IMPACT OF CLIMATE CHANGE ON THE GEOGRAPHICAL DISTRIBUTION OF A CLOUD FOREST INDICATOR TREE SPECIES

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ABSTRACT – The cloud forests are threatened due to the climate change process. Investigations seeking to predict how future climate change will affect species are of great importance as they are fundamental to generating conservation strategies. We aimed to detect how climate change affects the potential geographical distribution of *Drimys angustifolia* Miers, a tree species that is an indicator of the upper-montane cloud forest in the Brazilian subtropical Atlantic Forest. The areas where *D. angustifolia* occurs were obtained from geographic coordinates available in scientific publications and the Global Biodiversity Information database. For climate niche modeling, we used the maximum entropy algorithm with 19 climate variables. Two climate change scenarios were considered for 2061-2080: one of low and one of high impact. *D. angustifolia* predominantly occurs in the upper-montane forests and is absent from dry and warm sites. The variables that best explained the *D. angustifolia* climatic niche were mean temperature of the warmest quarter, precipitation of driest month, and precipitation of the warmest quarter. Both scenarios indicated changes towards a more tropical regional future climate. Under the low impact climate change scenario, *D. angustifolia* coverage declined by 68.24% (± 7.32%) across its area of potential occurrence; it declined by 79.15% (± 9.65%) under the high impact scenario. In conclusion, the results of the present study showed that *D. angustifolia* and its associated ecosystem are threatened by the potential impacts of future climate change. Consequently, we highlight climatically stable areas for the occurrence of *D. angustifolia*, such as those located in the highest parts of the mountain ranges of the southern and southeastern regions of Brazil, which should be considered as priority areas for protection and conservation.

Keywords: Climate variable; *Drimys angustifolia*; Upper-montane cloud forest.

IMPACTO DAS MUDANÇAS CLIMÁTICAS NA DISTRIBUIÇÃO GEOGRÁFICA DE UMA ESPÉCIE ARBÓREA INDICADORA DE FLORESTA NEBULAR

*RESUMO – As florestas nebulares estão ameaçadas devido ao processo de mudanças climáticas. Investigações que buscam prever como estas mudanças afetarão as espécies são de grande importância, pois são fundamentais para gerar estratégias de conservação. Assim, objetivamos detectar como as mudanças climáticas afetarão a distribuição geográfica potencial de **Drimys angustifolia** Miers, uma espécie arbórea indicadora da floresta nebular na Mata Atlântica subtropical brasileira. As áreas de ocorrência de **D. angustifolia** foram obtidas a partir de coordenadas geográficas disponíveis em publicações científicas e no banco de dados Global Biodiversity Information. Para a modelagem de nicho climático, usamos o Algoritmo de Máxima Entropia, com 19 variáveis climáticas. Dois cenários de mudanças climáticas foram considerados para o período 2061-2080: um de baixo e outro de alto impacto. **D. angustifolia** ocorre, predominantemente, nas florestas alto-montanas e está ausente em locais quentes e secos. As variáveis que melhor explicaram o nicho climático de **D. angustifolia** foram temperatura média no trimestre mais quente, precipitação no mês mais seco e precipitação no trimestre mais quente. Ambos os cenários indicaram mudanças em direção a um clima futuro regional mais tropical. No cenário de baixo impacto de mudanças climáticas, a cobertura de **D. angustifolia** reduziu 68,24% (±7,32%) em sua área de ocorrência potencial; e diminuiu 79,15% (±9,65%) no cenário de alto impacto. Os resultados nos permitem concluir que **D. angustifolia** e seu ecossistema associado estão ameaçados pelos possíveis*

impactos das futuras mudanças climáticas. Assim, destacamos áreas climáticas estáveis para a ocorrência de ***D. angustifolia****, como as localizadas nas partes mais altas das cadeias montanhosas das regiões Sul e Sudeste do Brasil, que devem ser consideradas áreas prioritárias para proteção e conservação.*

*Palavras-Chave: Variável climática; **Drimys angustifolia**; Floresta nebular alto-montana.*

1. INTRODUCTION

According to projections from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), global temperatures will rise by up to 4.8°C, on average, by the year 2100 (IPCC, 2014). There is evidence of strong warming in recent decades, with temperature rise exceeding that registered since 1861 when instrumental records began (IPCC, 2001). Consequently, several impacts of climate change on the planet's ecosystems have already been reported (Walther et al., 2002). Thus, investigations seeking to predict how future climate change will affect biological communities are of great importance as they are fundamental to generating mitigation strategies, including the identification of refuge areas, the protection of threatened populations, and assisted dispersal (Hoegh-Guldberg et al., 2008).

Recent studies (Becker-Scarpitta et al., 2019; Boisvert-Marsh et al., 2019) have shown that one of the main responses of species to the global warming process is a shift in their respective naturally occurring distribution, with displacement towards the poles and to areas of higher altitude. This phenomenon occurs because the geographical distribution of a given species is determined by its physiological limits, which are related to temperature tolerance and precipitation (Walther et al., 2002). Consequently, plant species that are already restricted to higher altitudes are at greatest risk, with the upper-montane cloud forests representing terrestrial ecosystems that may be strongly impacted by climate changes (Forster, 2001). Because of environmental filters such as low temperatures, these forest ecosystems have a selective environment that limits the number of species that are able to thrive, reflected in an idiosyncratic floristic composition (Higuchi et al., 2013). Thus, in the face of a range of potential climate change scenarios, biological composition is expected to change in the upper-montane cloud forests, as a result of the arrival of species from lower altitudes and extinction of endemic species in high elevation areas (Foster, 2001).

The upper-montane cloud forests situated in the subtropical part of the Brazilian Atlantic Forest represent part of a global biodiversity hotspot (Myers et al., 2000). Despite having a smaller diversity of species compared with locations at lower altitudes, these areas present a unique set of endemic species (Higuchi et al., 2012). Besides being subject to the impacts of climate change, these forests are also susceptible to forest fragmentation and other chronic anthropogenic disturbances (Higuchi et al., 2013). According to the Brazilian vegetation classification system (IBGE, 2012), these forests appear above 1,000 m altitude.

In this study, we aimed to predict how climatic change will affect this important ecosystem type, which is characterized by high endemism and has important environmental functions, such as soil and water course protection (Martínez et al., 2009). We modelled the climate niche of *Drimys angustifolia* Miers, a species that exhibits a high affinity with this type of forest formation. Subsequently, we projected current and future areas of climatic suitability for this species. We hypothesized that there will be a reduction in the potential distribution area for *D. angustifolia* because this species is restricted to sites located at the highest altitudes. Our results are expected to provide baseline information to develop viable conservation strategies, such as the selection of conservation areas that could potentially serve as a climate refuge.

2. MATERIAL AND METHODS

We carried out a bibliographic review of published studies to select the species that had the highest affinity with the upper-montane cloud forest of the subtropical portion of the Brazilian Atlantic Forest. We considered two criteria: i) the study area should be a cloud forest; and ii) the study area should be part of the subtropical portion of the upper-montane Atlantic Forest. For i), in addition to existing knowledge of some of these forests, we assumed that these areas should have cloud coverage above 60%, according to Wilson and Jetz (2016). For ii), according to the Brazilian system of vegetation classification (IBGE, 2012), the area must have an altitude above 1,000 m and be located to the south of the Tropic of Capricorn. We found 26 studies (https://figshare.com/s/b56bf1877a40fc18894f) that

met these criteria. *D. angustifolia* was present in 15 areas and was selected as an indicator species because it has a broad distribution in the specified areas and predominantly occurs at the highest points of southern Brazil (https://figshare.com/s/0ad8dd97528c3403b25f). According to Hertzog et al. (2016), in Rio Grande do Sul State, in southern Brazil, *D. angustifolia* occurs from 700 to 1,400 m altitude. Furthermore, observations of its geographical area of distribution show that this species has a higher occurrence above 1,000 m altitude (Martins et al., 2012; Silva et al., 2017). Although other listed species are also frequently found in high montane cloud forests, what makes *D. angustifolia* unique is that it is mostly found exclusively in such environments (Uhlmann et al., 2013), besides being locally present in high abundance (Higuchi et al., 2013).

To complement the occurrence data for *D. angustifolia* obtained from the literature review, we also used information about geographical distribution provided by the GBIF database (GBIF Secretariat, 2017; GBIF.org, 2019). All coordinates were checked to find inconsistencies such as typos and/or doubtful geographical areas (Hijmans and Elith, 2017). In addition, spatial filtering was performed to select one occurrence in a 4.63 × 4.63 km grid area, as bias might exist in records related to nearby herbaria, research institutes, and universities (Boria et al., 2014). We considered this spatial resolution because the study species has a geographically restricted distribution (n = 103), concentrated on regional mountains tops. A total of 43 occurrence grid cells remained after spatial filtering.

We considered 19 climatic variables—which were obtained from the WorldClim 1.0 database (Hijmans et al., 2005)—as explanatory variables of the geographical distribution of the species. We choose this version of WorldClim because it is the only version that provides future climatic conditions. These climatic variables were derived from monthly values of temperature and precipitation (averaged for 1961-1990), with the purpose of representing climatic conditions relevant for developing different life forms, in a grid of 2.5 minutes resolution (~4.63 km^2). The following variables were used: bio 1 (Annual Mean Temperature), bio 2 (Temperature Mean Diurnal Range), bio 3 (Isothermality), bio 4 (Temperature Seasonality), bio 5 (Maximum Temperature of Warmest Month), bio 6 (Minimum Temperature of Coldest Month), bio 7 (Temperature Annual Range), bio 8 (Mean Temperature

of Wettest Quarter), bio 9 (Mean Temperature of Driest Quarter), bio 10 (Mean Temperature of Warmest Quarter), bio 11 (Mean Temperature of Coldest Quarter), bio 12 (Annual Precipitation), bio 13 (Precipitation of Wettest Month), bio 14 (Precipitation of Driest Month), bio 15 (Precipitation Seasonality), bio 16 (Precipitation of Wettest Quarter), bio 17 (Precipitation of Driest Quarter), bio 18 (Precipitation of Warmest Quarter), and bio 19 (Precipitation of Coldest Quarter). To remove problems related to multicollinearity of the climatic explanatory variables (Graham, 2003), the Variance Inflation Factor (VIF) values for these variables were determined. All values that were highly correlated (VIF > 10) were removed through a stepwise procedure, using the vifstep R function from the usdm package (Naimi et al., 2014). Eight explanatory variables were used after accounting for multicollinearity (bio2, bio3, bio8, bio9, bio10, bio12, bio14, and bio18) (Figure 1). An elevation map with a grid of 2.5 minutes resolution was also extracted from WorldClim.

To predict how future climate changes will affect the distribution of *D. angustifolia*, we considered, for the year 2070 (average for 2061-2080), five atmospheric global circulation models (GCMs) (CCSM4, GISS-E2-R, ACCESS1-0, HadGEM2-AO, MIROC5). These GCMs are frequently used for predicting species distributions in South America (Yañez-Arenas et al., 2016; Graham et al., 2017) and they are part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the IPCC Fifth Assessment. In addition, we considered two scenarios of climate change: RCP 4.5 (considered to be relatively less impactful) and RCP 8.5 (considered to be most impactful). In the low impact scenario (RCP 4.5), it is assumed that society will adopt measures to control greenhouse gas emissions. In the high impact scenario (RCP 8.5), it is assumed that humanity will not try to reduce the emission of greenhouse gases, which will consequently continue to increase. The climatic data for the projections for the listed climatic variables were obtained from WorldClim (Hijmans et al., 2005).

Modeling of the climate niche was performed using the Maximum Entropy algorithm (Maxent) (Phillips et al., 2017). For this approach—as recommended by Phillips and Dudík (2008) and Barbet-Massin et al. (2012)—we used a large number of pseudo-absences (10,000) with no replication, which were distributed within 500 km radius buffers centered at each occurrence point. As we did not have independent data to test model accuracy (Pearson et al., 2007; Thuiller et al.,
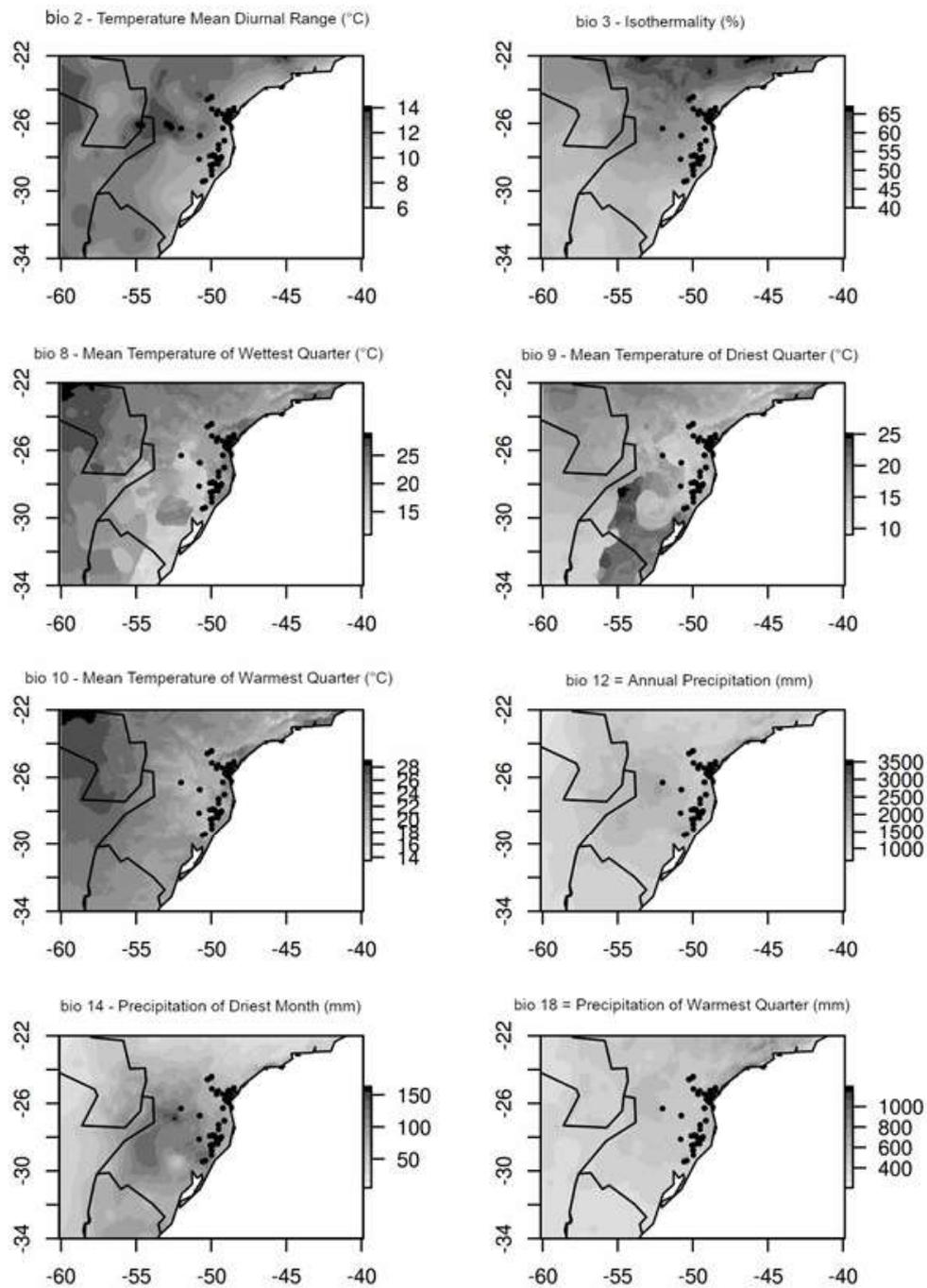
Figure 1 – Maps of climatic explanatory variables used in *Drimys angustifolia* distribution modeling. Darker gray shades represent higher values of bioclimatic variables. Black dots are the geographical occurrence of *D. angustifolia*.
*Figura 1 – Mapas das variáveis explicativas climáticas utilizadas na modelagem **Drimys angustifolia**. Tons mais escuros de cinza representam maiores valores das variáveis bioclimáticas. Pontos negros indicam a ocorrência geográfica de **D. nagustifolia**.*

2017), we evaluated model adjustment by splitting the data (presence plus pseudo-absence) into two groups: 70% randomly selected for model calibration (training) and the remaining 30% for model evaluation (testing) (Thuiller, 2003). This process of model evaluation was repeated five times and the performance of the adjusted models was evaluated through True Skill Statistics (TSS), with scores ranging from -1 to 1 (Allouche et al., 2006); the closer to 1, the better the fit of the model. TSS is determined as sensitivity + specificity -1, where sensitivity and specificity are, respectively, the proportion of correctly predicted presences and absences (Allouche et al., 2006). We adopted the classification of Landis and Koch (1977), in which TSS ≥ 0.75 indicates adjustments of excellent performance, 0.40≤ TSS< 0.75 indicates adjustments with good performance, and TSS < 0.40 indicates poor performance. Thus, based on the "evaluation strip" method proposed by Elith et al. (2005), which is an extension of other existing modelling techniques to be applied to raster data, we plotted response curves between the estimates of climatic suitability and the explanatory variables for the model adjustments. To reduce the inherent predictive uncertainty of adjustment in each individual model, current and future predictions (RCP 4.5 and RCP 8.5) of the potential geographic distribution of the species were performed using the consensus of all model adjustments that were classified with excellent performance (TSS ≥ 0.75). This is an important step, as the uncertainty related to poor performance adjustments may result in unrealistic climate suitability projections.

To quantify the impact of different climate change scenarios, we produced a binary projection of potential areas of geographic occurrence, both for the present and future. We considered suitable areas based on ROC analysis. Current and future (RCP 4.5 and 8.5) projections were superimposed and areas of stable habitat (suitable currently and in the future), unstable future habitat (suitable only in the future), unstable current habitat (only suitable currently), and stable non-habitat were determined. All analyses were performed using R statistical programming language (R Core Team, 2017), with the usdm (Naimi et al., 2014), dismo (Hijmans et al., 2017), raster (Hijmans, 2017) and biomod2 (Thuiller et al., 2017) packages.

3. RESULTS

The geographic distribution of the studied species, _D. angustifolia_, is restricted to southern Brazil (Figure 2 a, b). In general, the areas where _D. angustifolia_ is currently occurring will become more tropical, with higher temperatures and humidity, followed by a lower seasonality. (Table 1). Based on these adjustments and observed occurrence areas, high estimates of potential climate suitability were observed in high altitude areas, predominantly in southern Brazil, supporting the preference of _D. angustifolia_ for climatic niches typical of upper-montane forest formations.

According to model adjustments with excellent performance (TSS ≥ 0.75), the variables that best explained the climatic niche of _D. angustifolia_ were Mean Temperature of Warmest Quarter (bio10), Precipitation of Driest Month (bio14), and Precipitation of Warmest Quarter (bio18). For these adjustments, the TSS ranged from 0.934 to 0.798. _D. angustifolia_ is more likely to occur in places where, during summer (warmer quarter), the average temperature does not exceed 19°C, precipitation in the driest month exceeds approximately 100 mm, and precipitation in the warmest quarter exceeds 700 mm (Figure 2c). Thus, the area of potential occurrence for _D. angustifolia_ is characterized by summers with mild temperatures and an absence of dry periods.

When comparing the area of current climate suitability and the potential area according to the low (RCP 4.5, Figure 3) and high (RCP 8.5, Figure 4) impact scenarios, it is estimated that the potential area of occurrence of _D. angustifolia_ will decline by an average of 68.24% (± 7.32%) and 79.15% (± 9.65%), respectively. These losses will mainly occur in areas of lower altitude. Unstable future habitat (suitable only in the future) did not exceed an average of 1.5% for either scenario.

4. DISCUSSION

The results of this study showed that the distribution of _D. angustifolia_ is restricted mainly to southern Brazil, in the high altitude forests of this region. This geographic pattern is conditioned by the climatic niche of this species, which is characterized by mild temperatures and the absence of a dry season. This species is present at high abundance in cloudy upper-montane areas (Martins et al., 2012; Silva et al., 2017), suggesting that it has a high capacity to occupy this type of environment.

In relation to the impacts observed for the different scenarios of climate change, _D. angustifolia_ should be
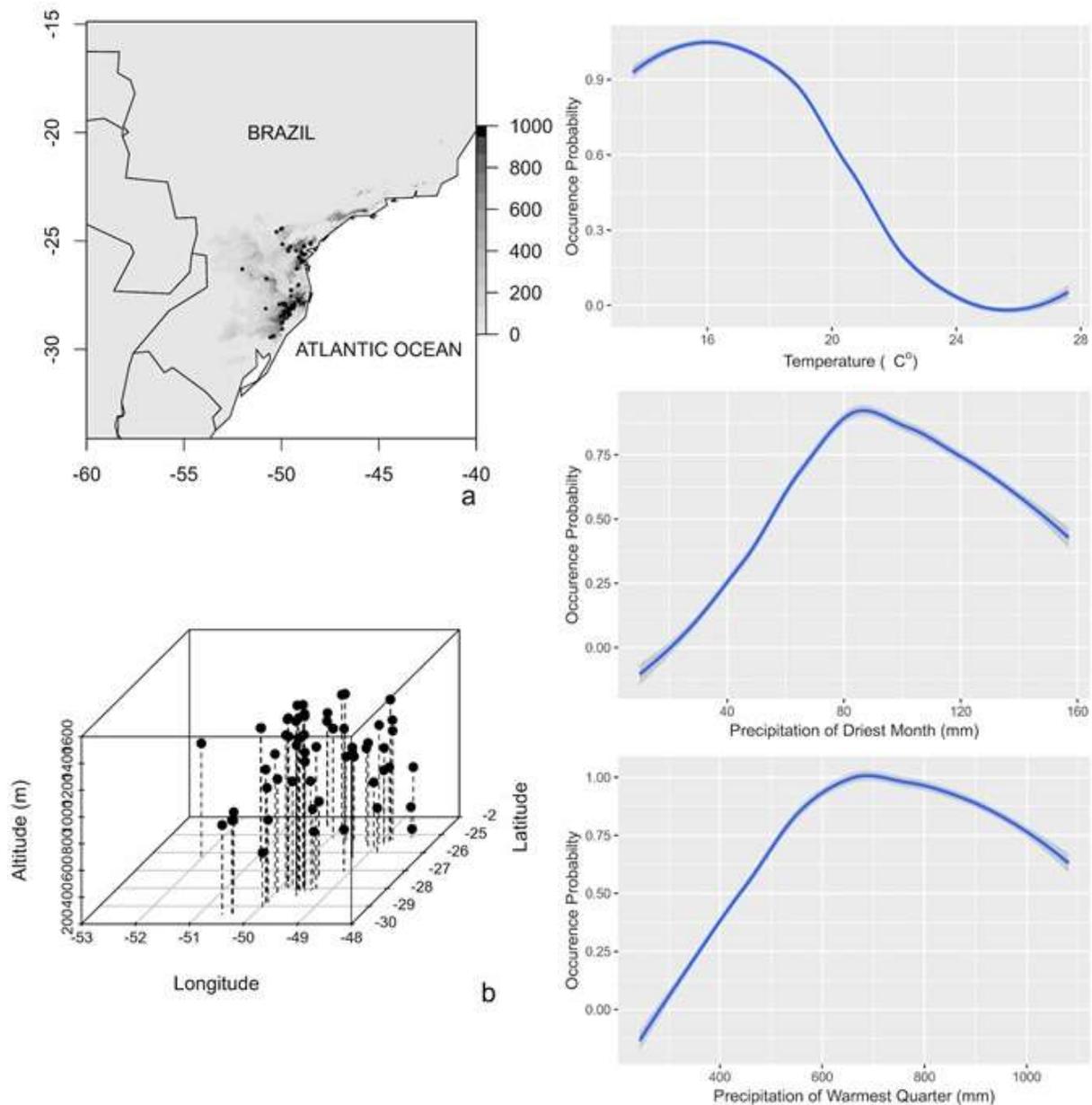
Figure 2 – Geographical distribution of *Drimys angustifolia* with (a) ensemble forecasting of species occurrence. (b) Three-dimension scatterplot of *D. angustifolia* occurrence, considering the latitude, longitude, and altitude. Shades of gray, from darker to lighter, represent the gradient of greater to lesser climatic suitability for the species (%). (c) Probability of occurrence of *D. angustifolia* along the most significant climatic gradients [bio 10 - Mean Temperature of Warmest Quarter (°C); bio 14 - Precipitation of Driest Month (mm); bio 18 - Precipitation of the Warmest Quarter (mm)].

Figura 2 – *Distribuição geográfica de* **Drimys angustifolia** *com (a) a projeção de ocorrência baseada na probabilidade média de todos os ajustes do modelo que foram classificados com excelente desempenho (TSS ≥ 0,75). (b) Gráfico dispersão tridimensional da distribuição geográfica de* **D. nagustifolia**, *considerando a latitude, longitude e altitude. Tons de cinza, de mais escuro para mais claro, representam o gradiente de maior a menor adequação climática para a espécie (%). (c) Probabilidade de ocorrência de* **D. angustilofia** *ao longo dos gradientes climáticos mais significativos [bio 10 – temperatura média do trimestre mais quente (°C); bio 14 – precipitação no mês mais seco (mm); bio 18 – precipitação no trimestre mais quente (mm)].*

Table 1 – Predicted future climate change (mean values and standard errors in parentheses) to occur in the region of *Drimys angustifolia* occurrence range, according to IPCC RCP 4.5 and RCP 8.5 scenarios (bio 2 = Temperature Mean Diurnal Range; bio 3 = Isothermality; bio 8 = Mean Temperature of Wettest Quarter; bio 9 = Mean Temperature of Driest Quarter; bio 10 = Mean Temperature of Warmest Quarter; bio 12 = Annual Precipitation; bio 14 = Precipitation of Driest Month; bio 18 = Precipitation of Warmest Quarter).

*Tabela 1 – Previsões de mudanças climáticas futuras (valores médios e erros padrão entre parênteses) que ocorrerão na região do intervalo de ocorrência de **Drimys angustifolia**, de acordo com os cenários do IPCC RCP 4.5 e RCP 8.5 (bio 2 = temperatura média diurna; bio 3 = isotermalidade; bio 8 = temperatura média no trimestre mais úmido; bio 9 = temperatura média no trimestre mais seco; bio 10 = temperatura média no trimestre mais quente; bio 12 = precipitação anual; bio 14 = precipitação no mês mais seco; bio 18 = precipitação no trimestre mais quente).*

Present	Change RCP 4.5	Change RCP 8.5	
		Future (2061-2080)	
bio 2 (°C)	10.89	-0.31(0.13)	-0.37 (0.05)
bio 3 (%)	55.10	-0.13(0.07)	-0.16 (0.07)
bio 8 (°C)	18.89	0.96 (0.53)	1.16 (0.48)
bio 9 (°C)	13.81	0.24 (0.43)	4.88 (0.92)
bio 10 (°C)	20.32	0.22 (0.17)	3.28 (0.30)
bio 12 (mm)	1606.44	531.41 (70.96)	834.96(130.72)
bio 14 (mm)	94.89	21.96 (2.60)	30.74 (5.82)
bio 18 (mm)	484.78	110.36 (20.73)	178.72 (25.13)

considered as a highly sensitive species, because the area of climatic suitability for this species was estimated to decline by 68 to 79%, in response to a climate change towards more tropical conditions (warmer and wetter) in the future. Previous studies have shown that one of the responses of different terrestrial species to past and present climate change is to shift their distribution towards higher altitudes and latitudes (Chen et al., 2011; Hickling et al., 2006; Kelly and Goulden, 2008). However, for species already restricted to areas of higher altitude, such as *D. angustifolia*, this strategy is not possible, which renders these species more susceptible to the impacts of climate change, like the upper-montane ecosystem itself. In general, the results for *D. angustifolia* are in line with the patterns observed for some other species in the Araucaria Forest, which are found in lower altitudinal levels (Bergamin et al., 2019; Wilson et al., 2019; Marchioro et al., 2020). Climate changes predicted for this century will have a substantial impact on the whole forest formation, reducing the species climatic suitability area, which will tend to be restricted to places of higher altitude (Bergamin et al., 2019; Wilson et al., 2019; Marchioro et al., 2020). Given this critical scenario, there is an urgent need to undertake mitigation initiatives, such as in-situ (climate refuge protection) and ex-situ (germplasm banks) conservation strategies.

One should note that our findings must be understood only under the context of the species' climatic niche, a part of the fundamental niche. The understanding of the realized niche, beyond our scope in this study, would require further investigation of other factors. Besides the climate, other ecological factors play important roles in species distribution, such as biotic interactions (Wisz et al., 2013) and anthropogenic disturbances (Escobar et al., 2015). The negative effects of anthropogenic activities on terrestrial ecosystems, such as habitat fragmentation, are one of the main causes of species extinction (Tilman et al., 1994). If unsuitable areas (e.g., agriculture, cattle pasture, urbanization) are missed in distribution models, projected available areas could be overestimated. Furthermore, such chronic disturbances might result in the biological homogenization of forests (Ribeiro et al., 2015) and cannot be overlooked, because the fostering of pervasive and disturbance adapted species may give rise to a greater constraint on the occurrence of relatively less generalist ones. In southern Brazil, forests (including upper-montane cloud areas) have been subject to intense disturbances of this nature (e.g., fragmentation, selective logging, and cattle ranching) since the beginning of the 20th century, with deforestation peaking in the 1970s (Carvalho and Nodari, 2008). Considering this, it is reasonable to assume that both aspects have the potential to influence species distribution and neither should be neglected when planning conservation strategies.

5. CONCLUSION

The results of the present study showed that *D. angustifolia* and its associated ecosystem, the cloud forests of the southern portion of the Atlantic Forest in
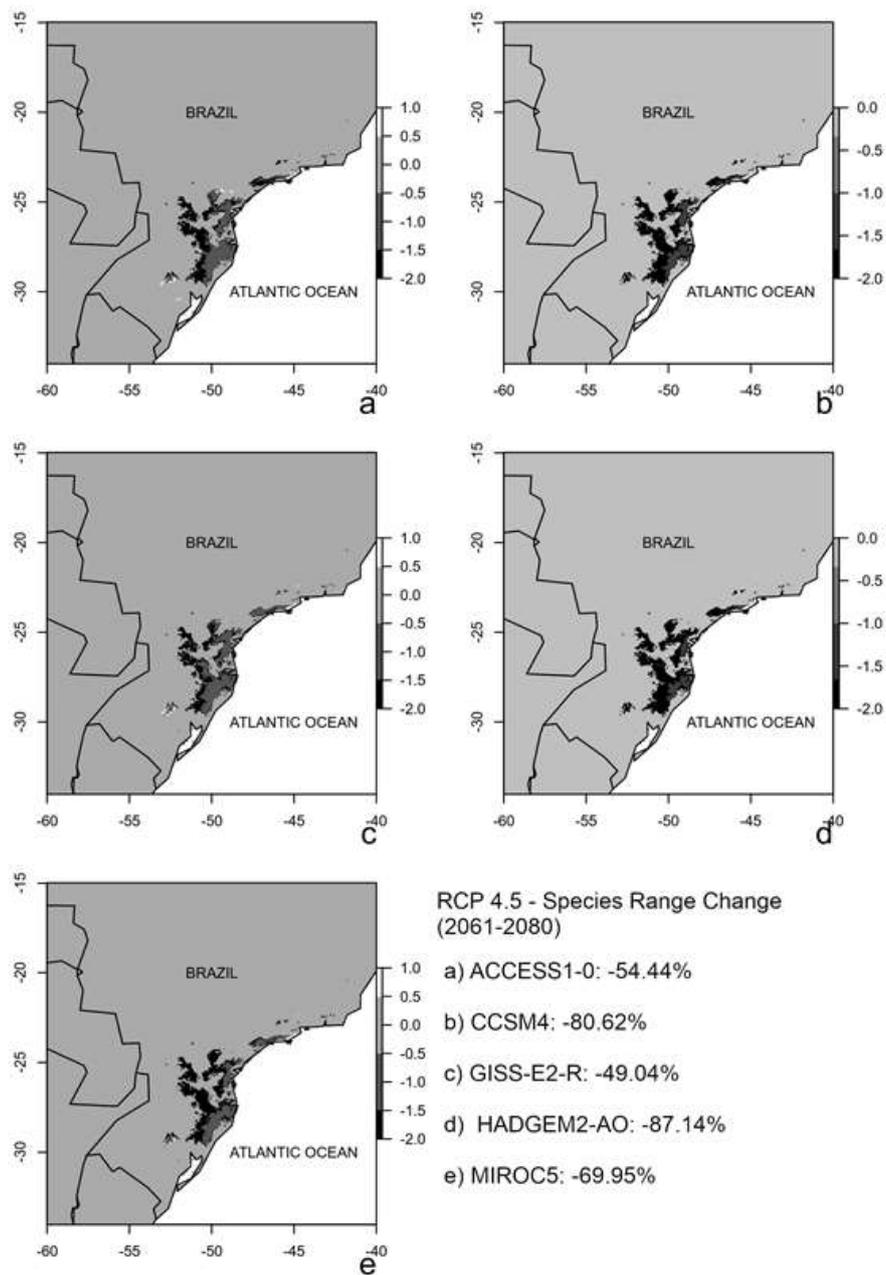
Figure 3 – Future (2061-2080) climatically suitable areas for *Drimys angustifolia*, indicating the patterns of change for low (RCP 4.5) impact scenarios, according to five different atmospheric global circulation models (GCMs) (CCSM4, GISS-E2-R, ACCESS1-0, HadGEM2-AO, MIROC5). Dark gray = stable habitat (suitable both in current and future); light gray = stable non-habitat; black = unstable current habitat (suitable only in current); white = unstable future habitat (suitable only in future).

Figura 3 – *Áreas climáticas futuras (2061-2080) adequadas para **Drimys angustifolia**, indicando os padrões de mudança para cenários de baixo impacto (RCP 4.5), de acordo com cinco modelos diferentes de circulação global da atmosfera (GCMs) (CCSM4, GISS-E2-R, ACCESS1-0, HadGEM2-AO, MIROC5). Cinza escuro = habitat estável (adequado tanto no presente quanto no futuro); cinza claro = habitat estável onde não há ocorrência da espécie; preto = habitat atual instável (adequado apenas no presente); branco = habitat futuro instável (adequado apenas no futuro).*
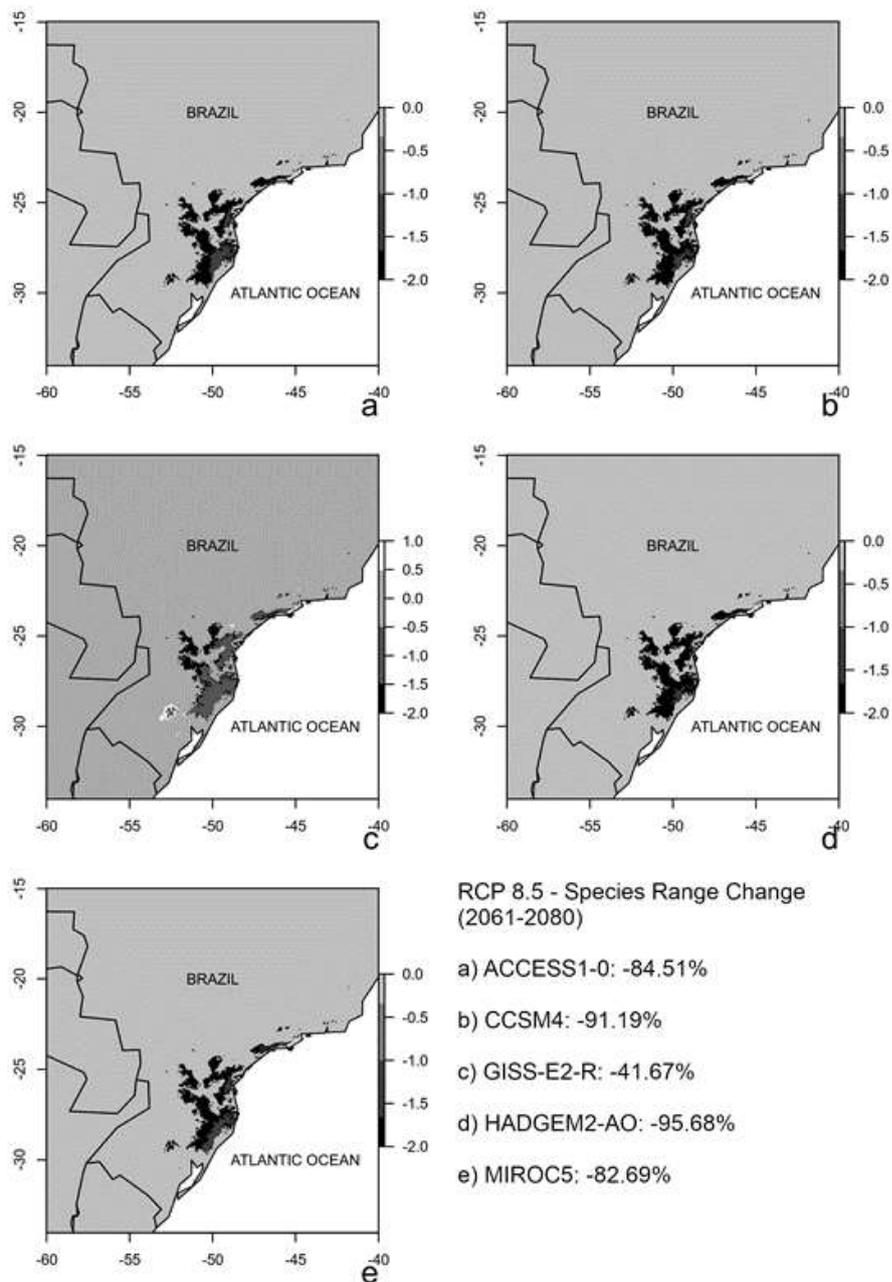
Figure 4 – Future (2061-2080) climatically suitable areas for *Drimys angustifolia*, indicating the patterns of change under a low (RCP 8.5) impact scenario, according to five different atmospheric global circulation models (GCMs) (CCSM4, GISS-E2-R, ACCESS1-0, HadGEM2-AO, MIROC5). Dark gray = stable habitat (suitable both in current and future); light gray = stable non-habitat; black = unstable current habitat (suitable only in current); white = unstable future habitat (suitable only in future).

Figura 4 – *Áreas climáticas futuras (2061-2080) adequadas para **Drimys angustifolia**, indicando os padrões de mudança para cenários de baixo impacto (RCP 8.5), de acordo com cinco modelos diferentes de circulação global da atmosfera (GCMs) (CCSM4, GISS-E2-R, ACCESS1-0, HadGEM2-AO, MIROC5). Cinza escuro = habitat estável (adequado tanto no presente quanto no futuro); cinza claro = habitat estável onde não há ocorrência da espécie; preto = habitat atual instável (adequado apenas no presente); branco = habitat futuro instável (adequado apenas no futuro).*

Brazil, are threatened by the potential impacts of future climate change. Consequently, we highlight climatically stable areas for the occurrence of *D. angustifolia*, such as those located in the highest parts of the mountain ranges of the southern and southeastern regions of Brazil, which should be considered as priority areas for protection and conservation as they are potential climatic refuges.

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