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1   **Title:** Expected impacts of climate change on tree ferns distribution and diversity  
2   patterns in subtropical Atlantic Forest

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4   **Running title:** Tree ferns distribution and diversity in future scenarios

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33 **ABSTRACT**

34 Tree ferns are common elements in subtropical Atlantic Forest, sometimes reaching  
35 more than half of dominance at forest sites. Climate change could impact the  
36 distribution and diversity of tree ferns, hence impacting the ecological processes  
37 provided by them. We investigate the impacts of future climate changes in the potential  
38 distribution of tree fern species, as well as in the  $\alpha$ - and  $\beta$ -diversity. Our first hypothesis  
39 ( $H_1$ ) is that warmer climate in the future will increase the distribution of Cyatheaceae  
40 species and decrease the distribution of Dicksoniaceae species. Due to a larger number  
41 of Cyatheaceae than Dicksoniaceae, the richness will tend to increase. However, the  
42 increase in richness might lead to homogenization, consequently decreasing  $\beta$ -diversity  
43 ( $H_2$ ). To test these hypotheses, we used distribution models to predict the potential  
44 species distribution in the present and future. Then, we calculated the changes in  
45 potential distribution areas,  $\alpha$ -, and  $\beta$ -diversity components between scenarios. Finally,  
46 we assessed the impact of these changes within Protected Areas. We found that  
47 Dicksoniaceae distribution tends to shrink in the future, while half of Cyatheaceae tend  
48 to lose distribution. Species richness tends to decrease in the future, as well as  $\beta$ -  
49 diversity. At least 43% of the sites tend to have their species richness reduced, while  
50 only 26% of sites tend to gain species. Our results suggest that species associated with  
51 cold environments will lose suitable areas and are more threatened. Richness tends to  
52 decrease mainly in sites with high precipitation seasonality. Furthermore, the tree ferns  
53 assemblage tends to homogenize.

54 **Keywords:** Beta-diversity, climate change, Cyatheaceae, Dicksoniaceae, species  
55 distribution modelling, tree ferns.

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58 **1. INTRODUCTION**

59

60 Tree ferns are expressive elements in (sub)tropical forest formations (Tryon &  
61 Tryon, 1982), sometimes establishing monodominant forests (Gasper et al., 2011). For  
62 this reason, tree ferns act in the dynamics of the ecosystem and may affect the  
63 regeneration of wood species and nutrient cycling (Brock, Perry, Lee & Burns, 2016).  
64 In addition, they contribute to the process of ecological succession (Arens & Baracaldo,  
65 1998), to biomass stock in tropical forests (Sarmiento, Pinillos, & Garay, 2005), and  
66 provide microhabitat for several epiphytic plants, many of them occurring exclusively  
67 on tree ferns caudices (Wagner, Mendieta-Leiva, & Zott, 2015).

68 Tree ferns have suffered intense exploitation in the tropical forest due to  
69 ornamental use of their caudices (Eleutério & Pérez-Salicrup, 2006; Hoshizaki, &  
70 Moran, 2001), causing populational exhaustion of many species (Santiago, Mynssen,  
71 Maurenza, Penedo, & Sfair, 2013). Combined with this, the actual high forest  
72 fragmentation in the Atlantic Forest (Ribeiro, Metzger, Martensen, Ponzoni, & Hirota,  
73 2009) plus climate change scenarios (IPCC, 2014; Lima, Ribeiro, Grelle, & Pinto, 2019)  
74 are other potential sources of threat to tree ferns. These threats might change the density  
75 and distribution of these species as well as the locations of the suitable area to grow and  
76 reproduce.

77 Moreover, despite tree ferns being an important group in forest structure, these  
78 plants are historically neglected in floristic and ecological studies in Brazil (Weigand &  
79 Lehnert, 2016). There are two main families of tree ferns in subtropical Atlantic Forest:  
80 Dicksoniaceae and Cyatheaceae. The former is represented by *Dicksonia sellowiana*, a  
81 species that inhabits high and cold environments (Gasper et al., 2011), and *Lophosoria*

82 *quadripinnata*, that grows in ravines, doing best on moist, well-drained soil and in full  
83 sun until 2000 m in eastern Brazil (Lehnert & Kessler, 2018). The later family (about 14  
84 species) exhibits a preference for warm, humid and low seasonal climates (Bystriakova,  
85 Schneider, & Coomes, 2011) and may benefit from warmer climate regimes.

86 The Intergovernmental Panel on Climate Change (IPCC) predicts shifts in  
87 rainfall and temperature in the subtropical Atlantic Forest, and since water availability is  
88 correlated to fern species richness (Kessler, Kluge, Hemp, & Ohlemüller, 2011), rainfall  
89 regimes modifications could impact in ferns distribution. Therefore, a reduction of cold  
90 environments and increasing of warm and humid environments may impact *D.*  
91 *sellowiana*, an already endangered species, through the restriction of its occurrence area.

92 In this regard, our study sought to predict the impacts of future climate changes  
93 in  $\alpha$ - and  $\beta$ -diversity of tree ferns in the subtropical Atlantic Forest, as well as to predict  
94 the impact in the potential distribution of each species. Our first hypothesis ( $H_1$ ) is that  
95 species from both families will change their potential distribution areas. We expect  
96 Dicksoniaceae species will have their potential distribution area reduced (specially  
97 *Dicksonia sellowiana*) because of their association with cold habitats — and  
98 Cyatheaceae species will increase their potential distribution areas since they generally  
99 occur along hot and humid regions. Our second hypothesis ( $H_2$ ) is that the changes in  
100 species distribution will affect  $\alpha$ - and  $\beta$ -diversity. Since we expect the Cyatheaceae  
101 species will increase their distribution range, hence increasing the overlap in species  
102 areas, we expect an increase in  $\alpha$ -diversity and a decrease in  $\beta$ -diversity, i.e., less  
103 variation in species composition among sites, leading to a homogenization of our study  
104 region.

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## 107 2. MATERIAL AND METHODS

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109

### 2.1 Study area

110 The study area is delimited by the subtropical Atlantic Forest, floristically distinct from  
111 the tropical Atlantic Forest (Eisenlohr & Oliveira-Filho, 2014). The subtropical Atlantic  
112 Forest occurs in southern Brazil as well as in parts of Argentina and Paraguay (C.  
113 Galindo-Leal & Câmara, 2005). The predominant climate type is Cfa (temperate humid  
114 with hot summer), with some areas fluctuating to Cfb (temperate humid with temperate  
115 summer). The relief ranges from sea level to altitudes near 1200 m, including peaks that  
116 reach almost 1900 m. Distinct forest types can be found, which includes Restinga, on  
117 the coastal areas; Rainforests, in low altitudes at the coastal region (< 800–900 m);  
118 Mixed Forests (*Araucaria* forest), generally in areas with altitudes over 800 m; and  
119 Semideciduous Forests in low areas with high seasonality in precipitation (Figure 1).

120

121

### 2.2 Data gathering

122 Among the species that occur in subtropical Atlantic Forest (following Brazilian  
123 Flora 2020 in construction 2019; Fernandes 1997; Lehnert & Weigand, 2016), we  
124 identified 1167 records and 15 species from the literature (Fernandes, 1997; Vibrans,  
125 Sevegnani, Lingner, Gasper, & Sabbagh, 2010) and herbaria (using SpeciesLink –  
126 <http://splink.cria.org> and GBIF Global Biodiversity Information Facility –  
127 <https://www.gbif.org>). Uncertain records were removed, as well as *Cyathea uleana* due  
128 to its low number of registers.

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130

The data available for the study area was under the effect of sampling biases.  
This issue arose because, in the state of Santa Catarina, the Floristic and Forest

131 Inventory of Santa Catarina (IFFSC; Vibrans et al., 2010) had strongly sampled the  
132 state's territory — an effort that did not take place in other locations of the study area.  
133 To minimize sample biases, we performed spatial filtering on the occurrence data by  
134 defining a buffer of  $\geq 30$  km as a minimum distance between occurrence records in all  
135 study areas (Fourcade, Engler, Rödder, & Secondi, 2014).

136 Climate data were obtained for the present and future climate change scenarios  
137 from WorldClim v2.0 (Fick & Hijmans, 2017) and WorldClim v1.4 (Hijmans,  
138 Cameron, Parra, Jones, & Jarvis, 2005), respectively. Data for the future scenario refers  
139 to the year 2050 and was based on the climate projections made by IPCC. We used the  
140 mean of four Earth System Models (ESM) for future modeling: NorESM1-M (Bentsen  
141 et al., 2013), MIROC-ESM (Watanabe et al., 2011), HadGEM2-ES (Jones et al., 2011),  
142 and CNRM-CM5 (Voldoire et al., 2013). For these models, two future scenarios were  
143 selected: the most optimistic (RCP 2.6) and the most pessimistic (RCP 8.5), which were  
144 elaborated and named accordingly to the concentration of carbon dioxide in the  
145 atmosphere ( $\text{W/m}^2$ ) between the pre-industrial period and the year 2100 (IPCC, 2014).  
146 In all tested ESMs we chose 19 environmental variables (bioclim) with 2.5' resolution.  
147 We used the Variance Inflation Factor (VIF) via the *vifstep* function on *usdm* R-package  
148 (Naimi, Hamm, Groen, Skidmore, & Toxopeus, 2014; R Core Team 2015) to remove  
149 collinearity. This function generates 5,000 random points across the climate layers and  
150 calculates the VIF for each variable using a step-by-step procedure. At each step, the  
151 layer with the highest VIF is removed from the set. The process is repeated until only  
152 variables with a VIF value below a defined threshold remain. We used a restrictive VIF  
153 value (VIF = 5) that reduced the 19 climate variables to six: Annual Mean Temperature  
154 (BIO01), Isothermality (BIO03), Temperature Annual Range (BIO07), Mean  
155 Temperature of Driest Quarter (BIO09), Precipitation of Wettest Month (BIO13) and  
156 Precipitation of Coldest Quarter (BIO19).

157

### 158 **2.3 Species Distribution Models (SDMs)**

159

160 We used SDMs to predict current and future distributions of each species. Our  
161 SDMs were formulated using the *sdm* R-package (Naimi & Araújo, 2016) through five  
162 different algorithms: MaxEnt (Phillips, Dudík, & Schapire, 2004), Boosted Regression  
163 Trees (BRT; Friedman, 2001), Generalized Linear Models (GLM; McCullagh &  
164 Nelder, 1989), Multivariate Adaptive Regression Spline (MARS; Friedman, 1991), and  
165 Support Vector Machine (SVM; Vapnik, 2013), all with default settings. Moreover, as  
166 proposed by Barbet-Massin, Jiguet, Albert, & Thuiller (2012), we applied 10 000  
167 pseudo-absences for each species randomly created across the study area.

168 We evaluated the performance of the models generated by each algorithm  
169 through a cross-validation procedure with 10 repetitions, where data were randomly  
170 divided into training, amounting to 70% of the data, and testing, comprising the  
171 remaining 30%. Two statistical methods were responsible for evaluating the robustness  
172 of the models: Area Under the Curve (AUC) of the receiver operating characteristic  
173 curve (ROC; Fielding & Bell, 1997) — a threshold-independent metric — and True  
174 Skill Statistic (TSS; Allouche, Tsoar, & Kadmon, 2006) — a threshold-dependent  
175 metric. All generated models were above the previously established cutoff values (AUC  
176  $> 0.70$  and TSS  $> 0.40$ ).

177 To avoid biases created by choosing a single statistical algorithm, as pointed out  
178 by several studies (e.g., Araújo & New, 2007; Grenouillet, Buisson, Casajus, & Lek,

179 2011), we built a single final model through an ensemble approach. In this sense, the  
180 models generated by statistical algorithms were projected using current and future  
181 climate, and the ensemble model for each scenario was considered as the mean  
182 weighted by the AUC value of the projections of each algorithm. Binary maps  
183 (presence-absence) were made based on the threshold that maximizes the sensitivity  
184 plus specificity of the models (maxSSS; Liu, Newell, & White, 2016), calculated with  
185 the R-package *SDMtools* (VanDerWal, Falconi, Januchowski, Shoo, & Storlie, 2014).  
186 The threshold was calculated for each species based on the final ensemble map of the  
187 current scenario. Likewise, the resulting threshold value for the current scenario was  
188 also used to build binary maps for future scenarios.

189

#### 190 **2.4 Species distribution and diversity patterns**

191

192 To understand how climate change will affect species distribution and diversity  
193 patterns, the study area was divided into hexagonal cells of  $\cong 200 \text{ km}^2$ . Based on SDM  
194 predictions for tree ferns, we measured for each scenario the changes of suitable cells  
195 for all species and the  $\alpha$ - and  $\beta$ -diversity indexes. We also evaluate the same metrics  
196 exclusively in grid cells that overlap Protected Areas (PAs) in the study region. We  
197 obtained the boundaries of PAs from the World Database on Protected Areas (UNEP-  
198 WCMC, 2019). Therefore, we can compare species distribution and diversity indexes  
199 between protected and non-protected areas for any specific scenario.

200

201 We measured  $\alpha$ -diversity as the number of species present in each cell, i.e., the  
202 predicted species richness. We calculated the  $\beta$ -diversity as the total variance of the  
203 community (Total  $\beta$ -diversity, or  $\text{BD}_{\text{TOTAL}}$ ; *sensu* Legendre & De Cáceres, 2013) and it  
204 was subsequently decomposed in Local Contributions to  $\beta$ -Diversity (LCBD). LCBD  
205 represents the ecological uniqueness of each hexagonal cell regarding species  
206 composition. We calculated  $\text{BD}_{\text{TOTAL}}$  based on the Jaccard dissimilarity coefficient (1 –  
207 similarity). Then, the LCBD was determined based on the partition of  $\text{BD}_{\text{TOTAL}}$  between  
208 the cells (Legendre & De Cáceres, 2013). The significance of the LCBD values for each  
209 cell was obtained through 999 permutations, where the species are distributed randomly  
210 and independently along the grid and the LCBD values are calculated for each random  
distribution. Significant LCBD values were those with  $p\text{-value} < 0.05$ .

211

212 Finally, we followed Legendre (2014) by partitioning the  $\text{BD}_{\text{TOTAL}}$  in species  
213 replacement and richness difference components, using the replacement ( $\text{Repl}_j$ ) and  
214 richness difference ( $\text{RichDiff}_j$ ) indexes of the Podani family (*sensu* Podani & Schmera,  
215 2011; Legendre, 2014). All  $\beta$ -diversity metrics were calculated with the *adespatial* R-  
216 package (Dray et al., 2019) using the functions *beta.div* and *beta.div.comp*. We used  
217 QGIS 3.8 (QGIS Development Team 2019) to generate the maps. Lastly, to test  
218 differences in  $\alpha$ -diversity between current and future scenarios, we conducted the  
219 Wilcoxon Rank-Sum Test, a non-parametric unpaired test, for the current scenario  $\times$   
RCP 2.6 scenario and current scenario  $\times$  RCP 8.5 scenario.

220

221

### 222 **3. Results**

223

224

All models had a good predictive power (AUC: mean = 0.825, sd = 0.05; TSS:  
mean = 0.623, sd = 0.14 — for individual distribution maps and statistical performance

225 of each SDM see the supporting information S1, and the interactive maps in  
226 <https://avrodrigues.shinyapps.io/tferns/>). Overall, the predicted impacts of climate  
227 change on species were similar in both RCP 2.6 and RCP 8.5 (Table 1), where  
228 Dicksoniaceae species tend to lose area of distribution and half of Cyatheaceae species  
229 tend to increase its area of occurrence — while the other half tends to decrease. Also,  
230 currently suitable areas inside PAs also suffer a significant reduction for many tree  
231 ferns.

232

### 233 **3.1 $\alpha$ -diversity**

234

235 The highest  $\alpha$ -diversity values (current and future scenarios, Figure 2) were  
236 found in the Rainforest areas. In the west, where  $\alpha$ -diversity is low in the current  
237 scenario, many sites tend to become unsuitable for all the species in the future.  
238 Furthermore, PAs harbor a higher average of  $\alpha$ -diversity when compared to the  
239 subtropical Atlantic Forest. At the same time, PAs will lose fewer species than non-PAs  
240 and gain more species than non-PAs regions (Table 2).

241

### 242 **3.2 $\beta$ -diversity**

243

244 The BD<sub>TOTAL</sub> is predicted to decrease with climate change (Table 3), indicating  
245 community homogenization along the study area. The LCBD values (Figure 3) ranged  
246 from  $3.2 \times 10^{-4}$  to  $5.5 \times 10^{-4}$  in the current scenario,  $2.7 \times 10^{-4}$  to  $5.8 \times 10^{-4}$  in the RCP  
247 2.6 scenario and  $2.5 \times 10^{-4}$  to  $6.0 \times 10^{-4}$  in the RCP 8.5 scenario, indicating an increase  
248 in LCBD at some locations in the future and a decrease in others. Considering only PAs,  
249 community homogenization is like the rest of the study area (Table 3).

250

251

## 252 **4. DISCUSSION**

253

### 254 **4.1 Changes in species distribution**

255

256 Our first hypothesis was that the species potential distribution would change in  
257 future climate scenarios — where Dicksoniaceae species would have its distribution  
258 reduced and Cyatheaceae species would have its distribution increased. We partially  
259 confirmed our expectation since Dicksoniaceae species indeed had their potential  
260 distribution reduced in both future scenarios, but only half of Cyatheaceae species had  
261 their potential distribution increased. *Cyathea phalerata*, a common species in southern  
262 Brazil, had its potential area reduced in both scenarios, and *Alsophila setosa* — one of  
263 the most common tree ferns in forest communities in subtropical Atlantic Forest  
264 (Lingner et al., 2015) — increased its area of occurrence in scenario RCP 2.6 but  
265 decreased in RCP 8.5. *Cyathea feeana*, recently segregated from *C. corcovadensis*  
266 (Lehnert & Weigand, 2013), had the most reduced potential occurrence area. All  
267 Cyatheaceae species that were predicted to lose potential area in the future by our model  
268 showed climatic suitability for the coldest regions of the study area at the current  
269 scenario (Figures S1-S14 and interactive maps in  
270 <https://avrodrigues.shinyapps.io/tferns/>).

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273

A global analysis of Cyatheaceae distribution patterns showed a clear preference  
of the group for hotter and wetter locations with low seasonality, although some species  
show a capacity to occupy relatively cold regions, rarely where minimum temperatures

274 drop below freezing (Bystriakova et al., 2011). Half of the Cyatheaceae species  
275 analyzed here were able to occupy the coldest areas of the current Mixed Forest.  
276 However, few Cyatheaceae species were able to occupy areas of Semideciduous Forest,  
277 where there is higher seasonality in precipitation than areas of Rainforest and eastern  
278 Mixed Forest (Oliveira-Filho, Budke, Jarenkow, Eisenlohr, & Neves, 2015; Oliveira-  
279 Filho & Fontes, 2000). The effects of high temperatures, reducing the cold intensity  
280 (Wilson, Walters, Mayle, Lingner, & Vibrans, 2019), set up favorable conditions for  
281 some of Cyatheaceae, since they expanded to it.

282 *Dicksonia sellowiana*, a species able to withstand colder environments (Gasper et  
283 al., 2011), was restricted to higher and colder locations, wherein the Mixed Forest  
284 predominates. In the same way, *L. quadripinnata* seems able to inhabit the colder  
285 regions of the Mixed Forest. In addition, the warmer areas of the Rainforest also  
286 showed high climatic suitability for this species. In fact, *L. quadripinnata* has been  
287 recorded in both temperate (Ricci, 1996) and tropical (Bernabe et al., 1999) Rainforests.  
288 In this sense, precipitation rather than temperature appears to be the main determinant of  
289 *L. quadripinnata* occurrence.

290

## 291 **4.2 Changes in diversity patterns**

292

293 The second hypothesis was that the different responses of Dicksoniaceae and  
294 Cyatheaceae species should cause significant changes in diversity patterns. Our  
295 expectation was that species richness ( $\alpha$ -diversity) would increase, following the  
296 increase in overlapping distributions of Cyatheaceae species, which in turn would lead to  
297 a decrease of  $\beta$ -diversity. Our expectation about  $\alpha$ -diversity was not confirmed since we  
298 found evidence for less species richness per cell in the future scenarios. Nevertheless,  
299 we found evidence for future homogenization of cells in the subtropical Atlantic Forest,  
300 since both BD<sub>TOTAL</sub> and LCBD values tend to decrease in future scenarios.

301 Our estimates indicate that at least 40% of the sites (cells) will lose richness in  
302 the subtropical Atlantic Forest. This is due to a reduction in the area of distributions for  
303 Cyatheaceae species, against our expectations. This loss can affect the conservation of  
304 other biological groups that depend on tree ferns caudices, such as epiphytes — some of  
305 these growths exclusively in tree ferns (Mehltreter, 2008). These changes may be  
306 associated with variations in precipitation since water availability seems to be an  
307 important species richness predictor for ferns, as pointed out by several authors  
308 (Aldasoro, Cabezas, & Aedo, 2004; Gasper, Eisenlohr, & Salino, 2015; Kessler et al.,  
309 2011). The current low  $\alpha$ -diversity of tree ferns observed in the midwest and far west, as  
310 well as the reduction of  $\alpha$ -diversity in the future scenarios, may be caused by the rainfall  
311 regime and high climatic seasonality (Bystriakova et al., 2011; Cabré, Solman, &  
312 Núñez, 2016).

313 In the study region, the BD<sub>TOTAL</sub> is more influenced by *RichDiff*, among the  
314 sites than by *Repl<sub>J</sub>* (Figure 3 and Table 3). Together, these results indicate that local  
315 extinctions are important drivers of homogenization in species composition of tree  
316 ferns. The high influence of *RichDiff* in  $\beta$ -diversity could be explained by the  
317 environmental filtering process (Atmar & Patterson, 1993). This process is evidenced  
318 by the loss of species in the west region, with high precipitation seasonality, and by the  
319 loss of more suitable areas by species from a colder climate. Working with ferns  
320 communities in the northern Atlantic Forest, da Costa, Arman, de Paiva Farias, & Barros  
321 (2019) found a higher contribution of species replacement than of species differences in  
322 ferns on a regional and local scale in tropical Atlantic Forest. The authors listed high

323 dispersal ability, niche preferences, and the heterogeneous structure of the Atlantic  
324 forest as the three main factors that contribute to species replacement. Two differences  
325 between the studies could explain the different results: i) our study used local  
326 assemblage in coarse scale, provided by the stack of SDMs, which is not able to capture  
327 differences in microhabitats as in da Costa et al. (2019), and ii) we focused on the tree  
328 ferns niches rather than all ferns species in the subtropical Atlantic Forest.  
329

### 330 **4.3 Implications for biodiversity conservation agenda**

331

332 Our results provide relevant insights to the conservation of tree ferns by predicting  
333 which species will lose larger proportions of adequate habitat in the future (Table 1).  
334 We note that this phenomenon will mainly affect species that occupy higher areas such  
335 as *A. capensis*, *C. feeana*, *C. villosa*, *S. gardneri*, *L. quadripinnata*, and *D. sellowiana*.  
336 Although extinctions did not occur in our study area, historically endangered species  
337 such as *D. sellowiana* had their potential distribution area greatly diminished (~42%).  
338 Also, the climate changes can alter the threatened status from endangered (Santiago et  
339 al. 2013) to critically endangered (considering IUCN 2012 criteria of population size  
340 reduction: A1cB1b). *C. feeana* and *S. gardneri* (currently present in 424 and 386 cells,  
341 respectively), both endemic to eastern Brazil, seem to be the most threatened species in  
342 the future considering the reduction in cell numbers (to 208 in RCP 2.6 and 95 in RCP  
343 8.5 for *C. feeana*; and to 217 in RCP 2.6 and 134 cells in RCP 8.5 for *S. gardneri*).  
344 *Cyathea feeana* occurs from 500 to 1750 m and was recently segregated from *C.*  
345 *corcovadensis* (Lehnert & Weigand, 2013), which may bias our results since not all  
346 herbaria (despite our best efforts) review these records. *Sphaeropteris gardneri* occurs  
347 between 450–600 m and few individuals were found by the IFFSC project (Gasper et  
348 al., 2018).

349 More than half of the studied species are predicted to lose suitable areas, even  
350 inside PAs (Table 2). So, in order to safeguard these species, new PAs will be needed as  
351 they play an essential role in protecting species *in situ* (Chape, Harrison, Spalding, &  
352 Lysenko, 2005). However, these new PAs may too have reduced long-term  
353 effectiveness in species conservation since they are also going to be impacted by  
354 climate change. Then, to optimize cost-benefit analysis of implementing new PAs,  
355 lawmakers and specialists should always consider species conservation now and in the  
356 future (Araújo, Alagador, Cabeza, Nogués-Bravo, & Thuiller, 2011). Also, LCBD  
357 values should be interpreted with caution when looking at alternative indexes for  
358 conservation use since they are not always positively correlated to species richness  
359 (Legendre & De Cáceres, 2013; Silva & Hernández, 2014).

360 Unfortunately, some PAs in higher altitudes, such as Parque Nacional de São  
361 Joaquim — where *D. sellowiana*, as well as other threatened species (such as *Araucaria*  
362 *angustifolia*; Wilson et al., 2019) may find suitable areas in the future — are threatened  
363 to be downsized (see the workgroup created to study the protected area boundaries;  
364 ICMBio 2019).

365 At last, we expected that some tree fern species could expand their distributions  
366 as a result of climate change. However, we must not extrapolate, without deep analysis,  
367 this expansion to other groups. It is well known that animals (Radchuk et al., 2019) and  
368 plants (Corlett & Westcott, 2013) will not be able to keep up, in general, with the  
369 changes affecting the planet.

370  
371

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616    **Table 1.** Comparisons between potential areas occupied by the tree ferns in all  
617 scenarios (current, RCP 2.6, and RCP 8.5). The percentages are based on the subtropical  
618 area of the Atlantic Forest ( $\cong 731.788 \text{ km}^2$ ) and Protected Areas inserted into the study  
619 region. Negative values (**bold**) indicate a reduction of the potential area, while positive  
620 values indicate an increase in the potential area. The “Current” column indicates the  
621 predicted number of suitable cells at the present.

Protected Areas			Species (record number)	Subtropical Atlantic Forest		
Current	RCP 2.6	RCP 8.5		Current	RCP 2.6	RCP 8.5
<b>CYATHEACEAE</b>						
340	<b>-27.06</b>	<b>-43.82</b>	<i>Alsophila capensis</i> (20)	815	<b>-40.61</b>	<b>-55.71</b>
477	<b>-9.43</b>	<b>-24.32</b>	<i>Alsophila setosa</i> (144)	1239	4.68	<b>-17.68</b>
219	41.10	12.33	<i>Alsopahila sternbergii</i> (19)	297	86.87	21.89
481	<b>-9.15</b>	<b>-10.81</b>	<i>Cyathea atrovirens</i> (204)	1084	4.89	3.97
349	<b>-0.57</b>	2.87	<i>Cyathea corcovadensis</i> (142)	615	7.15	17.40
385	1.56	17.92	<i>Cyathea delgadii</i> (95)	849	14.02	39.58
188	<b>-40.43</b>	<b>-69.68</b>	<i>Cyathea feeana</i> (29)	424	<b>-50.94</b>	<b>-77.59</b>
301	3.32	<b>-2.33</b>	<i>Cyathea hirsuta</i> (29)	470	28.30	20.21
248	24.60	41.53	<i>Cyathea leucofolis</i> (20)	312	85.58	145.19
371	<b>-6.47</b>	<b>-9.16</b>	<i>Cyathea phalerata</i> (205)	777	<b>-5.15</b>	<b>-6.18</b>
-	-	-	<i>Cyathea uleana</i> <sup>1</sup> (6)	-	-	-
354	<b>-25.99</b>	<b>-49.72</b>	<i>Cyathea vilosa</i> (21)	801	<b>-41.32</b>	<b>-68.16</b>
205	<b>-35.61</b>	<b>-57.56</b>	<i>Sphaeropteris gardneri</i> (21)	386	<b>-43.78</b>	<b>-65.28</b>
<b>DICKSONIACEAE</b>						
304	<b>-22.70</b>	<b>-39.80</b>	<i>Dicksonia sellowiana</i> (146)	923	<b>-25.79</b>	<b>-42.15</b>
336	12.50	0	<i>Lophosoria quadripinnata</i> (66)	1255	<b>-22.23</b>	<b>-29.48</b>

622    <sup>1</sup>Species not considered in the analysis due to the low number of records.

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635      **Table 2.** Mean species per cell and changes in  $\alpha$ -diversity in the future scenarios (RCP  
636      2.6, and RCP 8.5) for the whole study area and PAs only. “Gain”, “equal” and “loss”  
637      indicates the proportion of cells that will respectively gain, keep the same number, or  
638      lose species in each future scenario.

Protected Areas			$\alpha$ -diversity	Subtropical Atlantic Forest		
Current	RCP 2.6	RCP 8.5		Current	RCP 2.6	RCP 8.5
3.6	3.4	3.1	Mean per cell <sup>2</sup>	5.53	5.15	4.68
-	26.56	21.83	Gain (%)	-	23.52	18.06
-	30.32	25.97	Equal (%)	-	28.00	20.36
-	43,12	52.20	Loss (%)	-	48.48	61.58

639      <sup>2</sup>Mean differences between current and future scenarios were supported by the  
640      Wilcoxon Rank-Sum Test (p-value < 0.001).

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677      **Table 3.** BD<sub>TOTAL</sub> and its components (*RichDiff<sub>J</sub>* and turnover) between the current and  
678      future climate scenarios for the whole study area and PAs only.

Protected Areas			$\beta$ -diversity	Subtropical Atlantic Forest		
Current	RCP 2.6	RCP 8.5		Current	RCP 2.6	RCP 8.5
0.316	0.303	0.3	BD <sub>TOTAL</sub>	0.320	0.305	0.294
83.3	91.2	91.3	<i>RichDiff<sub>J</sub></i> (%)	80.8	88.3	90.4
16.7	8.8	8.7	Turnover (%)	19.2	11.7	9.6

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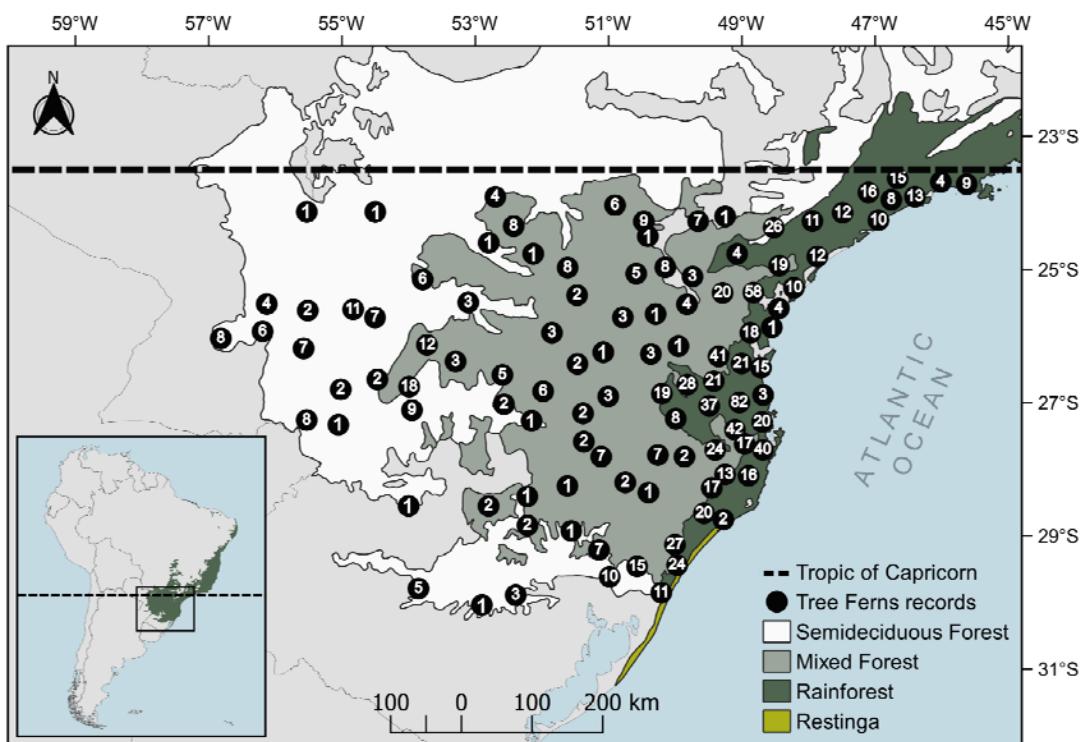
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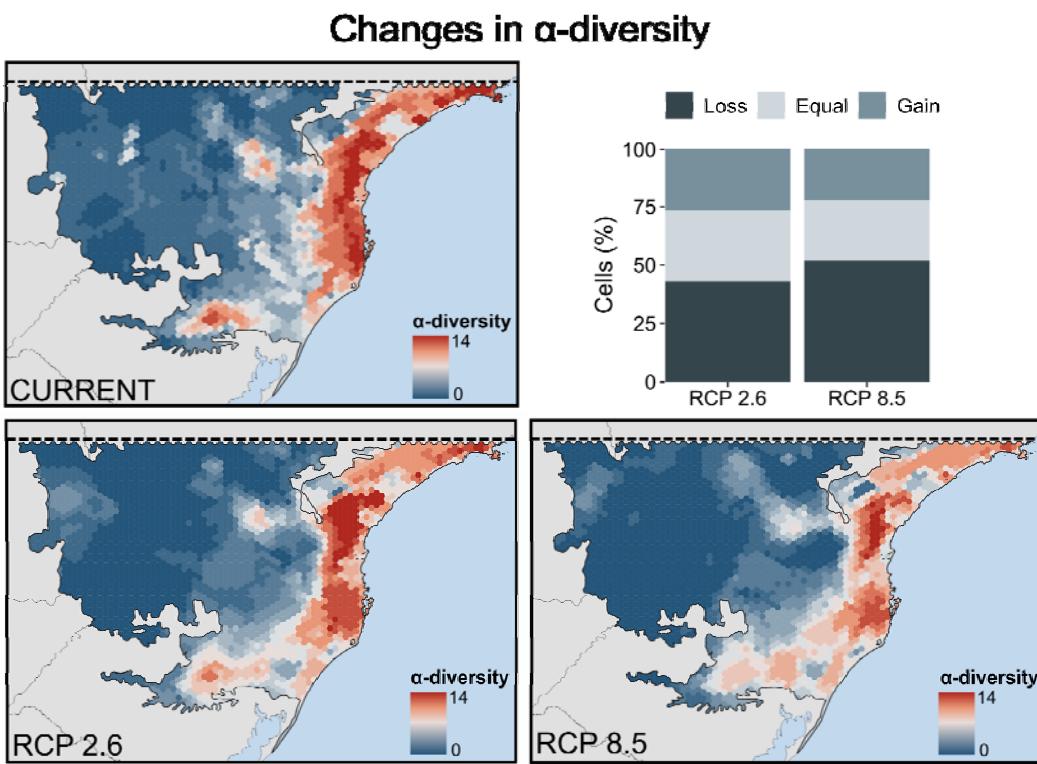
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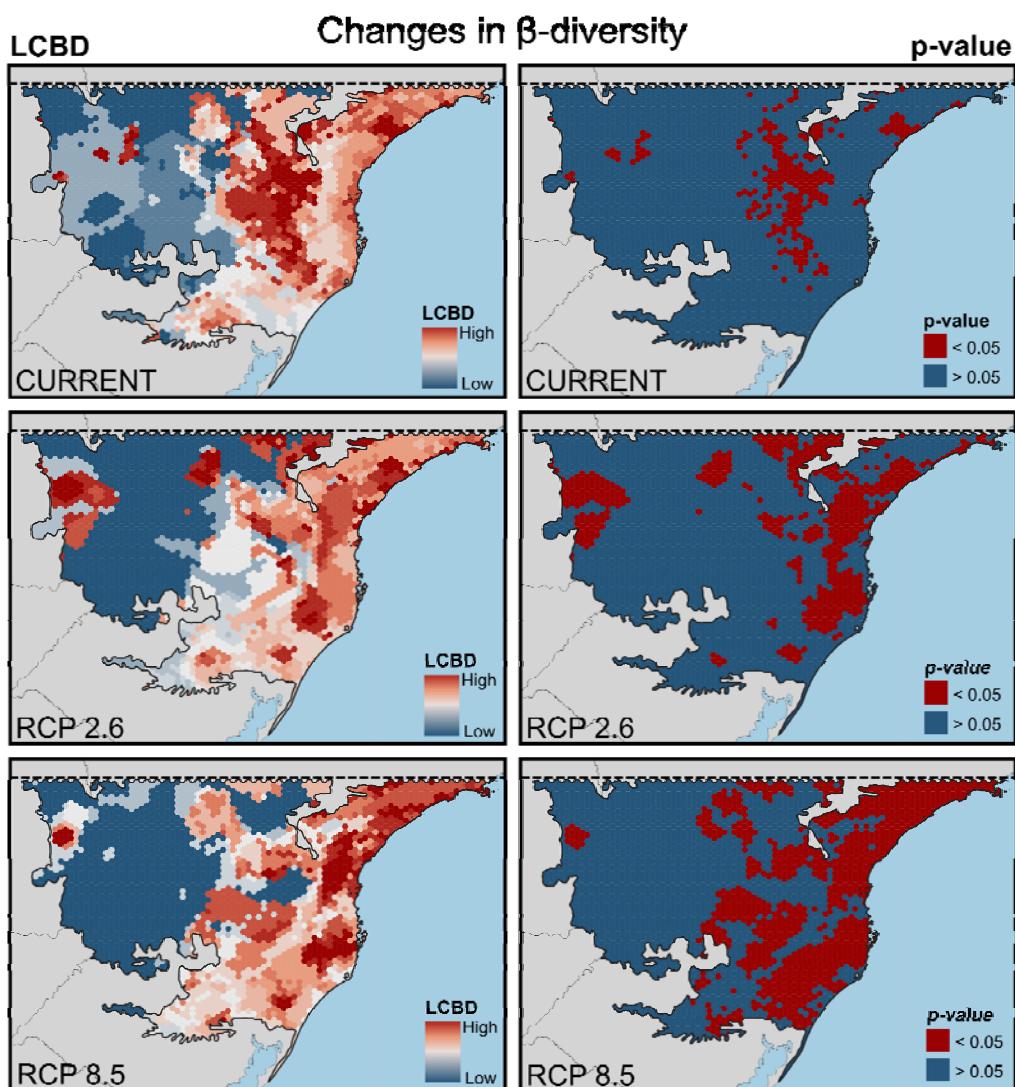
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710 **Figure 1.** Study area and forest types of subtropical Atlantic Forest. The occurrence  
711 data (black dots) was grouped into  $\geq 30\text{km}^2$  clusters to simplify the visualization. The  
712 respective numbers on the dots represent the number of records found in each cluster.  
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**Figure 2.**  $\alpha$ -diversity of tree ferns in the subtropical Atlantic Forest based on current and future (RCP 2.6 and RCP 8.5) climate scenarios. The bar chart demonstrates the predicted proportion of cells that will lose, keep and gain  $\alpha$ -diversity in the two future scenarios.

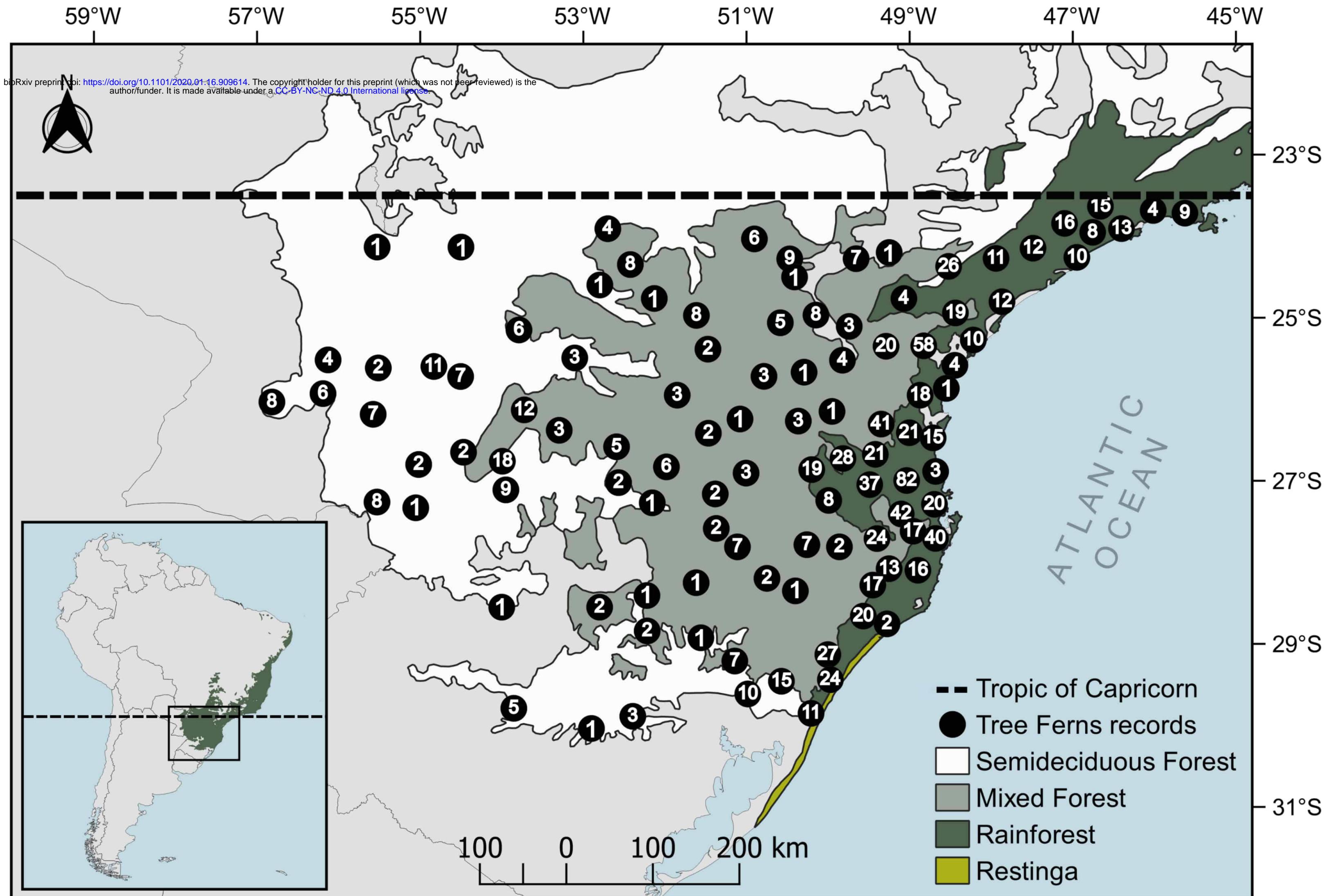
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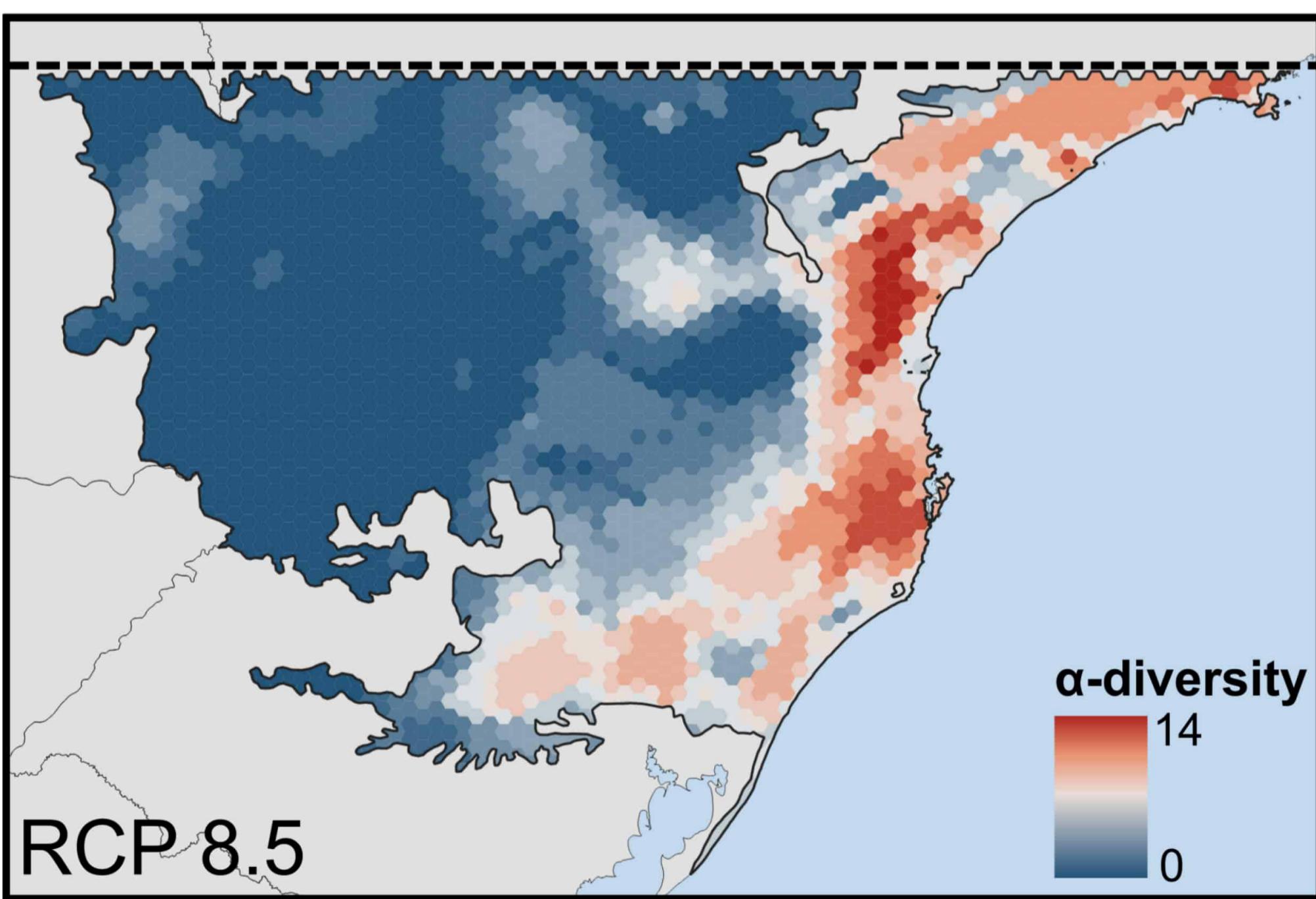
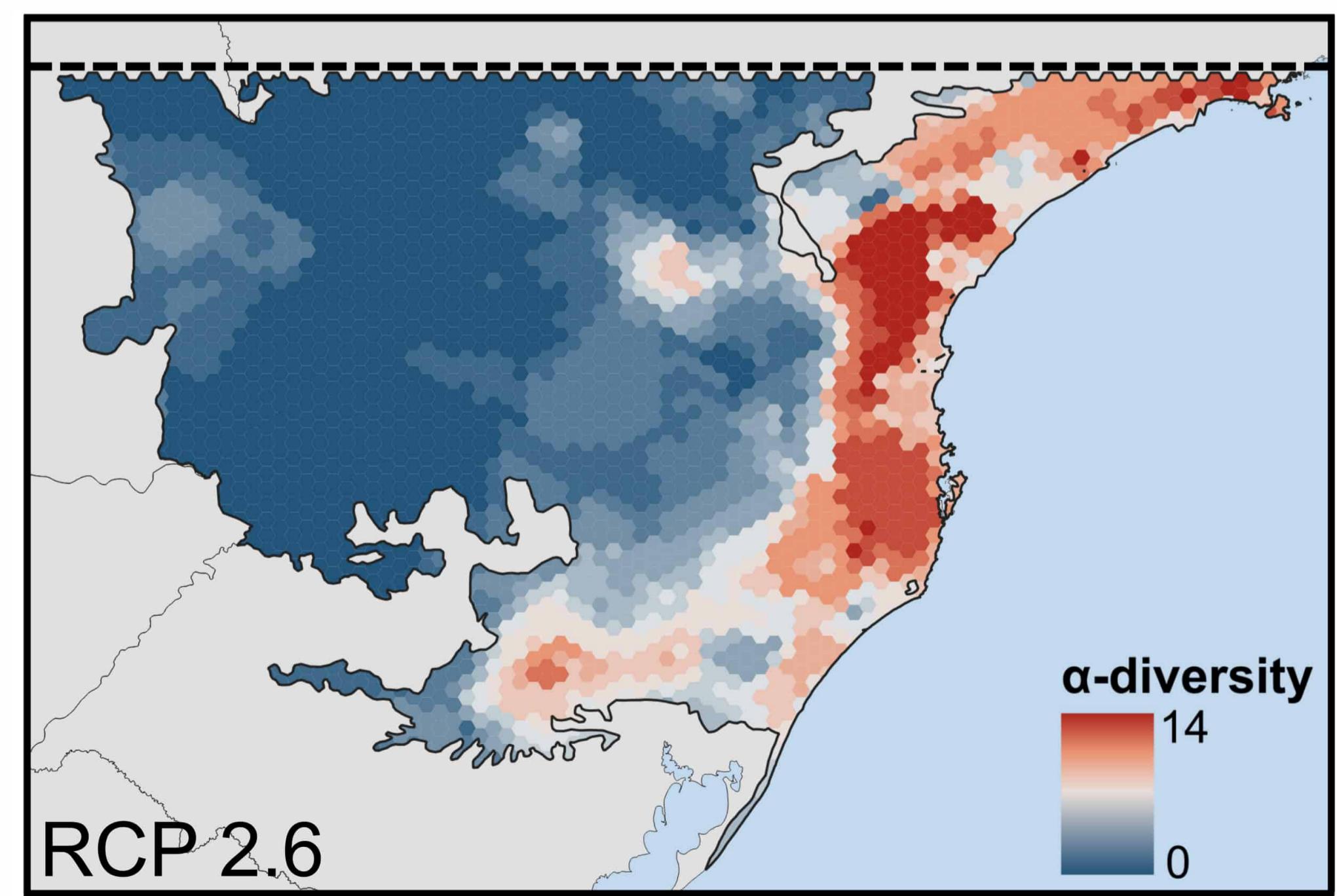
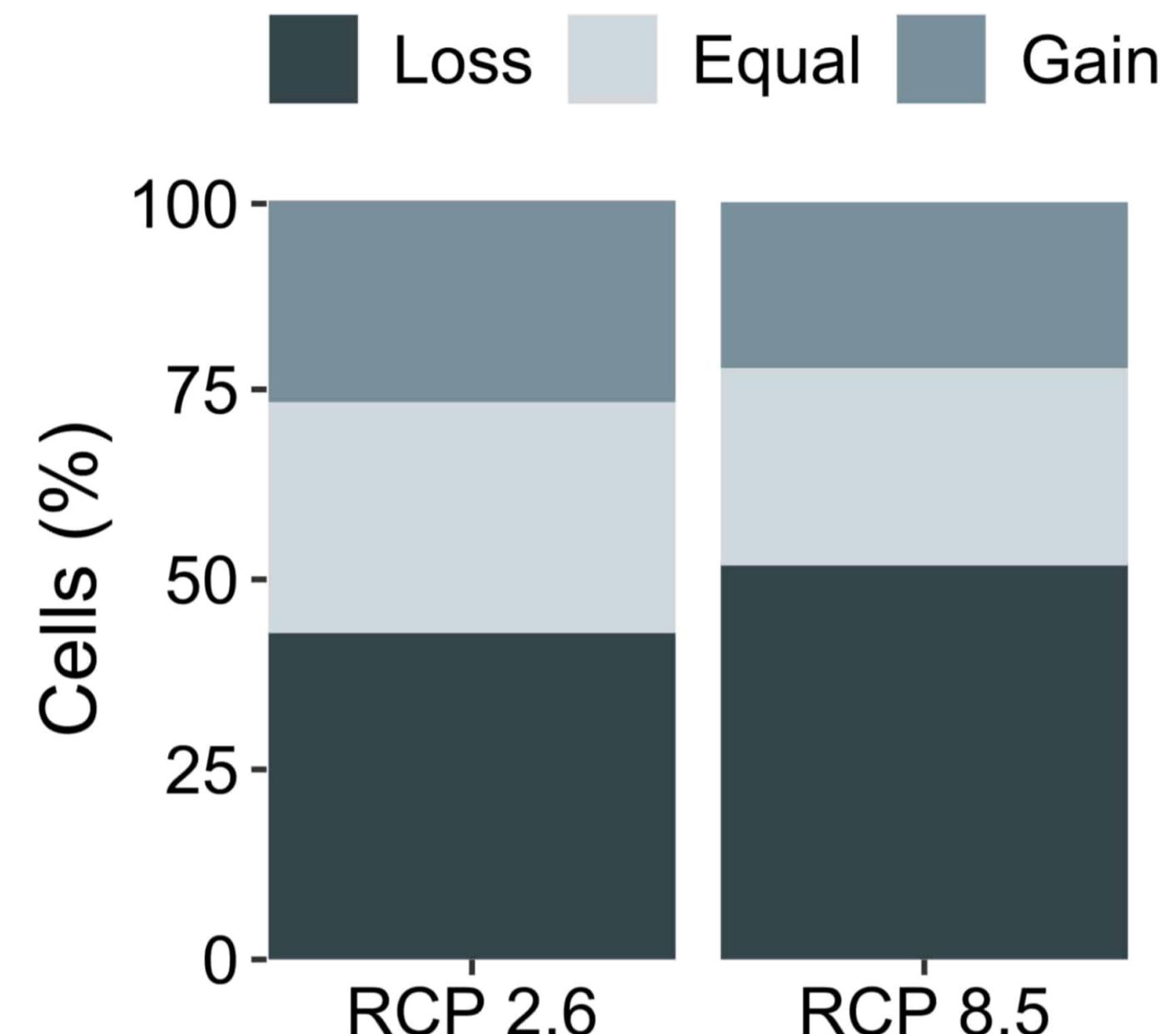
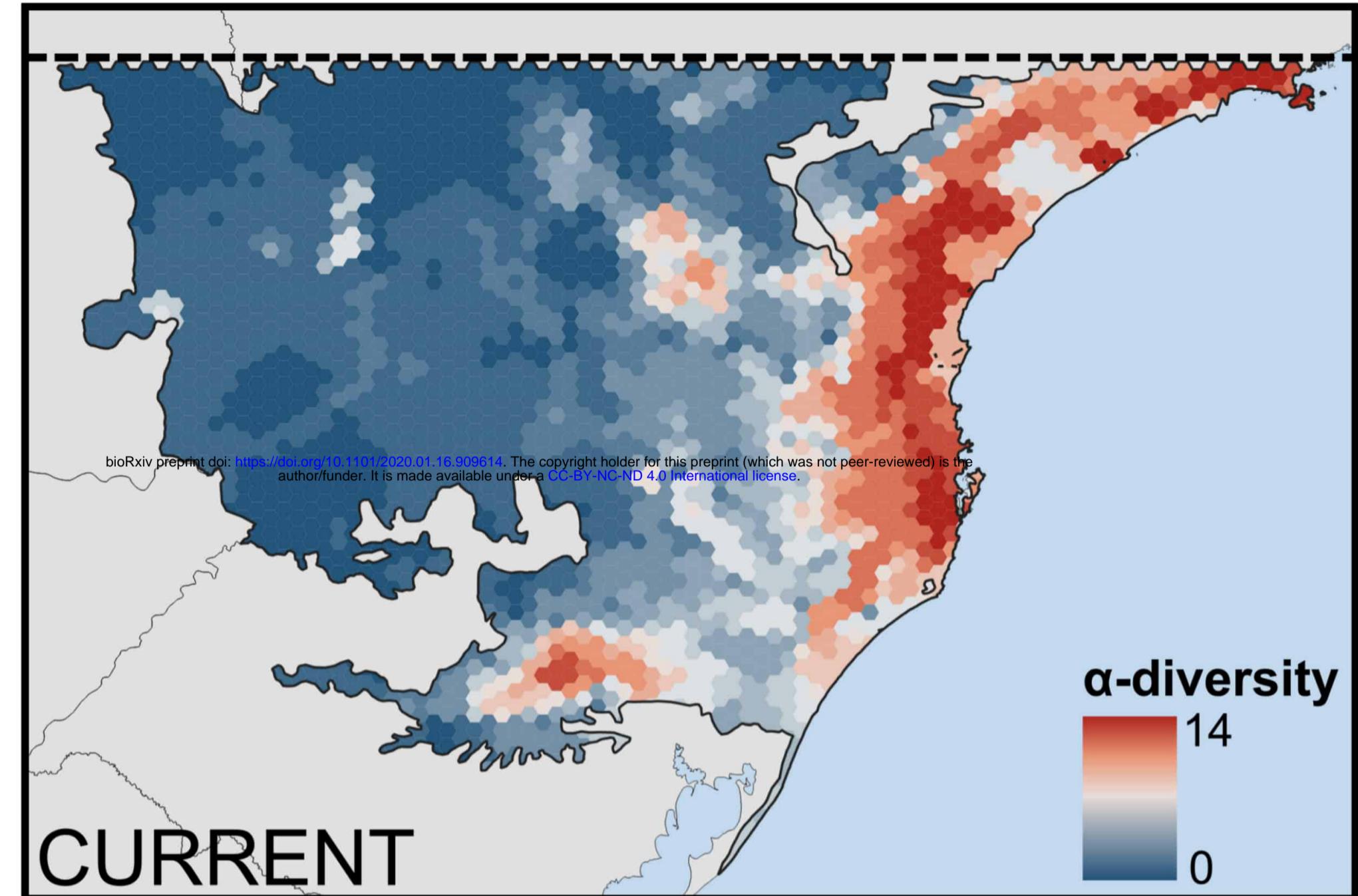


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**Figure 3.** Current and future (RCP 2.6 and RCP 8.5) distribution of LCDB (left column) and LCBD p-values (right column) of tree ferns in the subtropical Atlantic Forest. Cells with p-value < 0.05 show significantly higher than average LCBD values.



# Changes in $\alpha$ -diversity



LCBD

# Changes in $\beta$ -diversity

p-value

