



IMPACTS OF CLIMATE CHANGE ON SMALL-RANGED AMPHIBIANS OF THE NORTHERN ATLANTIC FOREST

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Abstract: Climate change is shifting species distribution all around the world. Amphibians are particularly vulnerable to these environmental changes, as they are highly sensitive to fluctuations in rainfall and temperature. While previous studies have shown that climate change may increase amphibian species extinctions worldwide, few have tested how these changes may impact small-ranged species. Here, we use simple Euclidean distance methods to evaluate how changes in climatic conditions predicted for 2050 and 2070 may impact ten small-ranged amphibians of Northern Atlantic Forest in Brazil. Specifically, we focused on changes in temperature and precipitation regimes during the breeding season of all target species. Our results indicate that future climatic conditions will be less favorable for the evaluated species. Environmental conditions similar to the ones currently experienced by the species may shift to southwestern regions. Likewise, we expect favorable climatic conditions to move in altitude, but without a common trend among species. In spite of these impacts, the most favorable climatic conditions for each species will keep the same connectivity patterns as observed in the present. Taken together, these findings suggest that small-ranged amphibians of the Northern Atlantic Forest will be negatively affected by climate change, mainly by the reduction and shifts of suitable climatic conditions. Finally, our results also indicate that actions to decrease greenhouse gas emissions would reduce the impact on these small-ranged species.

Keywords: anurans; ecological niche modelling; Euclidean distance; geographic distribution; global warming.

INTRODUCTION

Since the pre-industrial era, humans have been considerably increasing the concentration of greenhouse gases in the atmosphere, and therefore, altering the climate of our planet (IPCC 2014a). As a consequence, climate change is

already impacting biodiversity (Garcia *et al.* 2014, Young *et al.* 2016), and further ecological transformations are expected for the future (Moritz & Agudo 2013). Currently, it is a consensus that climate change will promote species range shift worldwide, which in turn, may also facilitate species invasion and disrupt ecosystem networks,

finally leading to an increase in global rates of species extinction (Pecl *et al.* 2017). Amphibians are particularly vulnerable to such changes (Parmesan 2006, Loyola *et al.* 2014). Because of their physiology, amphibians depend on external sources of heat to regulate body temperature, and their skin is highly sensitive to dehydration (Hopkins 2007). As a result, amphibian populations promptly respond to variations in temperature and precipitation, especially during their breeding season when the species are more active (Blaustein *et al.* 2001).

Previous studies have analyzed how climate change may affect future distributions of amphibians (*e.g.*, Blaustein *et al.* 2001, Araújo *et al.* 2006, Parmesan 2006, Pounds *et al.* 2006, Loyola *et al.* 2014). These studies have used mechanistic (based on physiological tolerances from ex-situ experiments) or correlative (based on the relationship between occurrence records and environmental layers) methods of ecological niche modelling (Kearney *et al.* 2010). The latter is most frequently adopted as the gap in physiological tolerances is higher than the gap in geographic distribution knowledge (Hortal *et al.* 2015). Efficient correlative ecological niche models implement complex algorithms that correlate occurrence records with environmental conditions to predict current, future, or past suitable conditions for species (Elith & Leathwick 2009, Maguire *et al.* 2015). While these complex algorithms generally have a better predictive power than simple methods, they require a minimum number of occurrence records to efficiently estimate the species niche and subsequently test its performance (Stockwell & Peterson 2002, Peterson *et al.* 2012). Thus, species with very limited known occurrence records (hereafter small-ranged species) are normally left out of analyses that investigate the effects of climate change on species distribution (*e.g.*, Thuiller 2004, Araújo *et al.* 2005, 2011, Engler *et al.* 2011). Nevertheless, small-ranged species are likely to be the ones most vulnerable to any kind of change in the environment, exactly because of its limited occurrence.

In this paper, we use a simple Euclidean distance method to investigate how climate change may affect suitability for small-ranged anuran amphibians in the Northern Brazilian

Atlantic Forest. Environmental distance methods are not estimating species ecological niche, but they have been previously used to indicate the most likely environments for the occurrence of a species (Siqueira *et al.* 2009). As suggested by Guisan *et al.* (2006), traditional niche-based models are not appropriate to predict small-ranged species distribution, as they need a minimum amount of data to be calibrated. Instead Guisan *et al.* (2006) apply a Generalized Linear Model (GLM) to predict the distribution of a rare endemic plant in Switzerland, a statistical method that requires real absence data, which is normally absent for most of the regions and species of the world. While other approaches were also proposed, they all require a minimum amount of data to be used (Pearson *et al.* 2007, Lomba *et al.* 2010). The Euclidean distance approach does not require a minimum set of occurrence records as it is neither based on a standard statistical method (*e.g.*, GLM) or a machine learning algorithm (*e.g.*, MaxEnt), in turn it can be applied to species even with one unique geographic register (Siqueira *et al.* 2009). So, although we cannot estimate the species ecological niche, we can still draw conclusions about how future climatic conditions will diverge from the current ones, and test its impacts on environmental similarity loss, shift and fragmentation. Specifically, we tested: (1) if future climate conditions will be more or less similar than the environments currently occupied by the species; (2) if the most similar conditions will change in latitude, longitude, and altitude; and (3) if climatic change will reduce the climatic connectivity of the region. Together, this information will help us understand how small-ranged amphibians of a biodiversity hotspot will cope with climate change.

MATERIAL AND METHODS

Study area and species data

The Atlantic Forest covers a wide latitudinal range, which results in large climate heterogeneity. Hence, it has been divided into eight Biogeographic Sub-Regions (BSR) based on species endemism patterns (*sensu* Silva & Casteleti 2003). The present study was conducted in the BSR Pernambuco (Figure 1), a hotspot of genetic

diversity and home of several endemic species (Carnaval *et al.* 2009).

We reviewed the literature to identify all small-ranged species that are endemic to forest environments of the region. By small-ranged we mean all species with 15 or less known occurrence points. In total, we identified ten endemic amphibian species (Table 1). Occurrence data for each species were then obtained from the literature and zoological collections. We identified a total of 19 localities along the states of Alagoas, Pernambuco, and Paraíba (Northeastern Brazil). The number of occurrence records ranged between 1 and 12, with three species only known from its type locality: *Crossodactylus dantei*, *Oloolygon muriciensis*, and *Oloolygon skuki* (Supplementary Material 1).

Climatic variables

Altitude, present climate data, and future global climate models, for the years 2050 (average for 2041-2060) and 2070 (average for 2061-2080) were

obtained from Worldclim v. 1.4 (Hijmans *et al.* 2005). Data had a resolution of 2.5 x 2.5 minutes of latitude and longitude (approximately 0.042 degrees). Future climate models follow the IPCC5 projections for four Representative Concentration Pathways (RCP; Moss *et al.* 2008). The four RCPs represent different expected trajectories of greenhouse gas emissions. The RCP 2.6 assumes that human emissions will decline after a peak in 2010-2020, the RCP 4.5 in 2040, the RCP 6 in 2080, and RCP 8.5 assumes continuous growth in greenhouse gases emissions. Because our target species breed during the raining season (*e.g.*, Nascimento & Skuk 2006, Vilela *et al.* 2015), we only used the mean temperature and precipitation of the wettest quarter in order to evaluate how changes in climate will affect breeding conditions. Also, because the precipitation and temperature are in different scales, which could affect the relative contribution of each variable to the Euclidean distance calculated, all variables were standardized to have zero-mean and unit-variance.

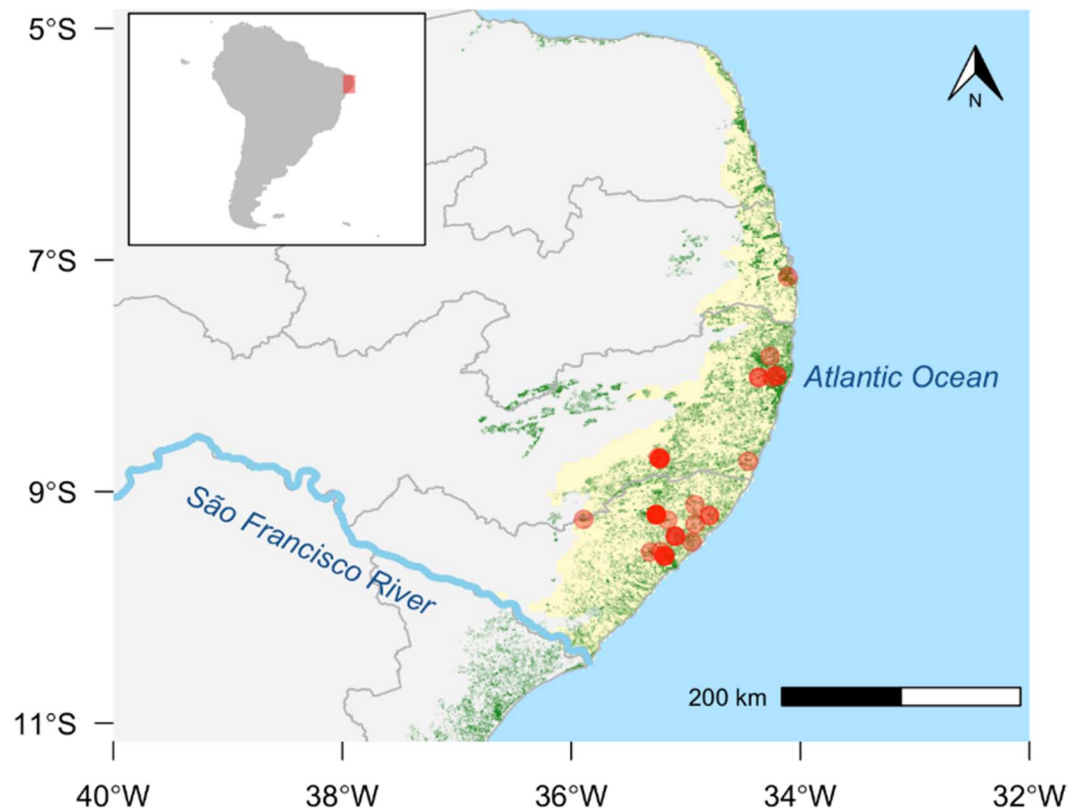


Figure 1. Occurrence records of the small-ranged anurans endemic to the Brazilian Northern Atlantic Forest. The yellow region indicates the limits of the Brazilian Northern Atlantic Forest biome, where the study was conducted. Green areas indicate remaining forest fragments. Red dots indicate the species occurrence records.

Table 1. Small-ranged anurans endemic to the Brazilian Northern Atlantic Forest. The table includes the species name, the taxonomic family, and the conservation status given by the IUCN Red List (International Union for the Conservation of Nature 2017) and the Brazilian Red List (Instituto Chico Mendes de Conservação da Biodiversidade - ICMBio 2016). DD: Data deficient. LC: Least Concern. VU: Vulnerable. EN: Endangered. CR: Critically Endangered.

Species	Family	IUCN Red List	Brazilian Red List
<i>Chiasmocleis alagoana</i>	Microhylidae	DD	EN
<i>Crossodactylus dantei</i>	Hylodidae	DD	EN
<i>Dendropsophus studerae</i>	Hylidae	DD	-
<i>Hylomantis granulosa</i>	Phyllomedusidae	LC	VU
<i>Hypsiboas freicanecae</i>	Hylidae	DD	-
<i>Oolygon muriciensis</i>	Hylidae	CR	-
<i>Oolygon skuki</i>	Hylidae	EM	-
<i>Phyllodytes edelmoi</i>	Hylidae	DD	-
<i>Phyllodytes gyrinaethes</i>	Hylidae	DD	CR
<i>Physalaemus caete</i>	Leptodactylidae	DD	-

Species Environmental Distance Models

We used a simple Euclidean distance method (*i.e.*, the shortest distance between two points in the variable space; Equation 1) to calculate how the current and future environmental conditions differs from the environment currently occupied by the species. For species that have more than one occurrence point, the minimum Euclidean distance value was chosen (see Equation 2). The following equations summarize how the Euclidean distance was calculated between points *q* and *p*:

$$d_k = \sqrt{\sum_{i=1}^n (q_i - p_i)^2}$$

(Equation 1)

$$\text{if } k > 1, \text{ then } d(q, p) = \min\{d_k\}_{k=1}^N$$

(Equation 2)

$$\text{if } k = 1, \text{ then } d(q, p) = d_k$$

(Equation 3)

where *n* is the number of variables (in this case, *n* = 2), and *N* is the number of observed occurrence records for a given species. For each species, we calculated the distance for each cell in a 2.5 x 2.5 minutes grid, generating a value of environmental similarity (Siqueira *et al.* 2009). We measured the average distance per scenario (each combination

of year and RCP) to evaluate how future conditions will differ from current conditions.

To estimate geographical and altitudinal changes in environmental similarity, a weighted mean of altitude, latitude, and longitude was calculated for each scenario, where the weight (*w*) was given based on the inverse of the estimated distance (*d*) value of a cell *q* to a cell *p* ($w_{qp} = 1/d_{qp}$). These weighted means help understand whether the closest environmental conditions to the present areas occupied by the species are shifting its geographical and altitudinal position, working in a similar fashion as the centroid of a distribution. Finally, we built a Moran's I spatial correlogram [see Diniz-Filho *et al.* (2003) for details] for each scenario to identify if the spatial autocorrelation in the environmental distance values would change in the future. Moran's I values vary from -1 to 1, where values close to zero indicate low spatial autocorrelation and values close to one indicate high spatial structure, the sign indicates whether there is positive (+) or negative (-) autocorrelation. Higher positive spatial structure would indicate more connectivity. Therefore, this analysis tested if climate change would cause a fragmentation in environmental similarity values. All analyses were performed using R v. 3.4 (R Core Team 2017), packages 'raster' (Hijmans 2016), 'maptools' (Bivand & Lewin-Koh

2017), and 'letsR' (Vilela & Villalobos 2015). The Euclidean Distance calculation was performed using functions developed by the authors (the code is available as an Supplementary Material 2 in PDF and Rmd format).

RESULTS

Future climatic conditions will be more distant than the current ones experienced by all species (Figure 2). Under the optimistic scenario (RCP 2.6), environmental distance will increase in 2050, but no change from 2050 to 2070 is expected. The moderate optimistic scenarios (RCP 4.5 and 6.0) show equivalent quantitative results, both indicating that distances will increase by 2050 (more than the suggested in the RCP 2.6 scenario) and will continue to grow in 2070. In the most alarming scenario (RCP 8.5), climatic conditions will be considerably more distant both in 2050 and 2070 than in the other scenarios where greenhouses gases emissions are expected to decrease at some point. These results are consistent among all species, but the magnitude of the effect will change according to the species. For example, *Dendropsophus sturderae* will be more affected than *Chiasmocleis alagoana* or *Hylomantis granulosa* (Figure 2).

The most similar climatic conditions to the ones currently experienced by the species will move towards the southwest of the region, except for *C. alagoana*, in which the model indicates a move towards the southeast, and for *H. granulosa*, for which the similar conditions are expected to shift towards the northeast (Figure 3). With few exceptions, the different scenarios and different years show very similar values of environmental similarity shift. Note that although the values range between -1 to 1 degree of geographical variation, these values come from a weighted mean, which makes conclusions about absolute values of geographical environmental similarity shift impossible. However, comparison among species allows us to infer that, for example, *O. skuki* may experience the highest latitudinal variance, while *D. sturderae* the highest longitudinal variance.

Environmental similarity altitudinal changes show no general pattern across all evaluated

species. The results presented in Figure 4, reveal that similar environments will likely move towards higher altitudes for some species (*e.g.*, *D. sturderae*), while conditions will move towards lower altitudes for others (*e.g.*, *C. alagoana*). Although in some cases the different scenarios show increasing effect in altitudinal change (*e.g.*, *Hypsiboas freicanecae*), for others the effect may be nearly absent (*e.g.*, *D. sturderae*) or inverted (*e.g.*, *Phyllodytes gyrinaethes*). Magnitude of the effects also vary among species as the altitudinal shift in environmental conditions may affect more *D. sturderae*, while *Physalaemus caete* is expected to suffer less with shifts in altitude.

The results of spatial autocorrelation of environmental similarity showed no evidence that in the future species' similar climatic conditions will be more fragmented (Figure 5). No major differences can be noted across species, although environmental similarity seems to be more structured in the space for *D. sturderae* and *H. freicanecae* when compared to the other species.

DISCUSSION

Species with limited geographic range and small area of occupancy (*i.e.*, few aggregated occurrence records) tend to have specialized environmental requirements that make them particularly sensitive to climate change (Schwartz *et al.* 2006). However, few studies have showed how such small-ranged species could be affected by climate change. Exceptions include long-term experiments (*e.g.*, Willis *et al.* 2008, Dobrowski *et al.* 2011), which are very informative, but generally limited in its geographic scope, or climatic modelling approaches applied at the ecosystem level (*e.g.*, Ohlemüller *et al.* 2008, Dirnböck *et al.* 2011). To our knowledge, this is the first study to explore the potential effects of climate change for species with very few occurrence records. Our results support general findings that climate change will have a negative impact on species conservation (Pecl *et al.* 2017). Based on our findings, we expect that the conditions in the Northern portion of the Atlantic Forest will be less similar than the ones currently experienced by our target anurans (see Figure 2). Together with the high deforestation rates at the region (Ribeiro *et al.*

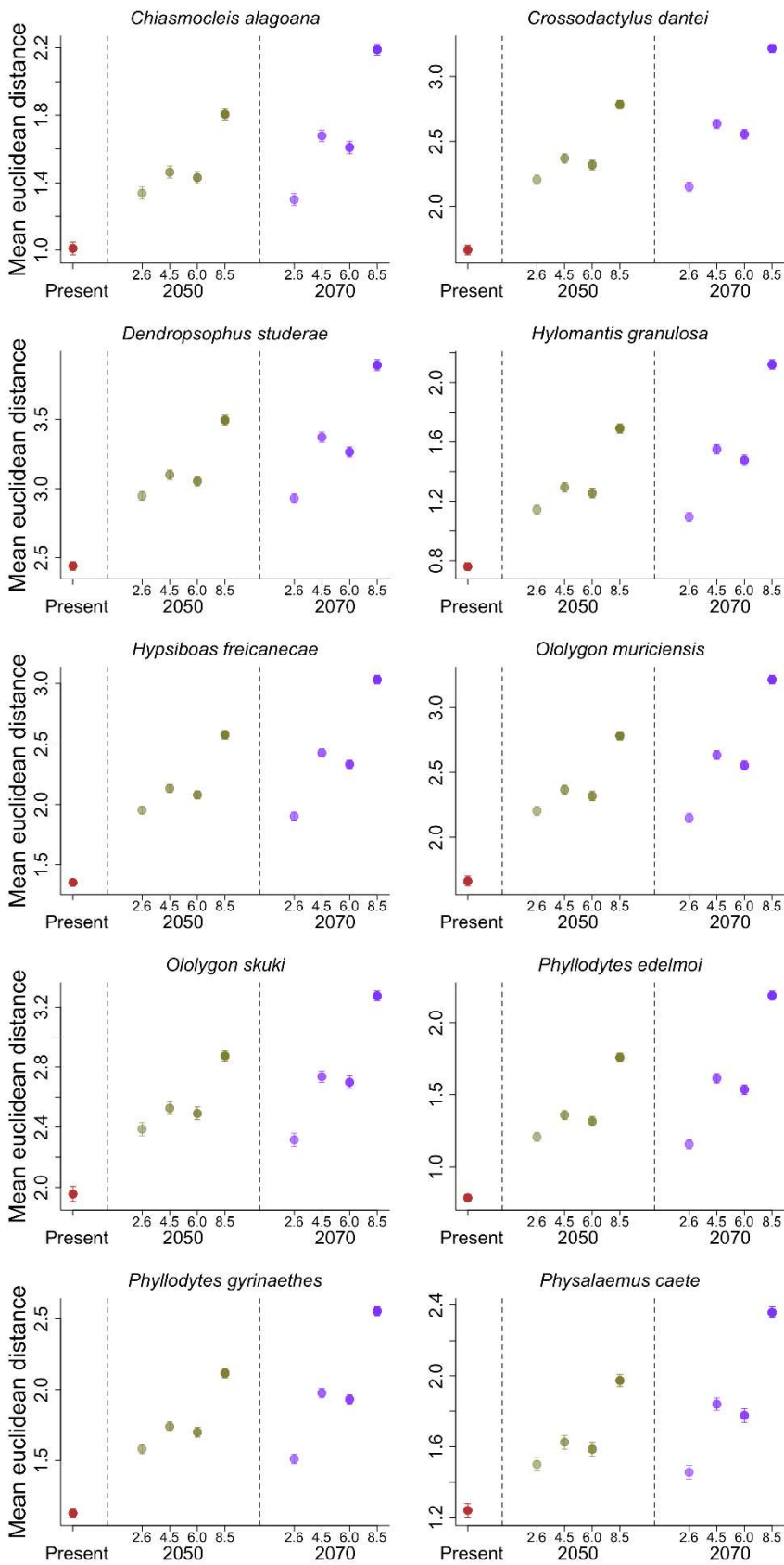


Figure 2. Mean Euclidean environmental distance from current species occurrences to all cells of squared grid (2.5 minutes resolution) of the North Atlantic Forest under different future scenarios. Values in the x-axis represent different Representative Concentration Pathways (RCPs) for 2050 and 2070. Error bars are the 95% confidence intervals.

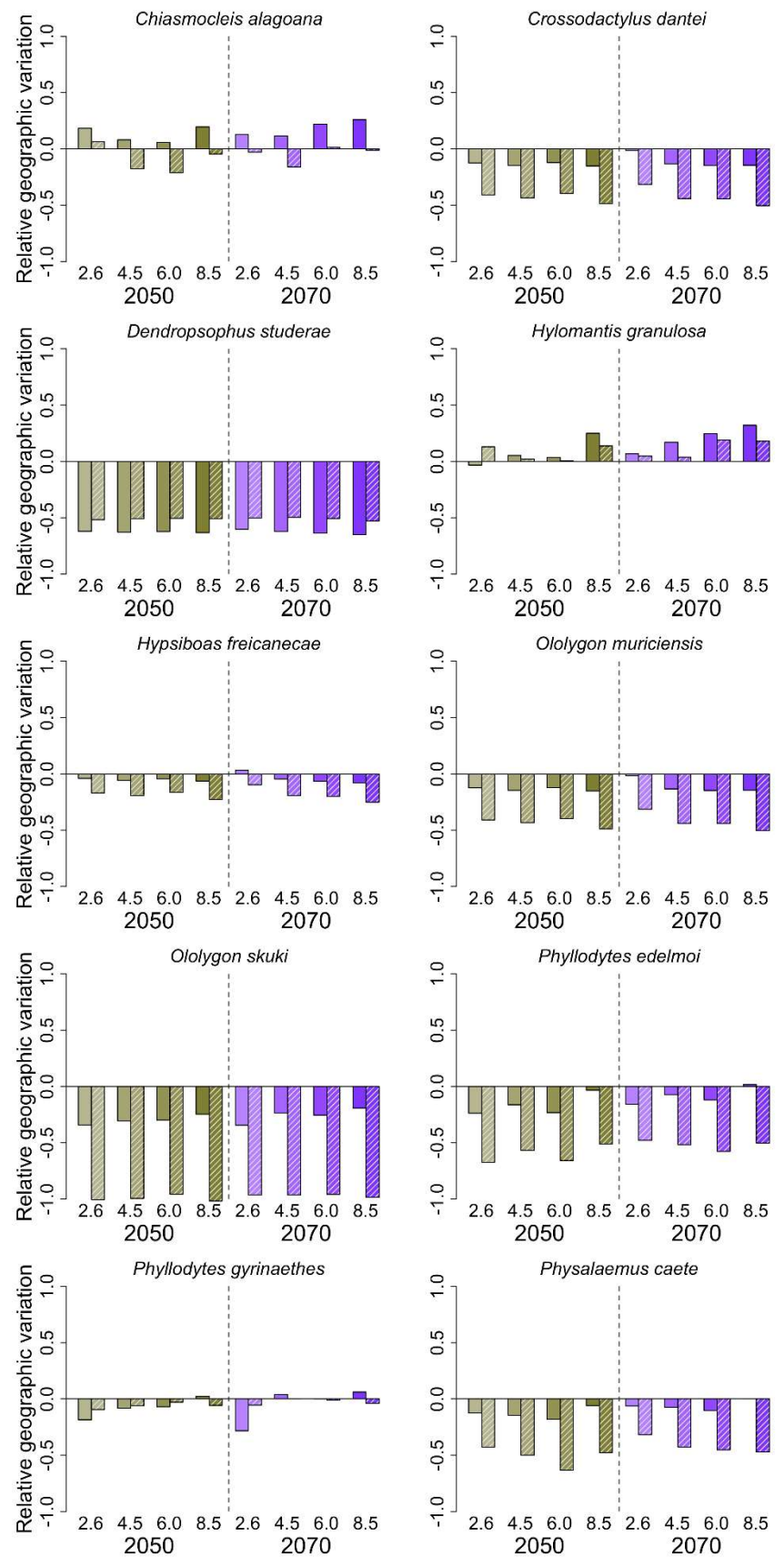


Figure 3. Relative geographic variation of environmental similarity for different future scenarios. Values in the x-axis represent different Representative Concentration Pathways (RCPs) for 2050 and 2070. Solid bars show the values of longitude and hashed the values of latitude variation.

2009), our results support that future climate dissimilarity will decrease the suitable habitats for species in the near future, threatening their persistence in the current areas of occurrence.

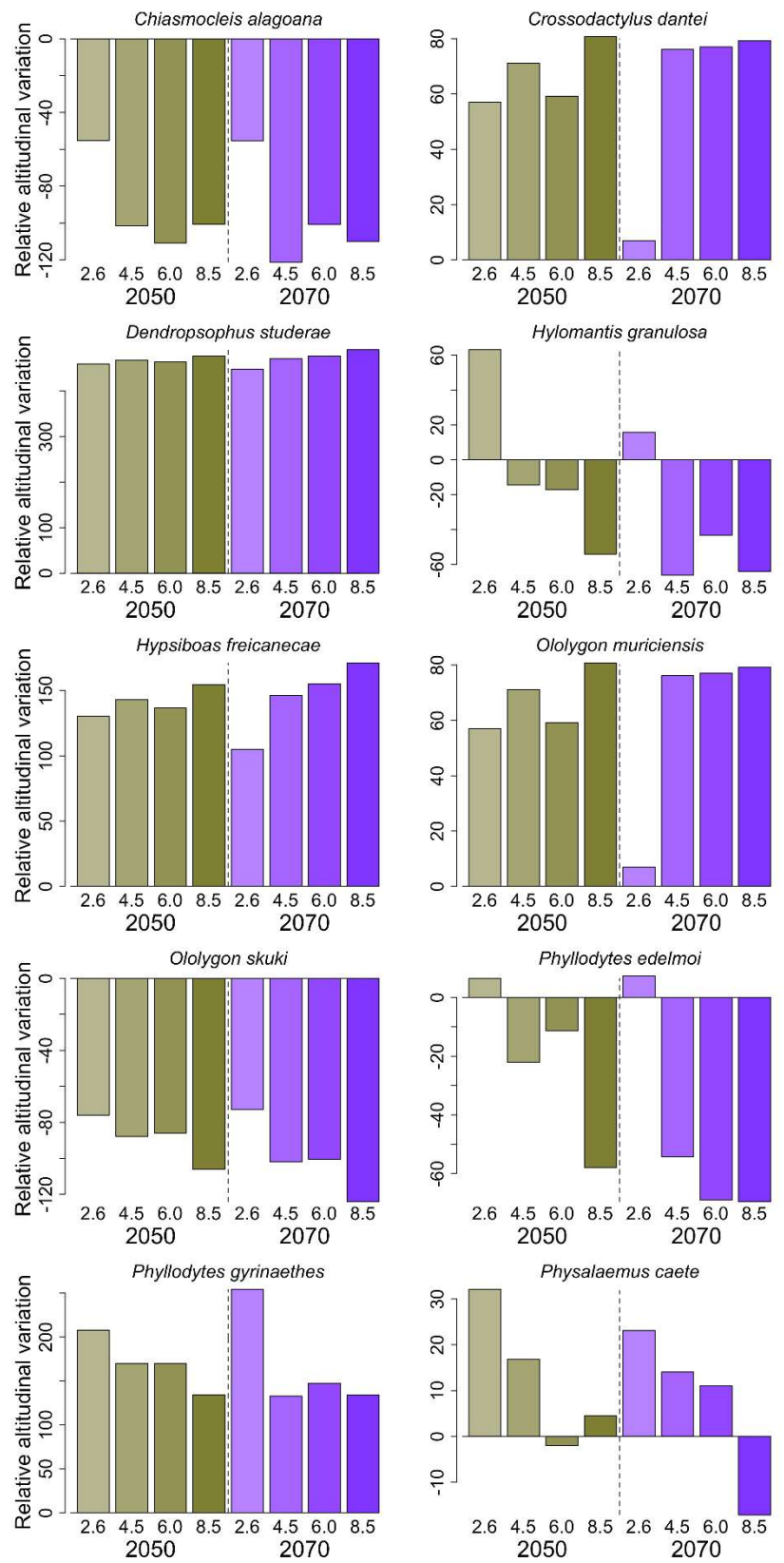
Previous studies using paleo data revealed that most of the species were able to cope with past climate changes by tracking their suitable conditions (Blois & Hadly 2009, Moritz & Agudo 2013). Our results suggest that most species would have to move towards the southwest to maintain similar breeding climatic conditions. Furthermore, we found that environmental similarity connectivity will remain comparable to current values, facilitating migration from the macroclimatic perspective. In contrast, due to the historical and continuous expansion of sugar cane fields in the southern portion of the region (Zuurbier & Van de Vooren 2008), forest patches in the area are highly fragmented, making it difficult for species to move across large distances. This is because dispersal through crop fields makes species not only more vulnerable to predators but also to dehydration, as trees maintain a higher humidity and lower temperature in the forest understory (Denslow 1980). Nevertheless, species ability to track climate change may be limited, unless an urgent and unlikely large reforestation program to reconnect forest patches in the region is instituted. Previous studies have also noted the importance that mountains may play as a climate refugia in the future as the temperature rises (Moritz & Agudo 2013, Loyola *et al.* 2014). Though, our results do not indicate a general pattern were species similar environments will shift towards higher altitudes. These results are possibly caused by the fairly small altitudinal variation in the region that do not lead to dramatic changes in local climatic conditions.

Previous studies have shown that current rates of climate change are much higher than past fluctuations in temperature and precipitation, and local adaptation to new climatic conditions would require rates of evolution much higher than the ones observed from phylogenetic reconstructions (Quintero & Wiens 2013). In addition, theory predicts that species adaptation should be faster if a large genetic pool is available (Barrett & Schluter 2008). However, small-ranged species experience less geographic variation and reduced population

size, which, all else being equal, should decrease genetic diversity and the likelihood of local resilience to new conditions. In this case, the persistence of species in the current areas would only be facilitated by pre-existing climatic tolerances broader than what can be observed from current occurrence records. This could happen if species geographic limits are mainly constrained by movement barriers or biotic interactions, creating a gap between the fundamental and realized niche (Barve *et al.* 2011). In this situation, species could be already adapted to future climatic conditions. Yet, if biotic interactions are the responsible for a limited occurrence, other species could also track their climate maintaining the non-favorable biotic conditions in future (Peterson *et al.* 2012). Another possibility is that the few occurrence records for the studied species may reflect only a limitation in our knowledge about the species distribution, the so-called Wallacean shortfall (Hortal *et al.* 2015). In this case, species could have broader climatic tolerances than the ones currently observed from the known occurrence records.

The different results of each RCP scenario indicate that a potential decrease of anthropogenic greenhouse gas emissions could minimize the impact of climate change on the studied species. For instance, if emissions start to decrease now, we may expect that between 2050 and 2070 there will be no substantial differences in climatic similarity. In contrast, a decline in 2040 or 2080 would not result in great differences on total environmental similarity. Still, a late decline in greenhouse gas emissions would be better than no decline, where distances would keep increasing more than in any other scenario. Therefore, proactive measures to reduce greenhouse gas emissions, such as through decreasing reliance on fossil fuels or reducing livestock production (IPCC 2014b), could mitigate the impacts of climate change on the studied species.

Although the limited data narrowed our conclusions, the methods we used here revealed to be a useful tool to explore the effects of climate change on small-ranged species. Notwithstanding the methodological limitations and the uncertainty associated to greenhouse gas emission scenarios, the present study has shown that small-



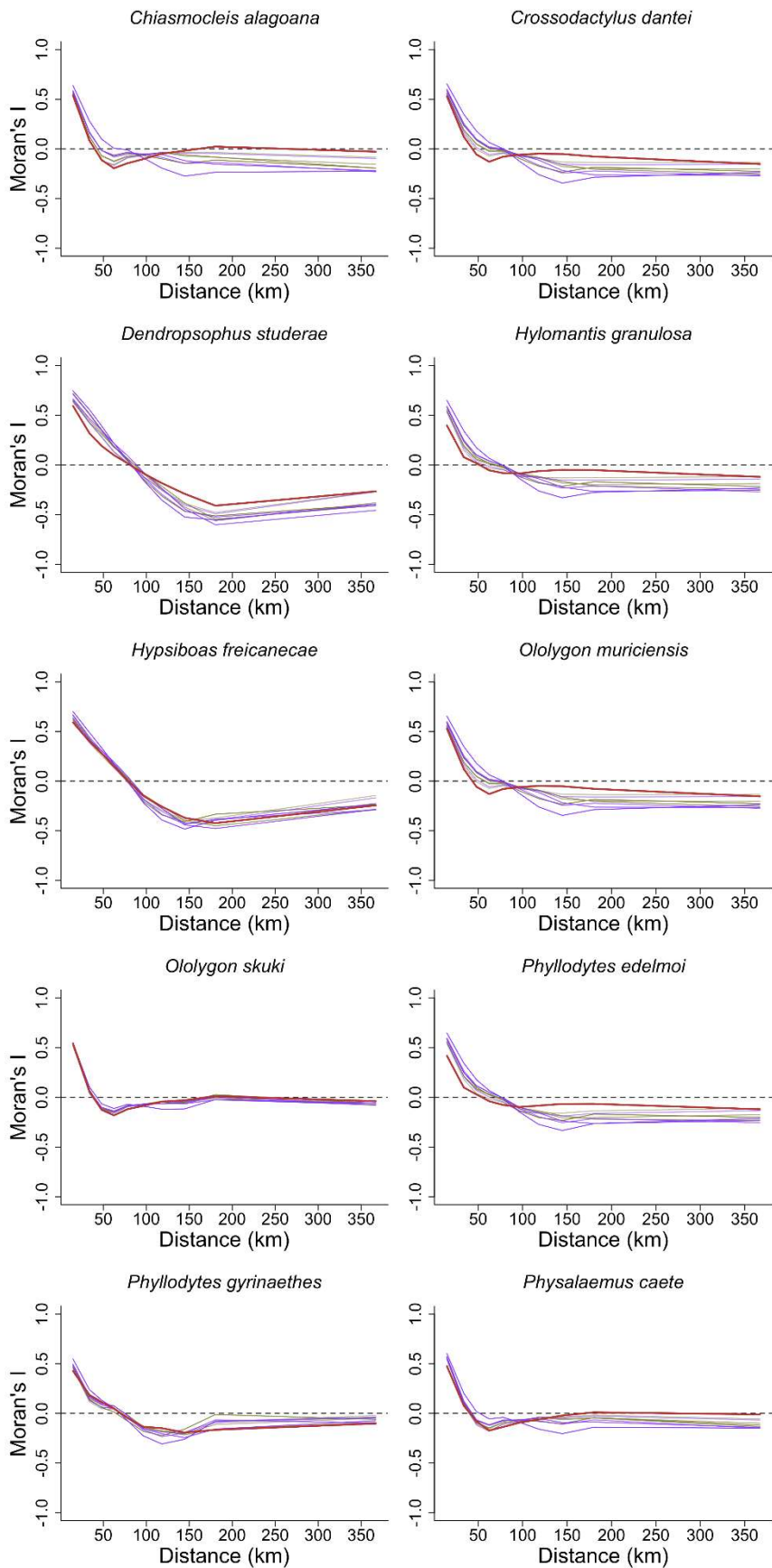


Figure 5. Spatial Moran's I correlogram of environmental similarity for different future scenarios. Red lines represent current climatic conditions, olive lines show the results for climate scenarios for the year 2050 and purple lines for the year 2070. Differences in color intensity represent different Representative Concentration Pathways (RCPs): RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5.

ranged anurans of the Northern Atlantic Forest are under an imminent threat. While most species in this study are currently classified as Data Deficient (IUCN 2017) or not evaluated yet by the Brazilian national red list (ICMBio 2016), a critical conservation window may be passing us by. Therefore, we recommend that both conservation practitioners and the scientific community give further attention not only to the studied species, but to all overlooked small-ranged species.

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- Supplementary Material 1.** Table including the list of small-ranged species of the Northern Atlantic Forest with its correspondent geographic location.
- Supplementary Material 2.** R code used to calculate species environmental Euclidean distance.

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