes flavifrons



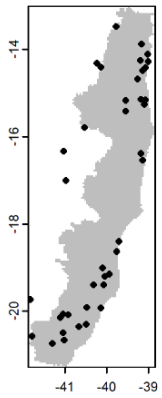
Micrastur mintoni



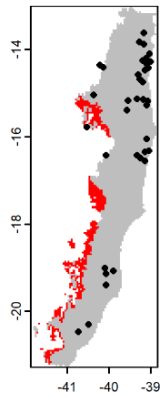
Micrastur ruficollis



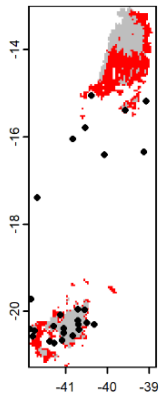
Micrastur semitorquatus



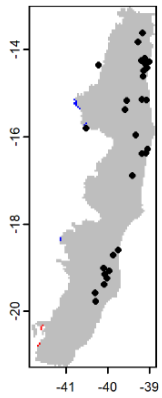
Mionectes oleagineus



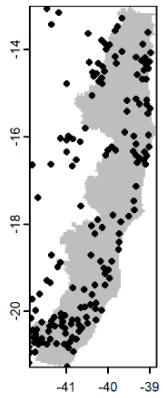
Mionectes rufiventris



Monasa morphoeus



Myiarchus ferox



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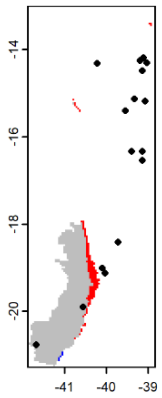
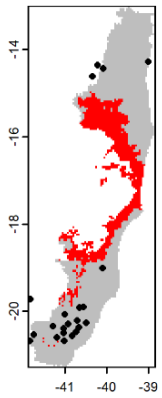


Myiobius atricaudus



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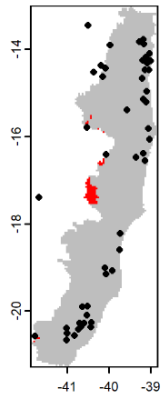
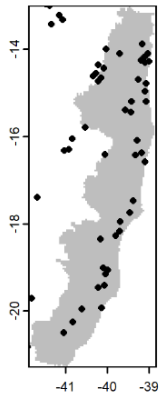
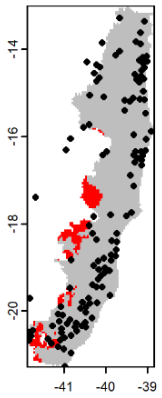


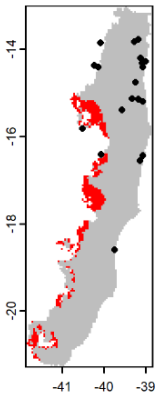
Myiopagis caniceps



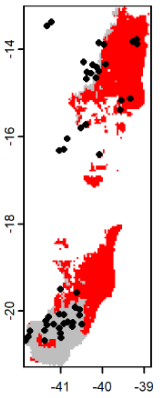
Myiornis auricularis



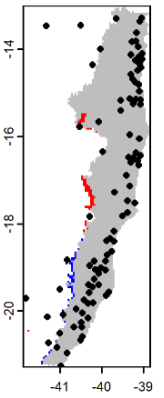
Myiothlypis rivularis



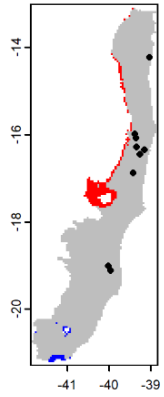
Myrmoderus loricatus



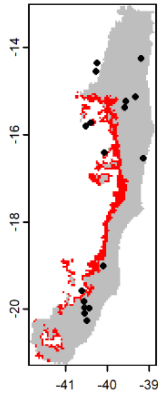
Myrmotherula axillaris



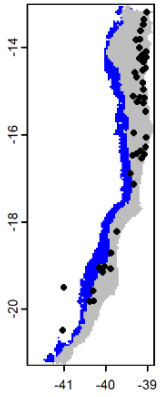
Myrmotherula luctuosa



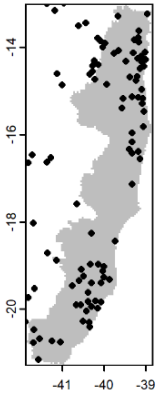
Myrmotherula minor



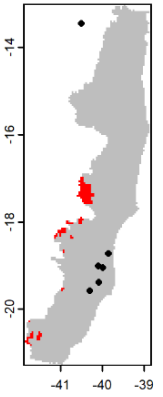
Myrmotherula urosticta



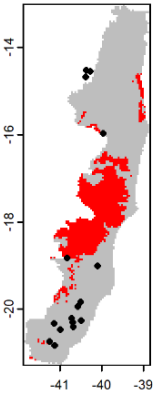
Nemosia pileata



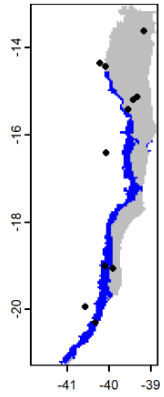
Neomorphus geoffroyi



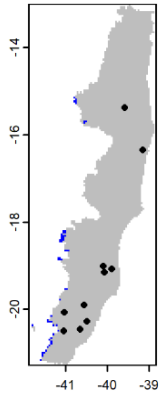
Neopelma aurifrons



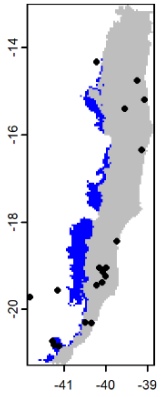
Notharchus swainsoni



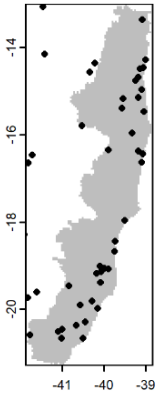
Nyctibius aethereus



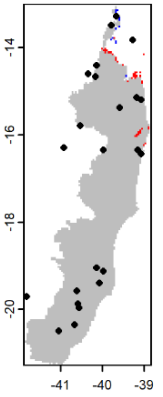
Nyctibius grandis



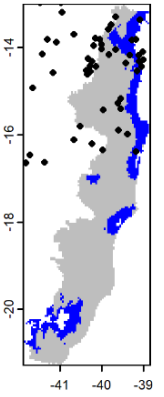
Nyctibius griseus



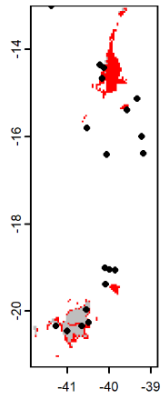
Nyctiphrynus ocellatus



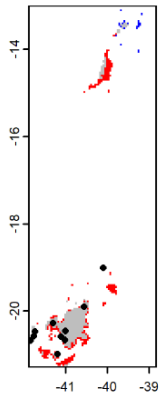
Nystalus maculatus



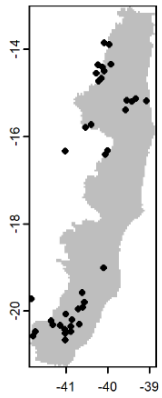
Odontophorus capueira



Orchesticus abeillei



Oxyruncus cristatus



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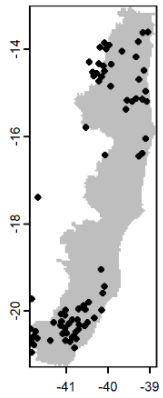

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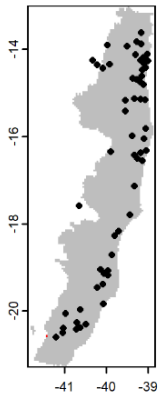

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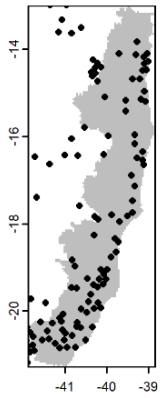

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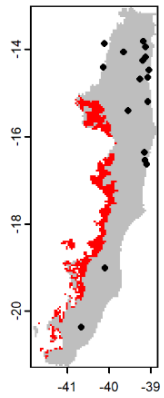
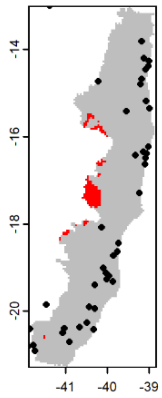


Patagioenas cayennensis



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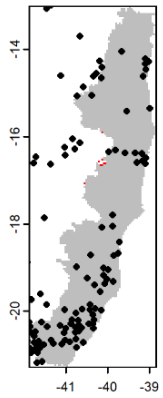

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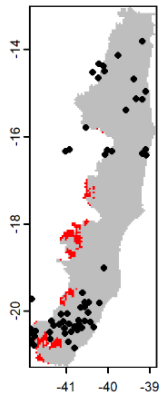

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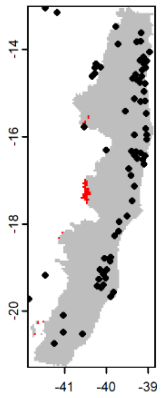
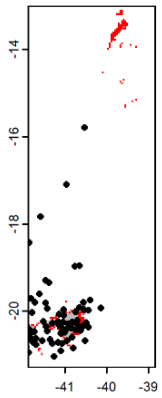
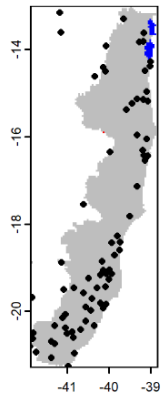


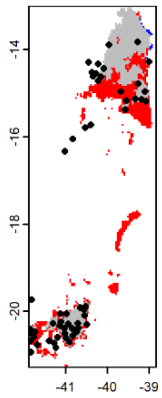
Penelope obscura



Penelope superciliaris



Phaethornis eurynome



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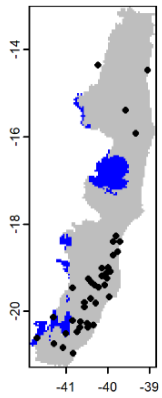

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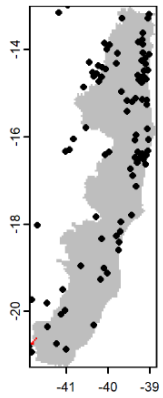

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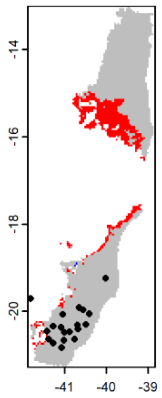
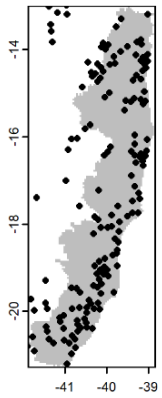


Pheugopedius genibarbis



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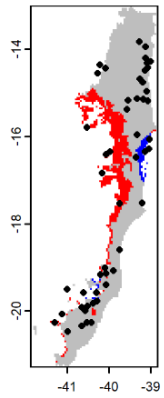

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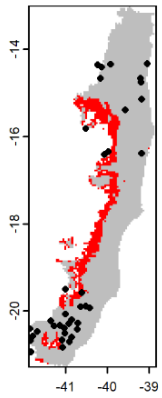
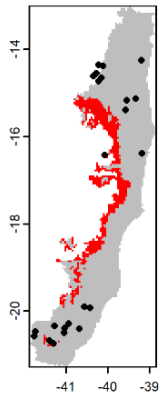


Phyllomyias burmeisteri



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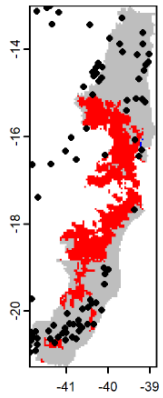

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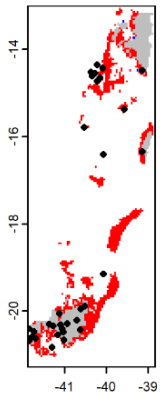

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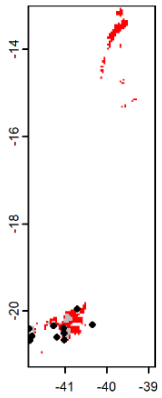
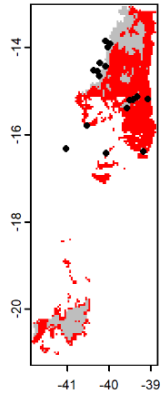


Phylloscartes beckeri



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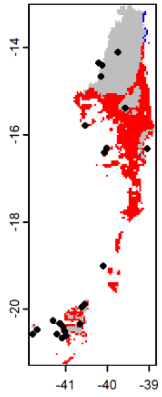
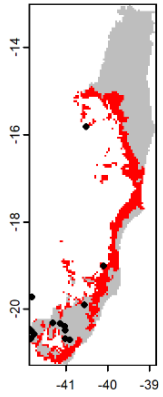
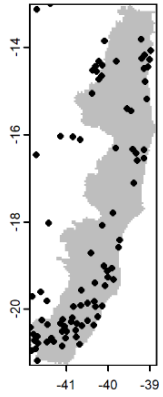


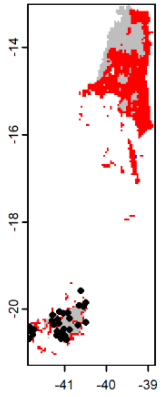
Phylloscartes ventralis



Piaya cayana



Piculus aurulentus



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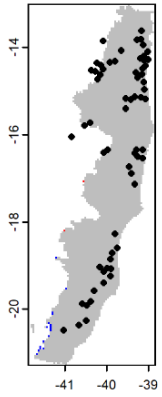

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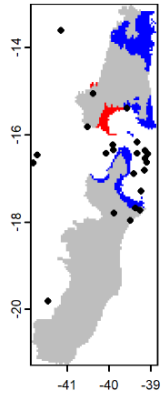
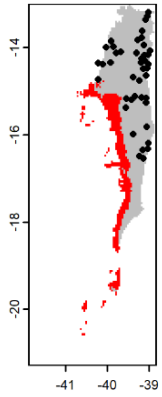


Picumnus exilis



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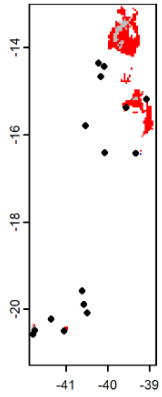
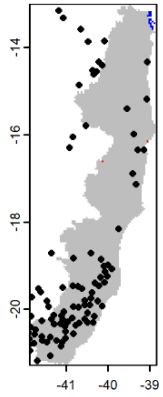
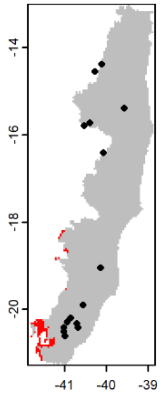


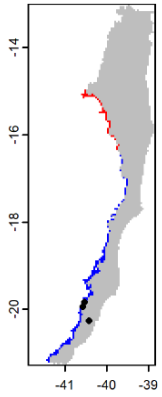
Pionus maximiliani



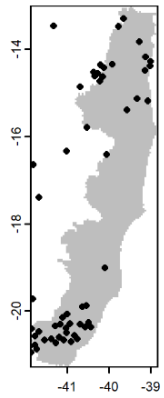
Piprites chloris



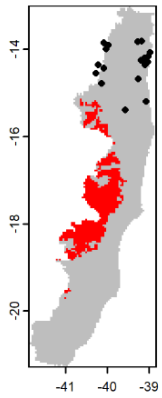
Platyrinchus leucoryphus



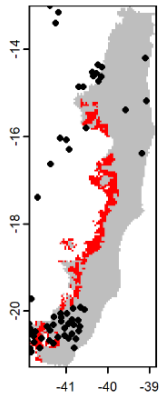
Platyrinchus mystaceus



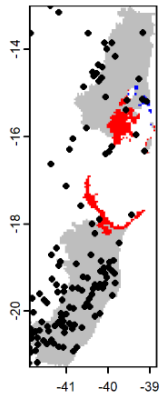
Poecilotriccus fumifrons



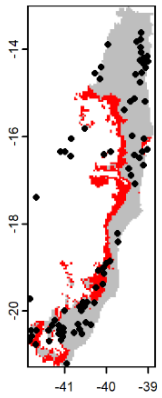
Poecilotriccus plumbeiceps



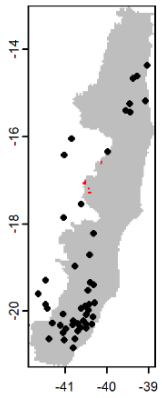
Primolius maracana



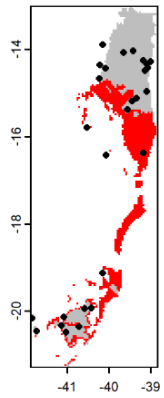
Procnias nudicollis



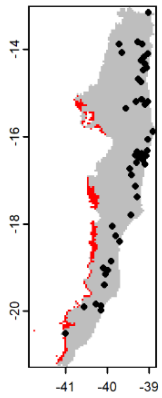
Psarocolius decumanus



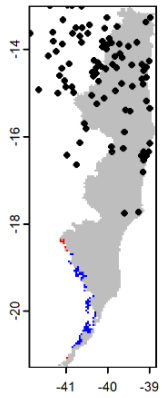
Pseudastur polionotus



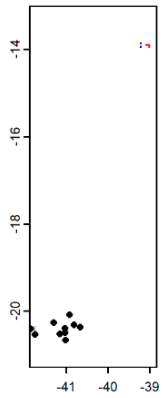
Pseudopipra pipra



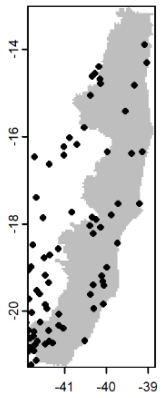
Pseudoseisura cristata



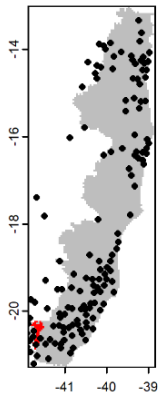
Psilorhamphus guttatus



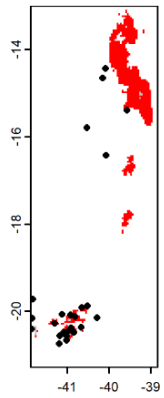
Psittacara leucophthalmus



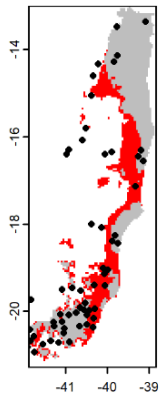
Pteroglossus aracari



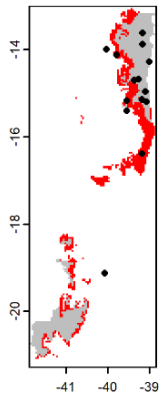
Pteroglossus bailloni



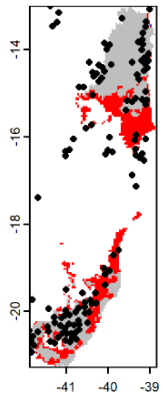
Pulsatrix koeniswaldiana



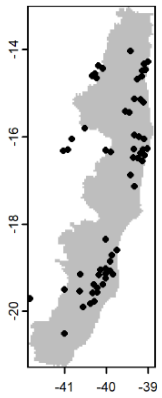
Pulsatrix perspicillata



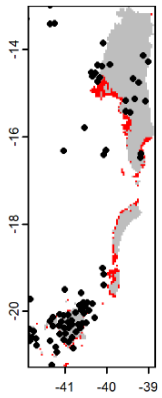
Pyriglena leucoptera



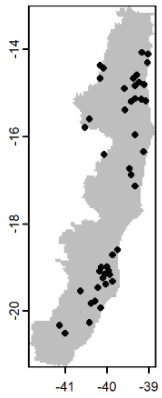
Pyrrhura cruentata



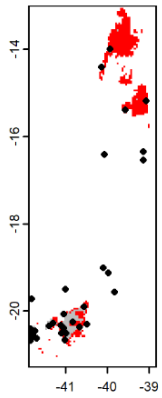
Pyrrhura frontalis



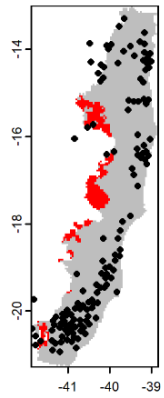
Pyrrhura leucotis



Ramphastos dicolorus



Ramphastos vitellinus



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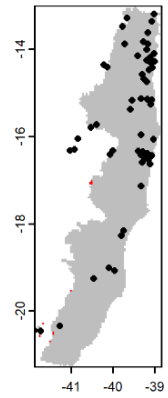

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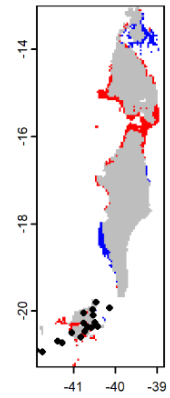

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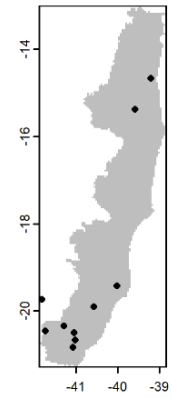

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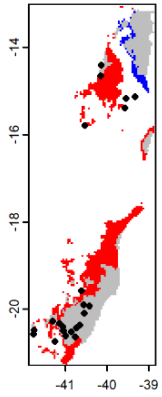

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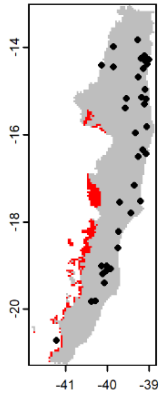

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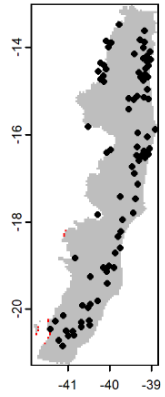

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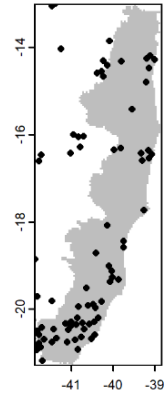
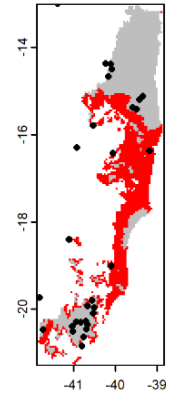


Saltator fuliginosus



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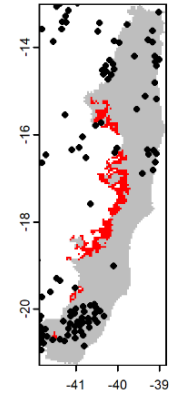
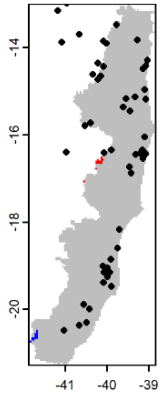


Sarcoramphus papa



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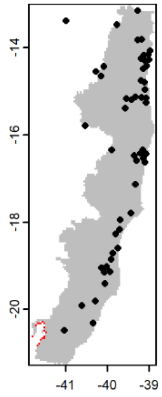

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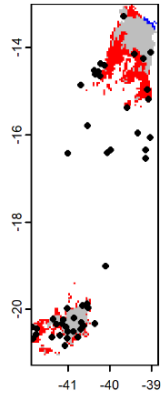

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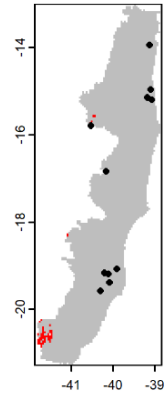

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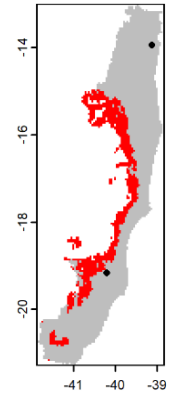

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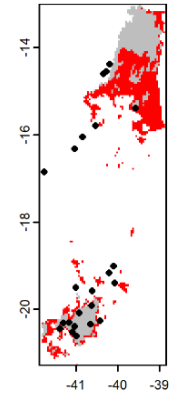

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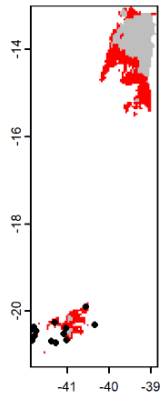

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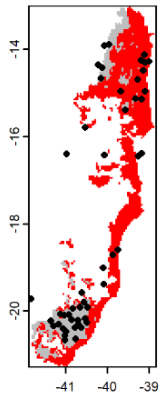

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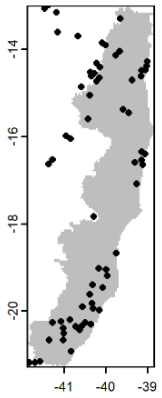
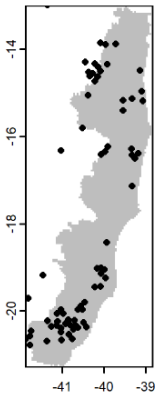
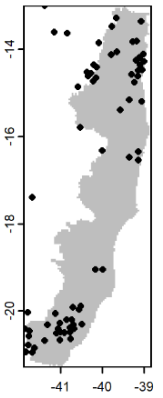


Sirystes sibilator



Sittasomus griseicapillus



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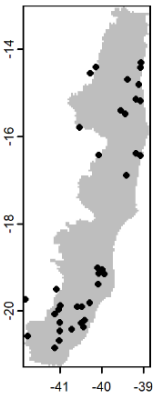

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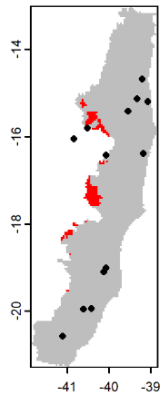

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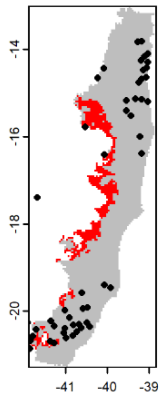

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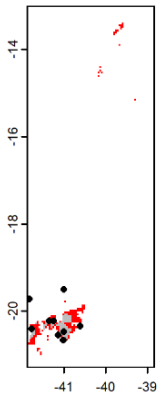

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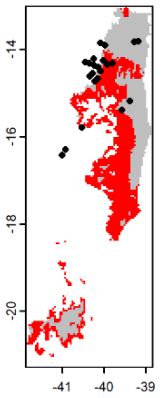

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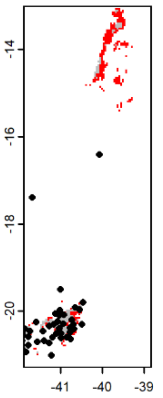

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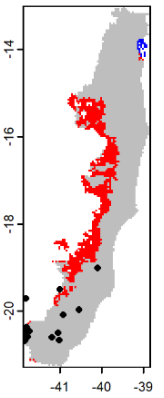
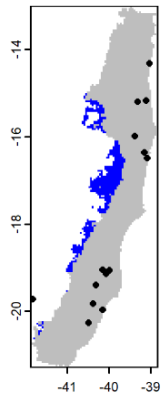


Tangara brasiliensis



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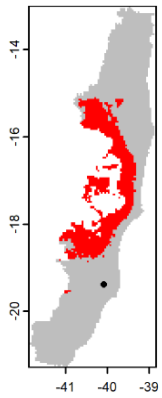

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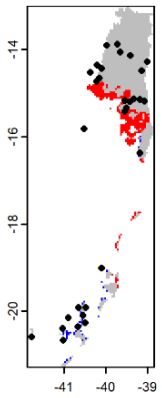

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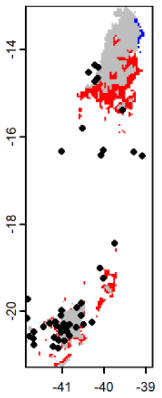

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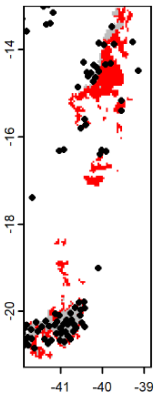

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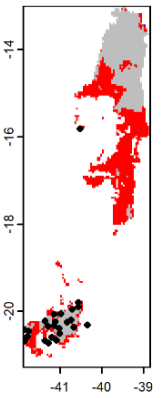

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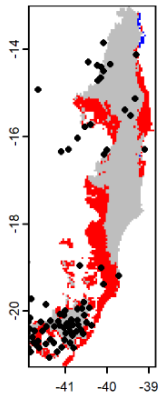

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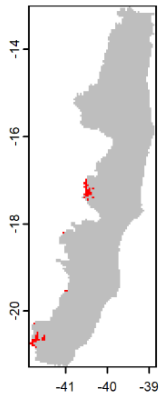

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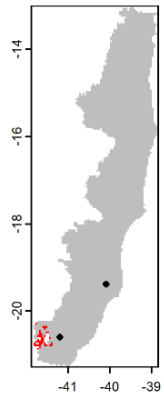

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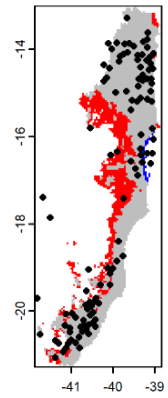
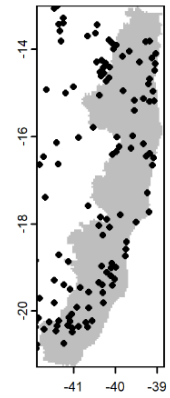
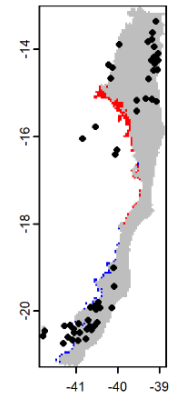


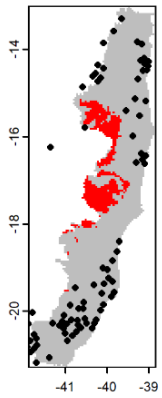
Taraba major



Terenura maculata



Tersina viridis



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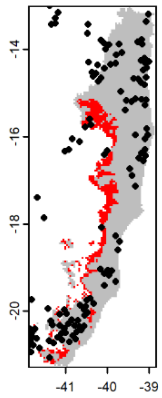
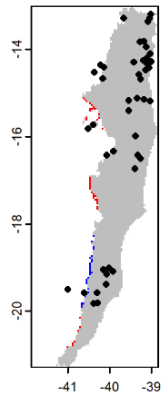
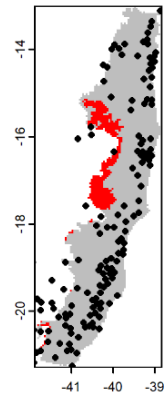


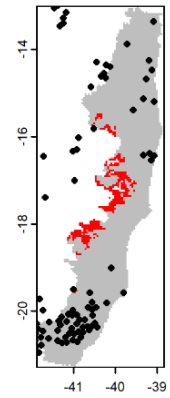
Thamnomanes caesius



Thamnophilus ambiguus



Thamnophilus caerulescens



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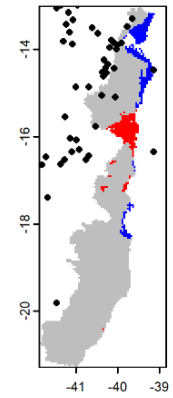
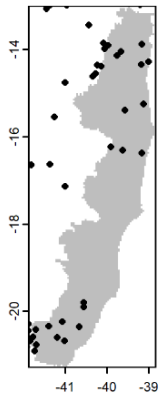


Thlypopsis sordida



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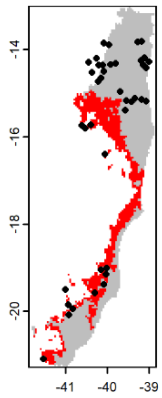
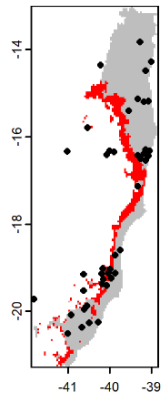
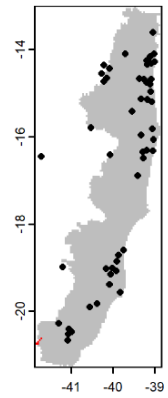


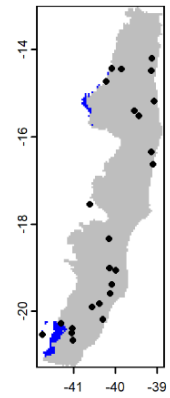
Tinamus solitarius



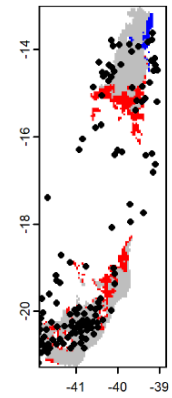
Tityra cayana



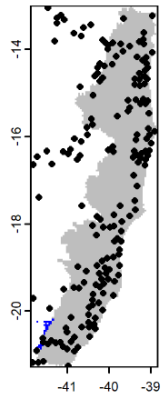
Tityra inquisitor



Todirostrum poliocephalum



Tolmomyias flaviventris



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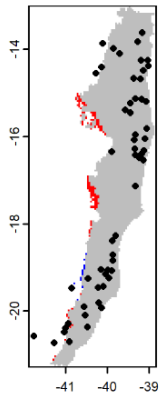

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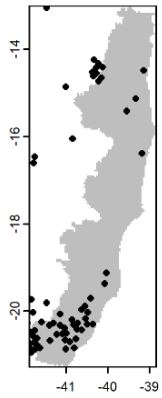

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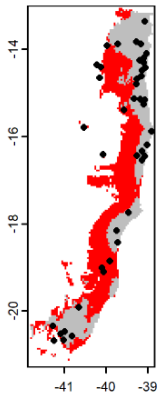

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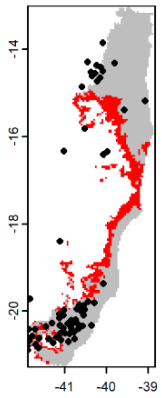

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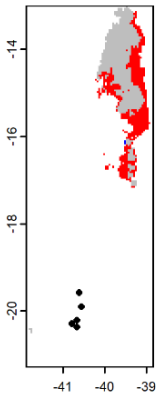

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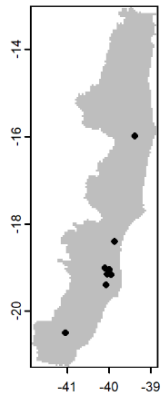

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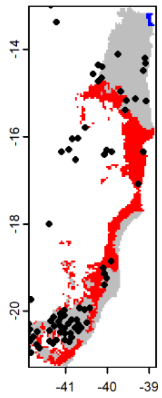

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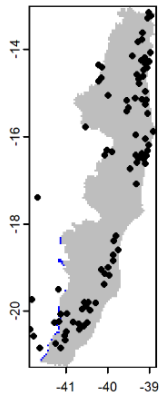

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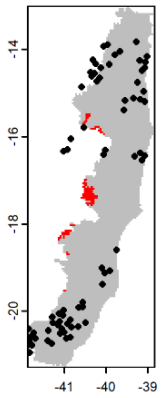

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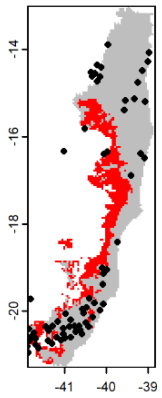

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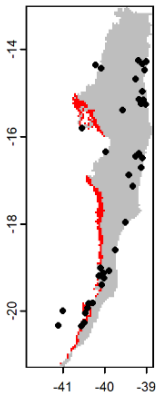
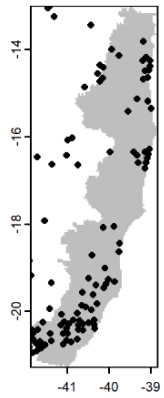


Turdus leucomelas



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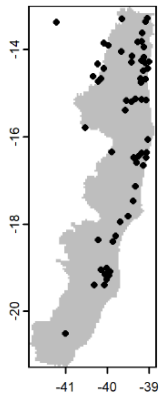

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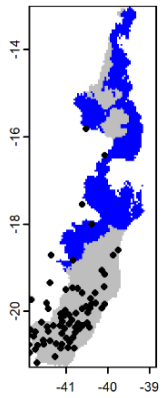

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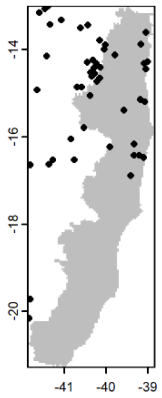

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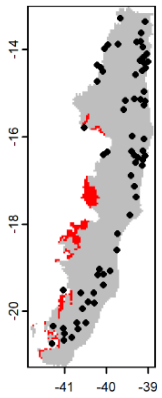

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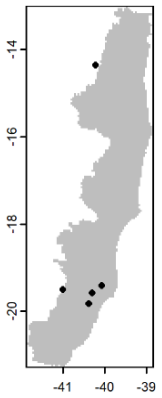

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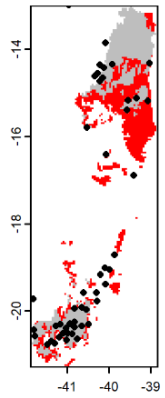

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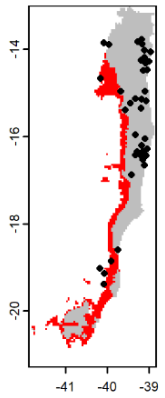

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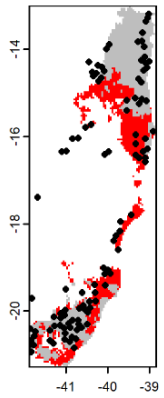

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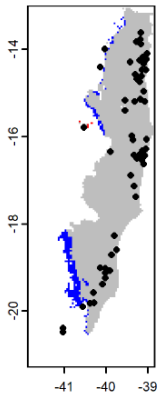

Conclusão geral

O tema das mudanças climáticas tem ganhado crescente relevância devido ao aumento na frequência de eventos climáticos extremos, como ondas de calor e alagamentos. Compreender como a biodiversidade responde a essas mudanças é fundamental para estabelecer estratégias de conservação adequadas, garantindo a existência futura de espécies importantes, como polinizadores e dispersores de sementes. Nossos resultados indicam que as mudanças climáticas promovem alterações na distribuição das aves, variando conforme as características das espécies e a escala considerada. Espera-se, em geral, que aves de menor tamanho e encontradas em florestas e ilhas percam mais área climaticamente adequada. Além disso, aves amplamente distribuídas são mais afetadas por grandes variações climáticas globais, enquanto em regiões menores a perda de área adequada tende a ser proporcionalmente maior.

As aves florestais desempenham um papel crucial em áreas degradadas, como a Mata Atlântica, atuando como principais dispersoras de sementes e contribuindo para a regeneração ambiental. O Corredor Central da Mata Atlântica, por exemplo, destaca-se por abrigar grande biodiversidade, endemismo e cobertura florestal. No entanto, muitas aves nessa região podem não encontrar condições climáticas favoráveis em algumas áreas, o que aumenta seu risco de extinção. Além da diversidade taxonômica, as funções que as espécies desempenham e o histórico evolutivo compartilhado entre elas fornecem informações cruciais sobre o impacto das mudanças climáticas sobre as comunidades. Isso permite identificar alterações na distribuição das espécies, incluindo substituições por espécies com diferentes características e as mais vulneráveis, bem como suas localizações.

A semelhança nos padrões de perda de diversidade taxonômica, funcional e filogenética alerta para o risco não apenas de perder espécies, mas também de funções e história evolutiva. Por outro lado, as divergências observadas entre essas dimensões destacam a importância de se considerar múltiplas métricas de diversidade no planejamento de conservação. Identificamos que o litoral do Corredor Central da Mata Atlântica manterá condições climáticas adequadas para a maioria das espécies, conectando áreas altamente diversas nas regiões norte e sul, que poderiam se beneficiar com ações de reflorestamento. Além disso, áreas protegidas na região sul, apesar de abrangerem uma pequena área, poderiam ser expandidas, beneficiando especialmente espécies mais vulneráveis encontradas em altitudes elevadas.

É crucial ressaltar que, embora algumas espécies possam expandir sua área climática adequada no futuro, elas ainda podem estar ameaçadas por outros fatores não relacionados ao clima, como o desmatamento, a caça e o tráfico. Consideramos que nossas projeções são conservadoras no sentido de não terem considerado cenários de não dispersão, onde as perdas

poderiam ser significativamente maiores. No entanto, esperamos que a distribuição potencial das aves florestais do Corredor Central da Mata Atlântica para os cenários otimista e pessimista até 2070 auxilie no planejamento de conservação.

Por fim, incentivamos o uso do pacote R desenvolvido para calcular métricas de diversidade para outros grupos e localidades, contribuindo para ampliar o conhecimento sobre os impactos das mudanças climáticas sobre a biodiversidade. Integrar as distribuições das espécies com mapas de uso da terra e unidades de conservação pode facilitar a criação e/ou expansão de áreas protegidas e a implementação de reflorestamento em regiões onde há condições climáticas adequadas no futuro. Dessa forma, é possível estabelecer corredores entre fragmentos, mitigando o risco de perda de espécies, protegendo serviços ecossistêmicos essenciais e preservando a história evolutiva diante das mudanças climáticas.