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Dispersal abilities favor commensalism in animal-plant interactions under climate change

Priscila Lemes[1*], Fabiana G. Barbosa[2], Babak Naimi[3], Miguel B. Araújo[3,4]

1. Laboratório de Ecologia e Conservação, Departamento de Botânica e Ecologia, Instituto de Biologia, Universidade Federal de Mato Grosso, Cuiabá, MT, Brazil.

2. Universidade Federal de Pelotas, Pelotas, RS, Brazil.

3. Rui Nabeiro Biodiversity Chair, MED Institute, University of Évora, Évora, Portugal.

4. Department of Biogeography and Global Change, National Museum of Natural Sciences, CSIC, Madrid, Spain.

***Corresponding author:**

Priscila Lemes, Departamento de Botânica e Ecologia, Instituto de Biologia, Universidade Federal de Mato Grosso, Cuiabá, MT, Brazil. E-mail: priscilalemes@ufmt.br

Abstract

Scientists still poorly understand how biotic interactions and dispersal limitation jointly interact and affect the ability of species to track suitable habitats under climate change. Here, we examine how animal-plant interactions and dispersal limitations might affect the responses of Brazil nut-dependent frogs facing projected climate change. Using ecological niche modeling and dispersal simulations, we forecast the future distributions of the Brazil nut tree and three commensalist frog species over time (2030, 2050, 2070, and 2090) in the regional rivalry (SSP370) scenario that includes great challenges to mitigation and adaptation. With the exception of one species, projections point to a decrease in suitable habitats of up to 40.6%. For frog species with potential reductions of co-occurrence areas, this is expected to reduce up to 23.8% of suitable areas for binomial animal-plant relationships. Even so, biotic interactions should not be lost over time. Species will depend on their own dispersal abilities to reach analogous climates in the future for maintaining ecological and evolutionary processes associated with commensal taxa. However, ecological and evolutionary processes associated with commensal taxa should be maintained in accordance with their own dispersal ability. When dispersal limitation is included in the models, the suitable range of all three frog species is reduced considerably by the end of the century. This highlights the importance of dispersal limitation inclusion for forecasting future distribution ranges when biotic interactions matter.

Keywords: biotic interaction, changing climate, dispersal limitation, ecological niche model, frog-plant interaction, MigClim

1. Introduction

Climate change is causing a global redistribution of species (e.g., Pecl et al. 2017; Taheri et al., 2021) as well as of other levels of biological organization (Bellard et al., 2012), from genetics (Pauls et al., 2013; Abreu-Jardim et al., 2021) to ecosystem levels (Grimm et al. 2013; Mishra et al., 2021). Future climate conditions are projected to further alter species geographic distributions (Pereira et al., 2010; Lavergne et al., 2010; Thuiller et al., 2011; Weiskopf et al., 2020), exacerbating extinction risk (Maclean and Wilson, 2011; Urban 2015) and compounding the negative effects of other environmental changes such as disease, invasive species and land-use change (e.g., Peterson et al., 2008; Hof et al., 2011; Fordham et al., 2013). When biodiversity is incapable of keeping pace with climate change through genetic adaptation (Salamin et al., 2010), phenotypic plasticity (Valladares et al., 2014; Herrando-Perez et al., 2019) or microhabitat use and behavioral adjustments (Gonzáles-del-Pliego et al., 2020), it does so by expanding, contracting, or shifting their geographic distributions (Van der Putten et al., 2010; Garcia et al., 2014). Future extinction risks are thus often associated with contractions in species geographical ranges (Sinclair et al., 2010; Urban 2015), which in turn affect the viability of the surviving populations (Brook et al., 2009; Fordham et al., 2013). Understanding the multi-dimensional nature of climate change effects on species redistributions across scales is far from simple (Wisz et al., 2013), particularly because of the great uncertainties associated with the compounding or buffering effects of biotic interactions (Meir et al., 2010; Wisz et al., 2013), the difficulty to predict species abilities to disperse across long distances (Travis et al., 2013; Kerr, 2020), and the complexities associated with interactions between dispersal and biotic interactions under climate change (e.g., García-Valdés et al., 2015).

Beyond changes in range size, climate changes can reduce suitable overlapping areas differently for each species in the community (Flores-Tolentino et al., 2020), considering that species could move at different speeds and directions (Singer et al., 2013; HilleRisLambers et al., 2013), leading to biota redistribution (Pecl et al., 2017). Biotic interactions are fundamental for ecosystem maintenance and function (Hulme-Beaman et al., 2016; Boukal et al., 2019), thus species range shifts imposed by climate change can impose a complex combination of threatening processes (Bascompte et al., 2019; Schleuning et al., 2020). Following climate change, species interactions may be disrupted (Zarnetske et al., 2012; Brambilla et al., 2020) and new interactions developed (Blois et al., 2013; Bascompte et al., 2019; Schleuning et al., 2020). When individuals or populations influence one another, climate changes can also result from spatial mismatches in such species relationships due to the dispersal limitations of each (Araújo et al., 2011; Urban et al., 2013). Areas projected to be climatically suitable in the future can be inaccessible to the species (Sahlean et al., 2014; Miller and Holloway, 2015) due to species dispersal limitations or habitat connectivity (De Kort et al., 2020) are not commonly integrated into ecological niche models (ENMs) (Peterson et al., 2011; Zurell et al., 2020; De Kort et al., 2020). Therefore, changes in landscape configuration and structure can create barriers preventing the dispersal of the organisms (Becker et al., 2007; Boulangeat et al., 2012; Arntzen et al., 2017).

Advances are being made to better encompass biotic interactions (e.g., Boulangeat et al. 2012; Fordham et al., 2013; Anderson, 2017, Dorman et al., 2018; Flores-Tolentino et al., 2020) and dispersal limitations (Engler et al., 2012; Miller and Holloway, 2015) in ENMs. For species that strongly depend on biotic interactions, their interactions and dispersion capacities are important to the determination of their geographic distribution in response to future climate changes (Araújo and Luoto, 2007; Boulangeat et al., 2012; Urban et al., 2013). Some pairwise interactions involve damages or benefits for one species and no effects for others. The climate change effects have been evaluated for interactions of parasitism (Araújo and Luoto 2007; Chapman et al., 2013; Feldman et al., 2017), predation (Fordham et al. 2013), mutualism (Gorostiague et al., 2018; Morales-Linares et al., 2021), commensalism and ammensalism (Singer et al., 2013; Flores-Tolentino et al., 2020), with most studies lacking explicit treatments of dispersal (but see Fordham et al. 2013).

Commensalistic interactions are particularly interesting because they are arguably among the most commonly found in nature (often referred to wildlife-habitat interactions with habitats encompassing - but not exclusively based on - the plants giving shelter to animals of varying types). An example of commensalism is the interaction between Amazonian frogs and the plants in which they lay their eggs in water-containing fruit capsules for offspring development (Moravec et al., 2009; Camera and Krinski, 2014); the plants are unaffected but their capsules are hugely important for the long term persistence of their populations. This is the case between three tropical frog species - *Adelphobates castaneoticus*, *Osteocephalus castaneicola*, and *Rhinella castaneotica* - and the Brazil nut tree (*Bertholletia excelsa* Bonpl.). Frogs do not cause any damage to the tree, but they need its capsule to develop their water life cycle, highlighting the Brazil nut tree's essential role for their occurrence and distribution. The *B. excelsa* occurs throughout the Amazon region (Thomas et al., 2014) and their fruits are hard and usually opened by scatter-hoarding rodents (Haugaasen et al., 2010). Empty after removal of the seeds, the capsule is not easily decomposed and creates small pools of rainwater inside them. By accumulating rainwater, these become an excellent place for frogs to deposit their eggs for tadpole development (Caldwell and Myers, 1990; Moravec et al., 2009).

Among the most endangered vertebrate groups (Powers and Jetz, 2019), amphibians are especially threatened by habitat modification (Becker et al., 2007; Arntzen et al., 2017; Ribeiro et al., 2017; Murray et al., 2021) and many species are currently on the edge of extinction (Stuart et al., 2004; Ficetola et al., 2015). Amphibians are particularly sensitive to changes in temperature and humidity (Greenberg and Palen, 2021), which makes climate an important factor for shaping their geographic distribution (Enriquez- Urzelai et al., 2019). If the temperature rises, it will most likely alter the distribution of amphibians (Zhang et al., 2020) and their responses to climate change could be species-specific (Miller et al., 2018). Climate change impacts on frog-plant interaction have been investigated (Vasconcelos et al., 2017; Gonzálezdel- Pliego et al., 2020) mainly for organisms that spend their entire life cycle inside plants for their development and breeding (Sabagh et al., 2017). In such cases, there is a mutual benefit since plants also increase their nutrient intake (Romero et al., 2010). If a species is highly dependent on beneficial interactions, it is likely to be particularly sensitive to climate change (e.g., Araújo and Rozenfeld 2014; Foden et al., 2018). Furthermore, future changes in the geographic distribution of the Brazil nut tree due to climate change may thus affect the distribution of frogs because of their reproduction requirements (e.g. Moravec et al., 2009) and amphibian limited dispersal abilities (D'Amen et al., 2011).

Knowledge of how climate change will alter interactions among organisms and the role of dispersal limitation can help us deliver conservation strategies in order to face a future of increasing warming. Considering these issues, we evaluated how animal-plant interaction and dispersal might affect the three selected frog species under climate change. To do so, we (i) used ensemble forecasts of ecological niche models (ENMs) to predict the potential redistribution of species under climate change, (ii) calculated the spatial overlapping between the potential geographic distribution of the modeled three frog species and the Brazil nut tree, and (iii) used a cellular automaton-based-dynamic model to predict the potential distribution of each frog species restricted by biotic interaction, climate, dispersal and landscape constraints.

2. Materials and Methods

2.1. Study system

The Brazil nut tree (*Bertholletia excelsa* Bonpl.) is a flagship species which extends throughout the Amazonian Forest and its distribution range is fragmented in the terra firme (non-flooded) forest between 5ºS and 14ºN (Mori and Prance, 1990). It's mostly found in groups – the "castanhais" – with densities from 10 to 20 trees per hectare (Mori and Prance, 1990; Scoles and Gribel, 2011), and most likely past human influences have contributed to shape its current distribution (Thomas et al., 2015). The Brazil nut tree depends on bee pollination and seed dispersal by the agouti (*Dasyprocta spp.*) (Mori and Prance, 1990; Haugaasen et al., 2010), but projections of climate change impacts have shown a decline in pollinator diversity that might threaten ecosystem services provided by the Brazil nut (Sales et al., 2021). In addition, the Brazil nut tree also plays an important social role, providing food resources that support the livelihood of traditional indigenous societies (Kainer et al., 2018). Because Brazil nuts have suffered anthropogenic and natural pressures (Peres et al., 2003; Escobar, 2019), this species is now considered threatened by the Brazilian Ministry of the Environment (law #443/2014 MMA, 2014).

2.2 Species data

We obtained presence records for the Brazil nut tree from the Global Biodiversity Information Facility (GBIF, http://www.gbif.org), SpeciesLink (http://splink.cria.org.br), and complemented these data with data from the National Center for Flora Conservation (Centro Nacional de Conservação da Flora - in Portuguese, CNCFlora; cncflora.jbrj.gov.br). Virtual databases were searched and matching records were downloaded using the function *occ()*, then collapsed into a single string with the function *fixnames()*, both available in the spocc package (Chamberlain et al., 2016). For the three frog species, we obtained presence records from the following sources: (i) literature data for *Adelphobates castaneoticus* (Camera and Krinski, 2014) and *Osteocephalus castaneicola* (Silva et al., 2016; Carvalho et al., 2017), and (ii) two virtual databases - the GBIF and Brazilian biodiversity website (Portal da Biodiversidade - in Portuguese, https://portaldabiodiversidade.icmbio.gov.br/portal/) - mainly for *Rhinella castaneotica*. The species occurrence records are available in Table S1.

We then critically reviewed this dataset by deleting ambiguous, duplicate, or unreliable records and removing those whose geographical location or taxonomic information were not precisely defined using a suite of *coord_ functions()* from scrubr package (Chamberlain, 2016). After data cleaning, we spatially thinned the occurrence localities by 10 km to minimize clustering of records due to biased sampling by using *thin()* available in the spThin package (Aiello-Lammens et al., 2015). We reached a frog dataset containing 14 presence records for *A. castaneoticus*, 15 records for *O. castaneicola*, and 40 records for *R. castaneotica*, along with 148 records for the Brazil nut tree. All spatial analyses were performed in R (R Core Team, 2020).

2.3. Environmental data

For frog species and the Brazil nut tree, we used 19 bioclimatic variables as candidate baseline predictors with a spatial resolution of 0.08333º (~9km x 9km) from the global dataset of WorldClim2 (Fick and Hijmans, 2017; Table S2). In addition, for the Brazil nut tree, we also included topsoil predictors acknowledged as physiologically important to plants, namely: cation exchange capacity, clay fraction, gravel fraction, pH in water, organic carbon content (in percent and volume-weighted), silt fraction and soil depth (Mod et al., 2016; Figueiredo et al., 2018). Only topsoil features were included since the Amazon territory is mostly composed of shallow soils. These data were obtained from the Regridded Harmonized World Soil Database v1.2 (https://daac.ornl.gov/SOILS/guides/HWSD.html), containing global soil parameters in the form of NetCDF files at 0.9 degree x 1.25 degree resolution, and further downscaled to the same resolution of climate predictors using the *resample()* function and the nearest-neighbor interpolation method. To avoid problems associated with multicollinearity, the candidate predictors were selected by the variance inflation factor (VIF, Zuur et al., 2010) and we only retained the variables with VIF values < 10 (Dormann et al., 2013) using the function *vifcor()* from the sdm package (Naimi et al., 2014; Naimi and Araújo, 2016) in R (R Core Team, 2020). Once collinearity was evaluated using species occurrence records, distinct subsets of environmental predictors were selected for each species, which were then used to calibrate species-specific ENMs.

Once the species-climate relationships were estimated, we projected the estimated conditions across temporal bins in the future (2030, 2050, 2070, and 2090) using available projections and scenarios in Wordclim2 (Fick and Hijmans, 2017). We used the downscaled data from three general circulation models (GCMs), namely, BCC-CSM2-MR, CanESM5, and MIROC6 (CMIP6, Eyring et al., 2016) for one shared socio-economic pathway (SSP; Eyring et al., 2016): SSP370. These GCMs characterize the wide variety of models based on the latest update on expected future climate change projections (Brunner et al., 2020). The future climate conditions were simulated into shared socio-economic pathways (SSPs), which are driven by changes to both precursor emissions and climate (Eyring et al., 2016). Specifically, the SSP370 represents the medium-to-high end of future emissions and forecasts a 4.1ºC warming until 2100 (Riahi et al., 2017).

2.4. Ecological Niche Modelling

The species spatial distribution records were associated with environmental data to characterize the conditions experienced by species and to predict their potential geographic distribution during the baseline period. We used the sdm package (Naimi and Araújo, 2016) in order to develop a large ensemble of forecasts (Araújo and New, 2007) of ENMs (Peterson and Soberón, 2012), that combines the output of multiple models to generate a single prediction through consensus. For each species, we calibrate models using Bioclim (Booth et al., 2014), DOMAIN (Carpenter et al., 1993), MaxLike (Royle et al., 2012), Support Vector Machine (SVM; Vapnik, 1995), Boosted Regression Tree (BRT; Friedman, 2001), and Multivariate Adaptive Regression Splines (MARS; Friedman, 1991). Because some methods required zeros to be fitted, we generated a random sample of 10,000 sites for modeling each species. For model performance of

A. castaneoticus and *O. castaneicola*, we used a bootstrapping replication method due to a small number of species presence records (Hastie et al., 2009), repeated 30 times. For models of *R. castaneotica* and *B. excelsa*, we used 30 runs of subsampling replication methods by splitting the data into training and test datasets (70 and 30 percent, respectively). Models were parameterized using default options of the sdm package (Naimi and Araújo, 2016) and performed in R (R Core Team, 2020).

We used the area under the curve (AUC) of the receiver operating characteristic (ROC) to assess the accuracy of ENMs (Fielding and Bell, 1997). A ROC curve estimates the proportion of instances of presence correctly predicted as presence (omission errors) and the proportion of instances of absence wrongly predicted as presence (commission error) across all possible thresholds between 0 and 1 (Jimenez-Valverde, 2012). AUC values of 0.5-0.7 correspond to low accuracy, 0.7-0.9 indicate good accuracy, and values above 0.9 indicate high accuracy (Swets, 1988). The true skill statistic (TSS) considers both model sensitivity and specificity (Allouche et al., 2006), and ranges from -1 to +1. If TSS is +1, this implies perfect agreement, while a value of 0 indicates agreement expected by random, and a value of less than 0 indicates agreement lower than expected by chance. We generated 90 individually calibrated models for each species, and we used the TSS to create a weighted average of each prediction model. For each species, we generated ensemble forecasting using the output models for each time slice. We classified continuous predictions into presence and absence maps based on maximizing the TSS (Allouche et al., 2006). Further, we assembled the binary maps by simple mean values for each species from single methods under current and future climate conditions. Also, we evaluated the variable importance (Murray and Corner, 2009) and plotted the predicted response curve (Elith et al., 2005) for inferring the relationship between the environmental variables and predicted habitat suitability.

2.5. Potential co-occurrence

From binary consensus maps, we forecasted how climate change may affect the potential co-occurrence between Brazil nut trees and each frog species. For this purpose, we superimposed the binary maps and afterward we calculated the number of suitable cells between the species pair, in the current and in the future (e.g., Araújo et al., 2011; Sales et al., 2021). These cells represent potential co-occurrences that indicate areas that host environmental conditions considered most suitable for each frog-plant binomial. Since the frog species studied here depend on the indehiscent fruit armory to lay eggs and reproduce, we considered that the absence of Brazil nut trees (in the form of unsuitable cells in maps of binary potential distribution) would prevent frog occupancy of climatically suitable cells. By doing so, we assume that frog occupancy of climatically suitable cells is also dependent on plant occurrence and, therefore, on shared environmental suitability.

2.6. Incorporating dispersal limitation

In order to dynamically explore the climate change consequences over time, we implemented species dispersal constraints through a cellular automaton-based model (Engler and Guisan, 2009). Therefore, we used the MigClim model (Engler et al., 2012) that calculates the probability a given cell will become colonized and simulates species dispersal under a changing climate by including (i) current map of habitat suitability, (ii) species dispersal ability, (iii) barriers to dispersal for our focal species, (iv) and future maps in *p* climate conditions. The simulations start with source pixels represented by actual occupied pixels and target pixels are considered those that will be climatically suitable for species colonization under future conditions. The resulting map of cellular automata represents the potential distribution restricted by dispersal over time.

Our simulations included the frog binary maps of habitat suitability filtered by Brazil nut tree presence**.** This assumes frogs’ dependency on the fruit capsules of the Brazil nut for breeding (Caldwell and Myers, 1990; Moravec et al., 2009; Camera and Krinski, 2014). As no information on dispersal distances potentially traveled by unit time for our focal frog species, we used two extreme datasets of kernel dispersal distance for incorporating dispersal limitation previously used in another study (Uribe-Rivera et al., 2017) as follows: *Bombina bombina* (minimum dispersal) and *Rana temporaria* (maximum dispersal) (Kovar et al., 2009). Furthermore, some landscape constraints can interpose the species' ability to colonize new areas (Ribeiro et al., 2017), and ongoing habitat transformation will become increasingly more susceptible to discontinuing their life cycle (Becker et al., 2007). We used a global model that predicts the potential future tree cover persistence for 2029 (Hewson et al., 2019) in generating a dispersal barrier layer from landscapes forecasted to host less than 30% remaining tree cover in the future. The first environmental step started in the current climate (1970-2000) followed by predictions of future climate in the years of 2030, 2050, 2070, and 2090, thus the cellular automaton model produced a total of four dispersal steps. The MigClim output informs species dispersal constraints and suitable areas until the end of the time period (2080-2100). Demographic criteria were parameterized using default options of the MigClim package (Engler et al., 2012) and performed in R (R Core Team, 2020).

3. Results

3.1. Potential species distribution

Forecasts of the Brazil nut tree's distribution matched the species' observed distribution (mean AUC = 0.80 ± 0.04; TSS = 0.54 ± 0.03) (Table S3 in Supplementary Material). Future climatic conditions will alter the habitat suitability of the Brazil nut tree, increasing suitability where mean temperature of the wettest quarter ranges from 20°C - 25°C and where precipitation of the wettest month exceeds 500mm, and decreasing where the pH levels become neutral, which is most likely to occur in its current easternmost distribution (Fig. 1ab). Forecasts showed that

Brazil nut tree species could lose roughly 7% of their suitable areas by the end of the century (Table S4).

The predictive accuracy of the frog species was high for almost all methods with an AUC average of 0.83 ± 0.06 and TSS of 0.65 ± 0.12 (Table S2 in Supplementary Material). The distribution of the frog species is fundamentally determined by precipitation. While the habitat suitability of *A. castaneoticus* increases in the areas where the precipitation of the coldest quarter (bio 19) is greater than 1,750mm, the habitat suitability (Fig. 1ef) of *O. castaneicola* increases in areas with precipitation up to 1,000mm in the warmest quarter (bio 18; Fig. 1ef). *Rhinella castaneostica* distribution is determined by precipitation seasonality (bio 15) with the relative importance of 36.5% (Fig. 1g). The response curve shows a decrease in the habitat suitability when precipitation seasonality is between 750mm and 1500mm (Fig. 1h). Whereas *O. castaneicola* and *R. castaneostica* should decrease up to 40% of climatic suitability areas, *A. castaneoticus* will probably increase their suitable areas in the last half century (Table S4).

3.2. Potential co-occurrence

By overlaying maps of the potential geographic distribution of the Brazil nut tree and each frog species, we assessed patterns of potential co-occurrence and their variation in space and time (Fig. 2). The overlap in current modelled distributions was highest for *O. castaneicola* with 94.4% (18.8% of the Brazil nut tree species' range overlapping with the latter), followed by *A. castaneoticus* with 93.8% (15%), and *R. castaneotica* reach 93.6% (50.6%, see Table S5 for absolute values). The potential overlap between the Brazil nut tree and *A. castaneoticus*, however, will change over time (Fig. 2a; Table S5). Almost the entire range of *A. castaneoticus* is predicted to be unsuitable in 2050 (Fig. 2a), but it is likely to substantially increase its suitable range by 2090. The potential co-occurrence between the Brazil nut tree and *O. castaneicola* will decrease in the future due to the latter's distribution contraction (Fig. 2b). The likely overlap between the Brazil nut tree and *R. castaneotica* will decrease in absolute values (Fig. 2c, Table S5). Considering the predictive species distribution, the average climatically suitable range of the Brazil nut tree and three commensalist frog species are projected to maintain animal-plant interaction (Fig. 2).

3.3. Dispersal limitation

The MigClim resulting maps allowed us to forecast areas that will be climatically suitable for each frog species even under dispersal constraints (Fig. 3). Climate refugia range was predicted to decrease for all frog species until end-of-century (95.8% for *A. castaneoticus*, 95.7% for *O. castaneicola*, and 85.7% for *R. castaneotica*). By combining areas of climate refugia (*i.e* always suitable) and potentially migration, *A. castaneoticus*' range may increase up to 207% (Fig. 3a), while both *O. castaneicola* and for *R. castaneotica* should decrease 20.4% (Fig. 3b) and 34.2% (Fig. 3c), respectively at maximum dispersal scenario (see Table S6 for absolute values). Many areas will become unavailable for *A. castaneoticus* due to dispersal constraints (Fig. 3d) and some Colombian and Venezuelan regions appear inaccessible due to dispersal limitation for *O. castaneicola* facing climate change (Fig. 3e). Our simulations suggest dispersal limitation will prevent *O. castaneicola* from occupying climate refugia areas in Peru, western Brazil and the eastern Madeira River (Fig. 3b,e). The Guyanas (French Guiana, Guyana and Suriname) and southeastern edge of the forest also appear to be unsuitable for *R. castaneotica* (Fig. 3f).

4. Discussion

We developed models that simulated changes in suitable areas for three Amazonian frogs and the Brazil nut tree, along with the inclusion of the frog species dispersal capacity. Possible disruptions in animal-plant commensalism in response to end-of-century climate change are projected. To track climate-driven shifts and allow species migrations, the species-specific dispersal needed to be surveyed. This is because future frog distribution will be highly reliant on the existence of permeable migratory routes across the habitat patch. Our findings are consistent with other studies showing that responses to climate changes will likely depend on species dispersal ability (e.g., Anderson et al. 2009; Travis et al., 2013; Sales et al., 2019). A minimum dispersal-case scenario is expected to lead to ecological bottlenecks in the future because species will be incapable of tracking the pace of climate change and only remain within climate refugia areas with high climate stability (e.g., Terrible et al. 2012). Our models forecast a severe reduction in climate refugia for all Brazilian nut tree frogs.

Positive species interactions can influence range limits or affect range expansion (Stephan et al., 2021). The climate-related changes of co-occurrence and biotic interactions should affect ecosystem functions and services mediated by animal–plant interactions (Sales et al., 2021). Even if a mismatch between Brazil nut trees and frogs has gone undetected in our study, biotic interactions are essential to the biological community structure (Brambilla et al., 2020; Flores-Tolentino et al., 2020). Commensalism or mutualism could affect the rate and ultimate extent of range expansion in response to changing environmental conditions, such as those caused by climate change (HilleRisLambers et al., 2013). The complex effects across species ranges arising from species interacting can lead to asymmetric range shift dynamics (Ettinger and HilleRisLambers, 2017**;** Sales et al., 2021). There are some studies on the response of co-occurrence and indirect interactions to climate change (Araújo et al., 2011; Losapio and Schöb, 2017), these are based on inferred rather than actual direct interactions.

Frogs have low dispersal and our more realistic projections indicate that all three commensalist species may become threatened by climate change in the future. Frog species with aquatic larvae depend on connectivity between aquatic and terrestrial habitats to complete their life cycle and suffer the negative effects of habitat split in discontinuous landscapes (Becker et al., 2007; Fonseca et al., 2013; Lion et al., 2014), even for frog species with specialized aquatic reproductive modes. The movement to and from breeding sites mainly with an aquatic larval phase is vitally important for not only reproduction (Becker et al., 2007), but also the survival of local populations (Becker et al., 2010). The species' abilities to shift their range limit or to expand their geographic distribution under changing climate, however, will assuredly depend on their dispersal capabilities (D’Amen et al., 2011; Schloss et al., 2012; Bateman et al., 2013; Zanatta et al., 2020), otherwise the species could be confined to unsuitable climate areas (Gouveia et al., 2016). Our models included the ability of species to disperse into a spatially explicit framework, although based on a number of simplifications due to limitations in the availability of empirical data for each frog species.

One the clearest signs of biotic response to climate change are range shifts where species will need to move into newer climate suitable areas (Kerr, 2020) just as quickly as temperatures increase, in order to maintain spatial insurance and their own persistence (Chen et al., 2011). However, species will depend on intrinsic dispersal ability (Scholls et al., 2012; Estrada et al., 2016) which is becoming especially challenging for frogs with low dispersion abilities (Kovar et al., 2009) and may prohibit them from reaching new areas (Uribe-Rivera et al., 2017). Rather few studies explicitly included species-specific dispersal abilities when modeling species distribution and even running models with unlimited dispersal tend to overestimate the potential future range (Thuiller et al., 2019), especially for species with moderate to low dispersal ability (Urban et al., 2016). By including dispersal ability information, we demonstrated that all three frog species should experience decreases in their geographic distribution over time. Although many studies have assumed no dispersal, unlimited dispersal or a previously defined limited dispersal distance (“buffers”) in post-processing ENM analyses, we advocated the inclusion of intrinsec dispersal capability proxies (Travis et al., 2013; Uribe-Rivera et al., 2017; Boyer et al., 2020) or even niche information (Penner and Rödel, 2019).

Inclusion of species dispersal abilities improves distribution models into more realistic scenarios (Thuiller et al., 2019). While there is still some debate on how to integrate dispersal metrics into ENMs (Monsimet et al., 2020; Zanatta et al., 2020) a variety of methods are already available through some R packages (e.g.,'ENMTML'; Andrade et al., 2020; 'megaSDM'; Shipley et al., 2022). In our study, inclusion of dispersal abilities in our ENMs revealed areas where colonization is highly unlikely and when and where suitable habitat will become accessible. A proposal would be areas where species will be to maintain interconnected suitable areas which should help conserve current habitats and promote species persistence over time, even in a changing world.

Because our simulations are based on some simplifications, it is important to highlight some caveats in our findings. Firstly, and most importantly, empirical data of intrinsic dispersal are currently unavailable for the study species. Unfortunately, minimal dispersal data are feasible and remain much less understood in organisms with complex life cycles, as is the case with amphibians (Cayuela et al., 2020). Secondly, we assumed an isotropic dispersal, which means, if there is a balance between climate and dispersal constraints, these are colonized; thereby, we ignored other ecological aspects important to maintain viable populations such as demography and other biotic interaction beyond that of our interest (frog species and the Brazil nut tree). Our assumptions imply in an over estimation of colonization rates as that used on Uribe-Rivera et al. (2017) study. Even so, our results show that few areas will be climatically suitable at the 21st century´s end for three Amazonian frog species (pink areas, Fig 3). Finally, beyond remarks underlying spatial predictions of ENMs (Zurell et al., 2020), we inferred biotic interactions from large-scale data through the spatial analysis of (co)distributions of species (*e.g.* Sales et al., 2021) to make the models more realistic. Although there are recent advances (Dorman et al., 2018), studies dealing with biotic interaction and dispersal constraints present the greatest challenges in the future.

5. Conclusion

In conclusion, we forecast the patterns of climate change response for commensalistic interaction between three Amazonian frog species and the Brazil nut tree, explicitly including the effects of frog dispersal limitation on estimates of potential distribution. Amazonian frog species depends on the Brazil nut tree capsule for completing their lifecycle (Caldwell and Myers, 1990; Moravec et al., 2009; Camera and Krinski, 2014) and our projections indicate their climate niche will maintain the overlap between each pairwise of animal-plant species. By including dispersal limitation, the areas with suitable climate for frog species will drastically reduce until the end of the 21st century. To maintain climate change pace, Amazonian frog species should remain in small and disconnected areas of climate suitability as *Adelphobates castaneoticus* does because of low intrinsic dispersal abilities. Our results highlight the important role of integrating dispersal constraints on projections of future distributions for low dispersive species, as Amazonian frogs.

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7. References

Abreu-Jardim TPF, Jardim L, Ballesteros-Mejia L, Maciel NM, Collevatti RG (2021) Predicting impacts of global climatic change on genetic and phylogeographical diversity of a Neotropical treefrog. Diversity and Distributions, 27, 1519-1535.

Aiello- Lammens ME, Boria RA, Radosavljevic A, Vilela B, Anderson RP (2015) spThin: an R package for spatial thinning of species occurrence records for use in ecological niche models. Ecography, 38, 541-545.

Allouche O, Tsoar A, Kadmon R (2006) Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). Journal of Applied Ecology, 43, 1223-1232.

Anderson RP (2017) When and how should biotic interactions be considered in models of species niches and distributions? Journal of Biogeography, 44, 8-17.

Anderson BJ, Akçakaya HR, Araújo MB, Fordham DA, Martinez-Meyer E, Thuiller W, Brook BW (2009) Dynamics of range margins for metapopulations under climate change. Proceedings of the Royal Society B, 276, 1415-1420.

Andrade AFA, Velazco SJE, De Marco, P (2020) ENMTML: An R package for a straightforward construction of complex ecological niche models. Environmental Modelling and Software, 125, 104615.

Araújo MB, Luoto M (2007) The importance of biotic interactions for modelling species distributions under climate change. Global Ecology and Biogeography, 16, 743-753. https://doi.org/10.1111/j.1466-8238.2007.00359.x.

Araujo MB, New M (2007) Ensemble forecasting of species distributions. Trends in Ecology and Evolution, 22, 42-44.

Araújo MB, Rozenfeld A, Rahbek C, Marquet PA (2011) Using species co- occurrence networks to assess the impacts of climate change. Ecography, 34, 897-908. https://doi.org/10.1111/j.1600-0587.2011.06919.x.

Arntzen JW, Abrahams C, Meilink WR, Iosif R, Zuiderwijk A (2017) Amphibian decline, pond loss and reduced population connectivity under agricultural intensification over a 38 year period. Biodiversity and Conservation, 26, 1411-1430.

Barrett K, Guyer C (2008) Differential responses of amphibians and reptiles in riparian and stream habitats to land use disturbances in western Georgia, USA. Biological Conservation, 141, 2290-2300.

Bascompte J, García MB, Ortega R, Rezende EL, Pironon S (2019) Mutualistic interactions reshuffle the effects of climate change on plants across the tree of life. Science Advances, 5, eaav2539.

Bateman BL, Murphy HT, Reside AE, Mokany K, VanDerWal J (2013) Appropriateness of full- , partial- and no- dispersal scenarios in climate change impact modelling. Diversity and Distributions, 19, 1224-1234.

Becker CG, Fonseca CR, Haddad CFB, Batista RF, Prado PI (2007) Habitat split and the global decline of amphibians. Science, 318, 1775-1777.

Becker CG, Fonseca CR, Haddad CFB, Prado PI(2010). Habitat split as a cause of local population declines of amphibians with aquatic larvae. Conservation Biology, 24, 287-294.

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. Ecology Letters, 15, 365-377.

Blois JL, Zarnetske PL, Fitzpatrick MC, Finnegan S (2013) Climate change and the Past, Present, and Future of Biotic Interactions. Science, 341, 499-504.

Boyer I, Cayuela H, Bertrand R, Isselin- Nondedeu F (2020) Improving biological relevance of model projections in response to climate change by considering dispersal amongst lineages in an amphibian. Journal of Biogeography, 48, 561-576.

Booth TH, Nix HA, Busby JR, Hutchinson MF (2014) BIOCLIM: the first species distribution modelling package, its early applications and relevance to most current MaxEnt studies. Diversity and Distributions, 20, 1-9.

Boulangeat I, Gravel D, Thuiller W (2012) Accounting for dispersal and biotic interactions to disentangle the drivers of species distributions and their abundances. Ecology Letters, 15, 584-593.

Boukal DS, Bideault A, Carreira BM, Sentis A (2019) Species interactions under climate change: connecting kinetic effects of temperature on individuals to community dynamics. Current Opinion in Insect Science, 35, 88-95.

Brambilla M, Scridel D, Bazzi G, Ilahiane L, Iemma A, Pedrini P, Bassi E, Bionda R, Marchesi L, Genero F, Teufelbauer N, Probst R, Vrezec A, Kmecl P, Mihelič T, Bogliani G, Schmid H, Assandri G, Pontarini R, Braunisch V, Arlettaz R, Chamberlain D (2020) Species interactions and climate change: How the disruption of species co- occurrence will impact on an avian forest guild. Global Change Biology, 26, 1212-1224.

Brook BW, Akçakaya HR, Keith DA, Mace GM, Pearson RG, Araújo MB (2009) Integrating bioclimate with population to improve forecasts of species extinctions under climate change. Biology Letters, 5, 723-725.

Brunner L, Pendergrass AG, Lehner F, Merrifield AL, Lorenz R, Knutti R (2020) Reduced global warming from CMIP6 projections when weighting models by performance and independence. Earth System Dynamics, 11, 995-1012.

Caldwell JP, Myers CW (1990) A new poison frog from Amazonian Brazil, with further revision of the quinquevittatus group of Dendrobates. American Museum Novitates, 2988, 1-21.

Camera BF, Krinski D (2014) Distribution extension and geographic distribution map of the Brazil-nut poison dart frog *Adelphobates castaneoticus* (Caldwell and Myers, 1990)(Anura: Dendrobatidae): New record for southwestern Pará State, Brazil. Check List, 10, 244-245.

Carpenter G, Gillison AN, Winter J (1993) DOMAIN: a flexible modelling procedure for mapping potential distributions of plants and animals. Biodiversity and Conservation, 2, 667-680.

Carvalho MA, Peloso PLV, Sturaro MJ (2017) On the distribution of *Osteocephalus castaneicola* Moravec, Aparicio, Guerrero-Reinhard, Calderón, Jungfer and Gvoždík, 2009 (Anura: Hylidae), with new records for Amazonian Brazil. Herpetology Notes, 10, 593-596.

Cayuela H, Valenzuela-Sánchez A, Teulier L, Martínez-Solano Í, Léna JP, Merilä J, Muths E, Shine R, Quay L, Denoël M, Clobert J, Schmidt BR (2020) Determinants and Consequences of Dispersal in Vertebrates with Complex Life Cycles: A Review of Pond-Breeding Amphibians. The Quarterly Review of Biology, 95, 1-36. DOI: https://doi.org/10.1086/707862

Chamberlain S (2016) Scrubr: Clean biological occurrence records. Retrieved from https://cran.r-project.org/package=scrubr.

Chamberlain S, Ram K, Hart T (2016) Spocc: interface to species occurrence data sources. Retrieved from https://cran.r-project.org/package=spocc.

Chapman DS, Saraiva AM, Alves-dos-Santos I, Biesmeijer JC (2013) Improving species distribution models using biotic interactions: A case study of parasites, pollinators and plants. Ecography 36, 649-656.

Chen I-C, Hill JK, Ohlemuller R, Roy DB, Thomas CD (2011) Rapid range shifts of species associated with high levels of climate warming. Science, 333, 1024-1026.

D'Amen M, Bombi P, Pearman PB, Schmatz DR, Zimmermann NE, Bologna MA (2011) Will climate change reduce the efficacy of protected areas for amphibian conservation in Italy? Biological Conservation, 144, 989-997.

da Silva DP, Ramalho WP, de Matos LRA, da Silva TL, Machado, DC (2016) First record of *Osteocephalus castaneicola* Moravec, Aparicio, Guerrero-Reinhard, Calderón, Jungfer and Gvoždík, 2009 (Anura: Hylidae) for Acre, Brazil. Check List, 12, 1826.

Dirzo R, Young HS, Galetti M, Ceballos G, Isaac NJB, Collen B (2014) Defaunation in the Anthropocene. Science, 345, 401-406. 10.1126/science.1251817.

Dormann CF, Elith J, Bacher S, Buchmann C, Carl G, Carré G, García Marquéz JR, Gruber B, Lafourcade B, Leitão PJ, Münkemüller T, McClean C, Osborne PE, Reineking B, Schröder B, Skidmore AK, Zurell, Lautenbach S (2013) "Collinearity: A Review of Methods to Deal with It and A Simulation Study Evaluating Their Performance." Ecography, 36, 27-46. doi:10.1111/j.1600-0587.2012.07348.x.

Dormann CF, Bobrowski M, Dehling DM, Harris DJ, Hartig F, Lischke L, Moretti MD, Pagel J, Pinkert S, Schleuning M, Schmidt SI, Sheppard CS, Steinbauer MJ, Zeus D, Kraan C (2018) Biotic interactions in species distribution modelling: 10 questions to guide interpretation and avoid false conclusions. Global Ecology and Biogeography, 27, 1004-1016.

Elith J, Ferrier S, Huettmann F, Leathwick J (2005) The evaluation strip: a new and robust method for plotting predicted responses from species distribution models. Ecological Modelling, 186, 280-289.

Engler R, Guisan A (2009) MigClim: predicting plant distribution and dispersal in a changing climate. Diversity and Distributions, 15, 590-601.

Engler R, Hordijk W, Guisan A (2012) The MIGCLIM R package – seamless integration of dispersal constraints into projections of species distribution models. Ecography, 35, 872-878.

Enriquez- Urzelai U, Kearney MR, Nicieza AG, Tingley R (2019) Integrating mechanistic and correlative niche models to unravel range- limiting processes in a temperate amphibian. Global Change Biology, 25, 2633-2647.

Estrada A, Delgado MP, Arroyo B, Traba J, Morales MB (2016) Forecasting Large-Scale Habitat Suitability of European Bustards under Climate Change: The Role of Environmental and Geographic Variables. PLoS ONE, 11, e0149810.

Ettinger A, HilleRisLambers J (2017) Competition and facilitation may lead to asymmetric range shift dynamics with climate change. Global Change Biology, 23, 3921-393.

Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, Taylor KE (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development (Online), 9(LLNL-JRNL-736881).

Feldman RE, Peers MJ, Pickles RS, Thornton D, Murray DL (2017) Climate driven range divergence among host species affects range-wide patterns of parasitism. Global Ecology and Conservation, 9, 1-10.

Ficetola GF, Rondinini C, Bonardi A, Baisero D, Padoa- Schioppa E (2015) Habitat availability for amphibians and extinction threat: a global analysis. Diversity and Distributions, 21, 302-311.

Fick SE, Hijmans RJ (2017) WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. International Journal of Climatology, 37, 4302-4315.

Fielding AH, Bell JF (1997) A review of methods for the assessment of prediction errors in conservation presence/absence models. Environmental Conservation, 24, 38-49.

Figueiredo FOG, Zuquim G, Tuomisto H, Moulatlet GM, Balslev H, Costa FRC (2018) Beyond climate control on species range: The importance of soil data to predict distribution of Amazonian plant species. Journal of Biogeography, 45, 190-200.

Flores-Tolentino M, García-Valdés R, Saénz-Romero C, Ávila-Díaz I, Paz H, Lopez-Toledo L (2020) Distribution and conservation of species is misestimated if biotic interactions are ignored: the case of the orchid *Laelia speciosa*. Scientific Reports 10, 9542.

Fordham DA, Akçakaya HR, Brook BW, Rodríguez A, Alves PC, Civantos E, Triviño M, Watts MJ, Araújo MB (2013) Adapted conservation measures are required to save the Iberian lynx in a changing climate. Nature Climate Change, 3, 899-903. https://doi.org/10.1038/nclimate1954.

Fonseca CR, Coutinho RM, Azevedo F, Berbert JM, Corso G, Kraenkel RA (2013) Modeling habitat split: landscape and life history traits determine amphibian extinction thresholds. PLoS ONE, 8, e66806.

Friedman JH (2001) Greedy function approximation: a gradient boosting machine. Annals of Statistics, 29, 1189-1232.

Friedman JH (1991) Multivariate adaptive regression splines. Annals of Statistics, 19, 1-67.

Garcia RA, Cabeza M, Rahbek C, Araújo MB (2014) Multiple Dimensions of Climate Change and Their Implications for Biodiversity. Science, 344, 1247579-1247579.

García- Valdés R, Svenning J- C, Zavala MA, Purves DW, Araújo MB (2015) Evaluating the combined effects of climate and land- use change on tree species distributions. Journal of Applied Ecology, 52, 902-912. https://doi.org/10.1111/1365-2664.12453.

González- del- Pliego P, Scheffers BR, Freckleton RP, Basham EW, Araújo MB, Acosta-Galvis A. R, Uribe CAM, Haugaasen T, Edwards DP (2020) Thermal tolerance and the importance of microhabitats for Andean frogs in the context of land use and climate change. Journal of Animal Ecology, 89, 2451-2460.

Gorostiague P, Sajama J, Ortega-Baes P (2018) Will climate change cause spatial mismatch between plants and their pollinators? A test using Andean cactus species. Biological Conservation, 226, 247-255.

Gouveia SF, Souza-Alves JP, Rattis L, Dobrovolski R, Jerusalinsky L, Beltrão-Mendes R, Ferrari SF (2016) Climate and land use changes will degrade the configuration of the landscape for titi monkeys in eastern Brazil. Global Change Biology, 22, 2003-2012.

Greenberg DA, Palen WJ (2021) Hydrothermal physiology and climate vulnerability in amphibians. Proceedings of the Royal Society B, 288, 20202273.

Grimm NB, Chapin III FS, Bierwagen B, Gonzalez P, Groffman PM, Luo Y, Melton F, Nadelhoffer K, Pairis A, Raymond PA, Schimel J, Williamson CE (2013) The impacts of climate change on ecosystem structure and function. Frontiers in Ecology and the Environment, 11, 474-482. https://doi.org/10.1890/120282.

González- del- Pliego P, Scheffers BR, Freckleton RP, Basham EW, Araújo MB, Acosta- Galvis A R, Uribe CAM, Haugaasen T, Edwards DP (2020) Thermal tolerance and the importance of microhabitats for Andean frogs in the context of land use and climate change. Journal of Animal Ecology, 89, 2451-2460.

Haugaasen J, Haugaasen T, Peres C, Gribel R, Wegge P (2010) Seed dispersal of the Brazil nut tree (*Bertholletia excelsa*) by scatter-hoarding rodents in a central Amazonian forest. Journal of Tropical Ecology, 26, 251-262.

Hastie T, Tibshirani R, Friedman J (2009) The elements of statistical learning. Springer.

Herrando- Pérez S, Monasterio C, Beukema W, Gomes V, Ferri- Yáñez F, Vieites DR, Buckley LB, Araújo MB (2020) Heat tolerance is more variable than cold tolerance across species of Iberian lizards after controlling for intraspecific variation. Functional Ecology, 34, 631-645.

Hewson J, Crema SC, González-Roglich M, Tabor K, Harvey CA (2019) New 1 km Resolution Datasets of Global and Regional Risks of Tree Cover Loss. Land, 8, 14. https://doi.org/10.3390/land8010014.

HilleRisLambers J, Harsch MA, Ettinger AK, Ford KR, Theobald EJ (2013) How will biotic interactions influence climate change–induced range shifts?. Annals of the New York Academy of Sciences, 1297, 112-125.

Hof C, Araújo MB, Jetz W, Rahbek C (2011) Additive threats from pathogens, climate and land-use change for global amphibian diversity. Nature, 480, 516-519. https://doi.org/10.1038/nature10650.

Hulme-Beaman A, Dobney K, Cucchi T, Searle JB (2016) An ecological and evolutionary framework for commensalism in anthropogenic environments. Trends in Ecology and Evolution, 31, 633-645.

Jiménez- Valverde A (2012) Insights into the area under the receiver operating characteristic curve (AUC) as a discrimination measure in species distribution modelling. Global Ecology and Biogeography, 21, 498-507.

Kainer KA, Wadt LHO, Staudhammer CL (2018) The evolving role of *Bertholletia excelsa* in Amazonia: contributing to local livelihoods and forest conservation. Desenvolvimento e Meio Ambiente, 48, 477-497.

Kerr JT (2020) Racing against change: understanding dispersal and persistence to improve species' conservation prospects. Proceedings of the Royal Society B, 287, 20202061.

De Kort H, Baguette M, Lenoir J, Stevens VM (2020) Toward reliable habitat suitability and accessibility models in an era of multiple environmental stressors. Ecology and Evolution, 10, 10937-10952.

Kovar R, Brabec M, Bocek R, Vita R (2009) Spring migration distances of some Central European amphibian species. Amphibia-Reptilia, 30, 367-378.

Lavergne S, Mouquet N, Thuiller W, Ronce O (2010) Biodiversity and climate change: integrating evolutionary and ecological responses of species and communities. Annual review of Ecology, Evolution, and Systematics, 41, 321-350. 10.1146/annurev-ecolsys-102209-144628.

Lion MB, Garda AA, Fonseca CR (2014) Split distance: a key landscape metric shaping amphibian populations and communities in forest fragments. Diversity and Distributions, 20, 1245-1257.

Losapio G, Schöb C (2017) Resistance of plant–plant networks to biodiversity loss and secondary extinctions following simulated environmental changes. Functional Ecology, 31, 1145-1152.

Maclean IMD, Wilson RJ (2011) Recent ecological responses to climate change support predictions of high extinction risk. Proceedings of the National Academy of Science of the United States of America, 108, 12337-12342.

Meier ES, Kienast F, Pearman PB, Svenning J- C, Thuiller W, Araújo MB, Guisan A, Zimmermann NE (2010) Biotic and abiotic variables show little redundancy in explaining tree species distributions. Ecography, 33, 1038-1048. https://doi.org/10.1111/j.1600-0587.2010.06229.x.

Miller JA, Holloway P (2015) Incorporating movement in species distribution models. Progress in Physical Geography: Earth and Environment, 39, 837-849.

Miller DA, Grant EHC, Muths E, Amburgey SM, Adams MJ, Joseph MB, Waddle, J. Hardin, Johnson PTJ, Ryan ME, Schmidt BR, Calhoun DL, Davis CL, Fisher RN, Green DM, Hossack BR, Rittenhouse TAG, Walls SC, Bailey LL, Cruickshank SS, Fellers GM, Gorman TA, Haas CA, Hughson W, Pilliod DS, Price SJ, Ray AM, Sadinski W, Saenz D, Barichivich WJ, Brand A, Brehme CS, Dagit R, Delaney KS, Glorioso BM, Kats LB, Kleeman PM, Pearl CA, Rochester CJ, Riley SPD, Roth M, Sigafus, B. H. (2018).

Quantifying climate sensitivity and climate-driven change in North American amphibian communities. Nature Communications, 9, 1-15.

Mishra S, Ghosh A, Rai K, Jaiswal B, Yadav DS, Agrawal M, Agrawal SB (2021) Dimensions of climate change and its consequences on ecosystem functioning. In: Global Climate Change (pp. 109-149). Elsevier.

Mod HK, Heikkinen RK, le Roux PC, Wisz MS, Luoto M (2016) Impact of biotic interactions on biodiversity varies across a landscape. Journal of Biogeography, 43, 2412-2423.

Monsimet J, Devineau O, Pétillon J, Lafage D (2020) Explicit integration of dispersal-related metrics improves predictions of SDM in predatory arthropods. Scientific Reports, 10, 16668.

Morales- Linares J, Flores- Palacios A, Corona- López AM, Toledo- Hernández VH (2021) Structure and robustness of the Neotropical ant- gardens network under climate change. Insect Conservation and Diversity, 14, 635-646.

Moravec J, Aparicio J, Guerrero-Reinhard M, Calderón G, Jungfer K-H, Gvozdik V (2009) A new species of Osteocephalus (Anura: Hylidae) from Amazonian Bolivia: first evidence of tree frog breeding in fruit capsules of the Brazil nut tree. Zootaxa, 2215, 37-54.

Murray AH, Nowakowski AJ, Frishkoff LO (2021) Climate and land-use change severity alter trait-based responses to habitat conversion. Global Ecology and Biogeography, 30, 598-610.

Murray K, Conner MM (2009) Methods to quantify variable importance: implications for the analysis of noisy ecological data. Ecology, 90, 348-35.

Naimi B, Araújo MB (2016) sdm: a reproducible and extensible R platform for species distribution modelling. Ecography, 39, 368-375.

Naimi B, Hamm NAS, Groen TA, Skidmore AK, Toxopeus AG (2014) Where is positional uncertainty a problem for species distribution modelling? Ecography, 37, 191-203.

Pauls SU, Nowak C, Bálint M, Pfenninger M (2013) The impact of global climate change on genetic diversity within populations and species. Molecular Ecology, 22, 925-946. https://doi.org/10.1111/mec.12152.

Pecl GT, Araújo MB, Bell JD, Blanchard J, Bonebrake TC, Chen I-C, et al (2017) Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. Science, 355, eaai9214.

Penner J, Rödel M-O (2019) Keep it simple? Dispersal abilities can explain why species range sizes differ, the case study of West African amphibians. Acta Oecologica, 94, 41-46.

Pereira HM, Leadley PW, Proença V, Alkemade R, Scharlemann JPW, Fernandez-Manjarrés JF, Araújo MB, et al (2010) Scenarios for global biodiversity in the 21st century. Science 330, 1496-1501.

Peterson AT, Stewart A, Mohamed KI, Araújo MB (2008) Shifting global invasive potential of European plants with climate change. PLoS ONE, 3, e2441.

Peterson AT, Soberón J (2012) Species distribution modeling and ecological niche modeling: getting the concepts right. Natureza and Conservação, 10, 1-6.

Peterson AT, Soberón J, Pearson RG, Anderson RP, Martínez-Meyer E, Nakamura M, Araújo M B (2011) Ecological Niches and Geographic Distributions. Princeton University Press.

Powers RP, Jetz W (2019) Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios. Nature Climate Change, 9, 323-329.

R Development Core Team (2020) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Riahi K, van Vuuren DP, Kriegler E, Edmonds J, O’Neill BC, Fujimori S, Bauer N, Calvin K, Dellink R, Fricko O, Lutz W, Popp A, Cuaresma JC, Samir KC, Leimbach M, Jiang L, Kram T, Rao S, Emmerling J, Ebi K, Hasegawa T, Havlik P, Humpenöder F, Da Silva LA, Smith S, Stehfest E, Bosetti V, Eom J, Gernaat D, Masui T, Rogelj J, Strefler J, Drouet L, Krey V, Luderer G, Harmsen M, Takahashi K, Baumstark L, Doelman JC, Kainuma M, Klimont Z, Marangoni G, Lotze-Campen H, Obersteiner M, Tabeau A, Tavoni M (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42, 153-168.

Ribeiro J, Colli GR, Caldwell JP, Ferreira E, Batista R, Soares A (2017) Evidence of neotropical anuran community disruption on rice crops: a multidimensional evaluation. Biodiversity and Conservation, 26, 3363-3383.

Romero GQ, Nomura F, Gonçalves AZ, Dias NY, Mercier H, Conforto EDC, Rossa- Feres DDC (2010) Nitrogen fluxes from treefrogs to tank epiphytic bromeliads: An isotopic and physiological approach. Oecologia, 162, 941-949. https://doi. org/10.1007/s00442-009-1533-4.

Royle JA, Chandler RB, Yackulic C, Nichols JD (2012) Likelihood analysis of species occurrence probability from presence- only data for modelling species distributions. Methods in Ecology and Evolution, 3, 545-554.

Sabagh LT, Ferreira RB, Rocha CFD (2017) Host bromeliads and their associated frog species: further considerations on the importance of species interactions for conservation. Symbiosis, 73, 201-211.

Sales LP, Rodrigues L, Masiero R (2021) Climate change drives spatial mismatch and threatens the biotic interactions of the Brazil nut. Global Ecology and Biogeography, 30, 117-127.

Sales LP, Rodrigues L, Masiero RC (2020) Climate change drives spatial mismatch and threatens the biotic interactions of the Brazil nut. Global Ecology and Biogeography 30, 117-127.

Sales LP, Ribeiro BR, Pires MM, Chapman CA, Loyola R (2019) Recalculating route: dispersal constraints will drive the redistribution of Amazon primates in the Anthropocene. Ecography, 42, 1789-1801.

Salamin N, Wüest RO, Lavergne S, Thuiller W, Pearman PB (2010) Assessing rapid evolution in a changing environment. Trends in Ecology and Evolution, 25, 692-698.

Schleuning M, Neuschulz EL, Albrecht J, Bender IMA, Bowler DE, Dehling DM, Fritz SA, Hof C, Mueller T, Nowak L, Sorensen MC, Böhning-Gaese K, Kissling WD (2020) Trait-Based Assessments of Climate-Change Impacts on Interacting Species. Trends in Ecology and Evolution, 35, 319-328.

Schloss CA, Nuñez TA, Lawler JJ (2012) Dispersal will limit the ability of mammals to track climate change in the Western Hemisphere. Proceedings of the National Academy of Sciences, 109, 8606-8611.

Sahlean TC, Gherghel I, Papeş M, Strugariu A, Zamfirescu ŞR (2014) Refining climate change projections for organisms with low dispersal abilities: a case study of the Caspian whip snake. PloS ONE, 9, e91994.

Serra-Diaz JM, Franklin J (2019) What's hot in conservation biogeography in a changing climate? Going beyond species range dynamics. Diversity and Distribution, 25, 492-498.

Shipley BR, Bach R, Do Y, Strathearn H, McGuire JL, Dilkina B (2022) megaSDM: integrating dispersal and time- step analyses into species distribution models. Ecography, e05450.

Sinclair SJ, White MD, Newell GR (2010) How useful are species distribution models for managing biodiversity under future climates? Ecology and Society, 15, 8.

Singer, A., Travis, J. M., and Johst, K. (2013). Interspecific interactions affect species and community responses to climate shifts. Oikos, 122, 358-366.

Stephan P, Mora BB, Alexander JM (2021) Positive species interactions shape species' range limits. Oikos, 130, 1611-1625.

Stuart SN, Chanson JS, Cox NA, Young BE, Rodrigues ASL, et al. (2004) Status and trends of amphibian declines and extinctions worldwide. Science, 306, 1783-1786.

Swets JA (1988) Measuring the accuracy of diagnostic systems. Science, 240, 1285-1293.

Taheri S, Naimi B, Rahbek C, Araújo MB (2021) Improvements in reports of species redistribution under climate change are required. Science Advances, 7, eabe1110.

Terribile LC, Lima-Ribeiro MS, Araújo MB, Bizão N, Collevatti RG, Dobrovolski R, Franco AA, Guilhaumon F, Lima JS, Murakami DM, Nabout JC, Oliveira G, Oliveira LK, Rabelo SG, Areas of climate stability of species ranges in the Brazilian Cerrado: disentangling uncertainties through time. Natureza and Conservação, 10, 152-159.

Thomas CD, et al (2004) Extinction risk from climate change. Nature, 427,145-148.

Thuiller W, Guéguen M, Renaud J, Karger DN, Zimmermann NE (2019) Uncertainty in ensembles of global biodiversity scenarios. Nature Communications, 10, 1-9.

Thuiller W, Lavergne S, Roquet C, Boulangeat I, Lafourcade B, Araújo MB (2011) Consequences of climate change on the tree of life in Europe. Nature, 470, 531-534.

Travis JMJ, Delgado M, Bocedi G, Baguette M, Bartoń K, Bonte D, Boulangeat I, Hodgson JA, Kubisch A, Penteriani V, Saastamoinen M, Stevens VM, Bullock JM (2013) Dispersal and species' responses to climate change. Oikos, 122, 1532-1540. https://doi.org/10.1111/j.1600-0706.2013.00399.x.

Turnock ST, Allen RJ, Andrews M, Bauer SE, Deushi M, Emmons L, Good P, Horowitz L, John JG, Michou M, Nabat P, Naik V, Neubauer D, O'Connor FM, Olivié D, Oshima N, Schulz M, Sellar A, Shim S, Takemura T, Tilmes S, Tsigaridis K, Wu T, Zhang J (2020) Historical and future changes in air pollutants from CMIP6 models. Atmospheric Chemistry and Physics, 20, 14547-14579.

Urban MC (2015) Accelerating extinction risk from climate change. Science, 348, 571-573.

Urban MC, Bocedi G, Hendry AP, Mihoub JB, Pe’er G, Singer A, Bridle JR, Crozier LG, De Meester L, Godsoe W, Gonzalez A, Hellmann JJ, Holt RD, Huth A, Johst K, Krug CB, Leadley PW, Palmer SCF, Pantel JH, Schmitz A, Zollner PA, Travis JMJ (2016) Improving the forecast for biodiversity under climate change. Science, 353, 1113.

Urban MC, Zarnetske PL, Skelly DK (2013) Moving forward: dispersal and species interactions determine biotic responses to climate change. Annals of the New York Academy of Sciences, 1297, 44-60.

Uribe-Rivera DE, Soto-Azat C, Valenzuela-Sánchez A, Bizama G, Simonetti JA, Pliscoff P (2017) Dispersal and extrapolation on the accuracy of temporal predictions from distribution models for the Darwin's frog. Ecological Applications, 27, 1633-1645.

Weiskopf SR, Rubenstein MA, Crozier LG, Gaichas S, Griffis R, Halofsky JE, Hyde KJW, Morelli TL, Morisette JT, Muñoz RC, Pershing AJ, Peterson DL, Poudel R, Staudinger MD, Sutton-Grier AE, Thompson L, Vose J, Weltzin JF, Whyte KP (2020) Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. Science of The Total Environment, 733, 137782.

Wisz MS, Pottier J, Kissling WD, Pellissier L, Lenoir J, Damgaard CF, Dormann CF, Forchhammer MC, Grytnes J-A, Guisan A, Heikkinen RK, Høye TT, Kühn I, Luoto M, Maiorano L, Nilsson M-C, Normand S, Öckinger E, Schmidt NM, Termansen M, Timmermann A, Wardle DA, Aastrup P, Svenning J-C (2013) The role of biotic interactions in shaping distributions and realised assemblages of species: implications for species distribution modelling. Biological Reviews, 88: 15-30.

Valladares F, Matesanz S, Guilhaumon F, Araújo MB, Balaguer L, Benito- Garzón M, Cornwell W, Gianoli E, van Kleunen M, Naya DE, Nicotra AB, Pooter H, Zavala, MA (2014) The effects of phenotypic plasticity and local adaptation on forecasts of species range shifts under climate change. Ecology Letters, 17, 1351-1364.

Van der Putten WH, Macel M, Visser ME (2010) Predicting species distribution and abundance responses to climate change: why it is essential to include biotic interactions across trophic levels. Philosophical Transactions of the Royal Society B: Biological Sciences, 365, 2025-2034.

Vapnik V (1995) The nature of statistical learning theory. Springer.

Vasconcelos TS, Antonelli CP, Napoli MF (2017) Mutualism influences species distribution predictions for a bromeliad- breeding anuran under climate change. Austral Ecology, 42, 869-877.

Zanatta F, Engler R, Collart F, Broennimann O, Mateo RG, Papp B, Munoz J, Baurain D, Guisan A, Vanderpoorten A (2020) Bryophytes are predicted to lag behind future climate change despite their high dispersal capacities. Nature Communications, 11, 5601.

Zarnetske PL, Skelly DK, Urban MC (2012) Biotic multipliers of climate change. Science, 336,

Zhang P, Dong X, Grenouillet G, Lek S, Zheng Y, Chang J (2020). Species range shifts in response to climate change and human pressure for the world's largest amphibian. Science of the Total Environment, 735, 139543.

Zurell D, Franklin J, König C, Bouchet PJ, Dormann CF, Elith J, Fandos G, Feng X, Guillera-Arroita G, Guisan A, Lahoz-Monfort JJ, Leitão PJ, Park DS, Peterson AT, Rapacciuolo G, Schmatz DR, Schroder B, Serra-Diaz JM, Thuiller W, Yates KL, Zimmermann NE, Merow C (2020) A standard protocol for reporting species distribution models. Ecography, 43: 1261-1277.

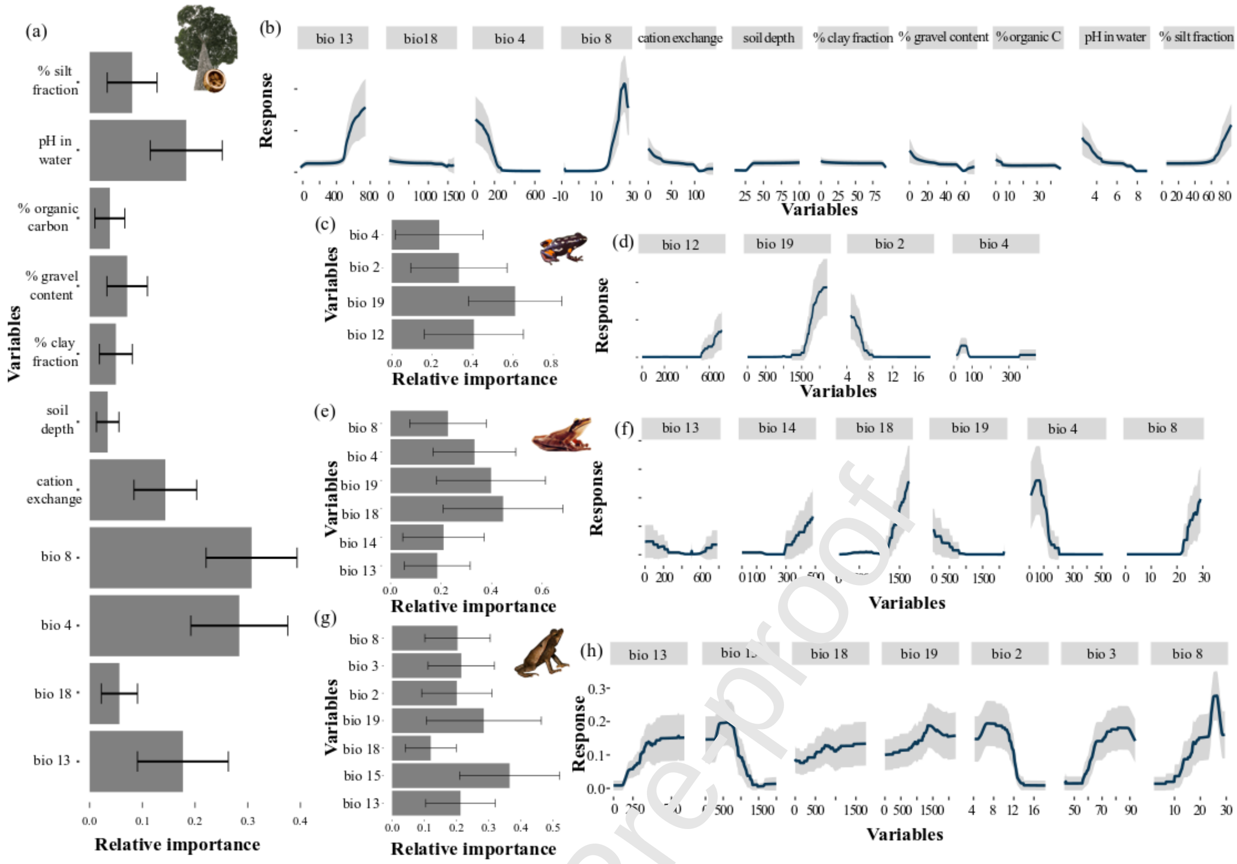
Zuur AF, Ieno EN, Elphick CS (2010) A protocol for data exploration to avoid common statistical problems. Methods in Ecology and Evolution, 1, 3-14.

List of figures

Fig. 1 Relative variable importance and predictive response curve, respectively, for (a-b) *Bertholletia excelsa*, (c-d) *Adelphobates castaneoticus*, (e-f) *Osteocephalus castaneicola*, and (g-h) *Rhinella castaneotica.* The response curve was fitted by the "glm" method. Error bars show the standard deviation.

Fig. 2. Forecasts of habitat suitability over time: (a) *Adelphobates castaneoticus*, (b) *Osteocephalus castaneicola*, and (c) *Rhinella castaneotica*. Note that green areas indicate only occurrence of the Brazil nut tree; purple areas, only frog species; and orange areas of potential co-occurrence of frog-plant binomial.

Fig. 3 Range dynamics of frog species considering the dispersal constraints to forecast the potential distribution of Brazil nut frog species over time. Dispersal scenarios are two extreme data of kernel dispersal distance: a-c, maximum dispersal (D_{max}) for *A. castaneoticus*, *O. castaneicola*, and *R. castaneotica*, respectively; and d-f, minimum dispersal (D_{min}), in the same species sequence. The resulting map of dispersal-restricted potential distribution is partitioned into climate refugia (cells in present and future), potential migration (newly suitable cells accessible via dispersal), dispersal limitation (newly suitable cells inaccessible via dispersal) and non-analogs (cells that are suitable in the present but will become unsuitable in the future, thus exposing populations to non-analog climates).


(a)
% silt fraction
pH in water
% organic carbon
% gravel content
% clay fraction
soil depth
cation exchange
bio 8
bio 4
bio 18
bio 13
Variables
0.0
0.1
0.2
0.3
0.4
Relative importance
(b)
bio 13
bio18
bio 4
bio 8
cation exchange
soil depth
% clay fraction
% gravel content
% organic C
pH in water
% silt fraction
Response
Variables
(c)
bio 4
bio 2
bio 19
bio 12
Variables
0.0
0.2
0.4
0.6
0.8
Relative importance
(d)
bio 12
bio 19
bio 2
bio 4
Response
Variables
(e)
bio 8
bio 4
bio 19
bio 18
bio 14
bio 13
Variables
0.0
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Relative importance
(f)
bio 13
bio 14
bio 18
bio 19
bio 4
bio 8
Response
Variables
(g)
bio 8
bio 3
bio 2
bio 19
bio 18
bio 15
bio 13
Variables
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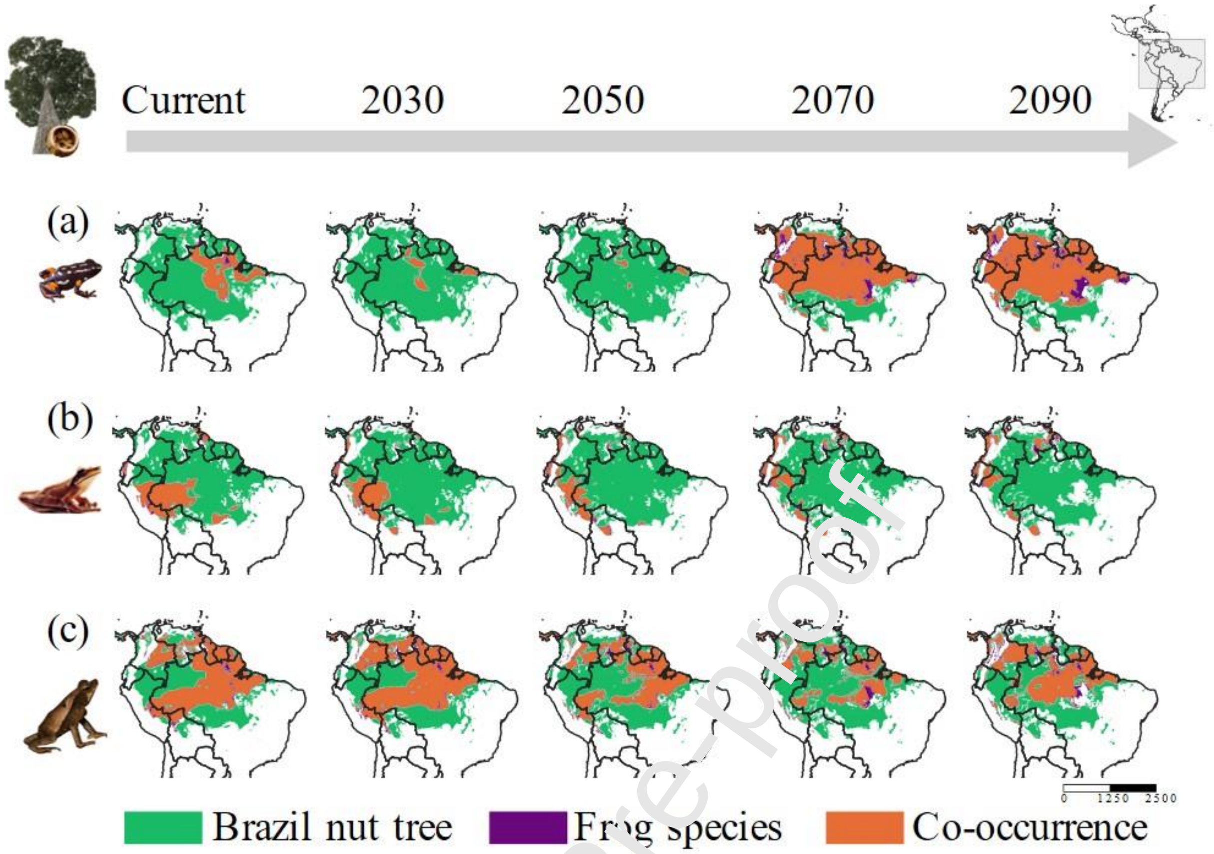
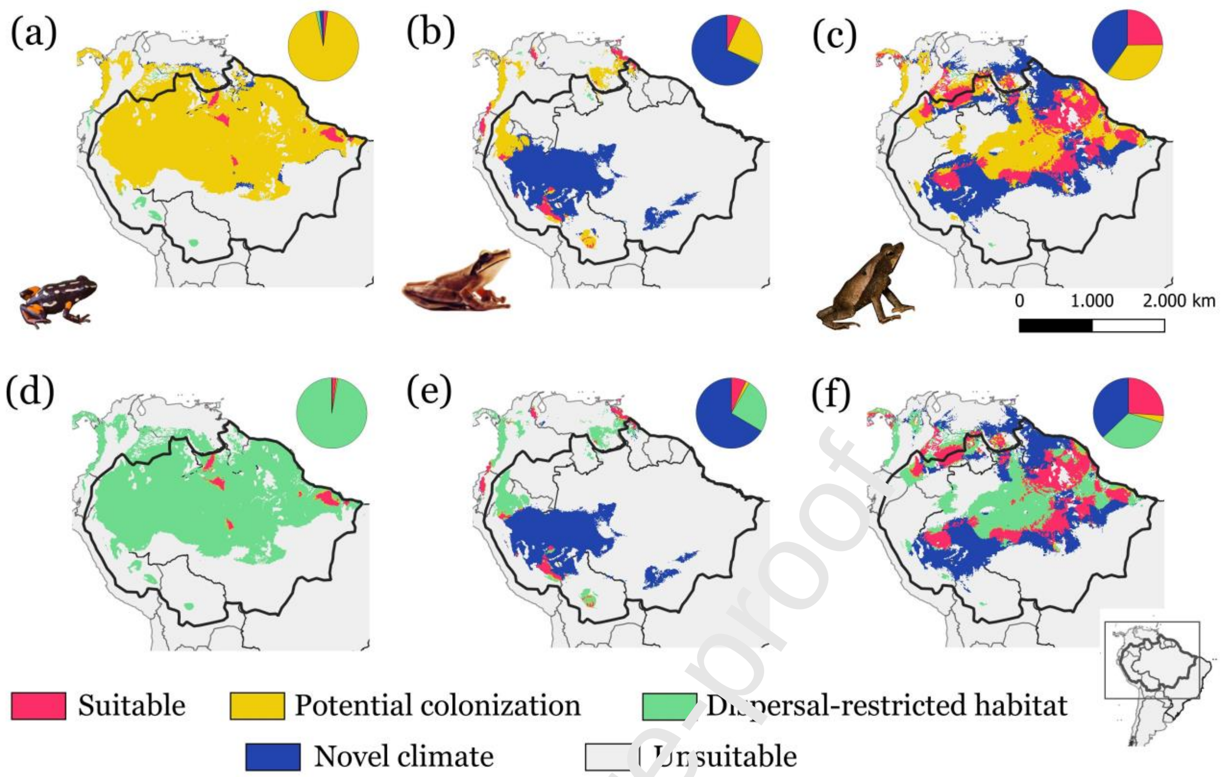
Response
Variables


Current
2030
2050
2070
2090
(a)
(b)
(c)
0 1250 2500
Brazil nut tree
Frog species
Co-occurrence


(a)
(b)
(c)
0
1.000
2.000 km
(d)
(e)
(f)
Suitable
Potential colonization
Dispersal-restricted habitat
Novel climate
Unsuitable

Credit authorship contribution statement

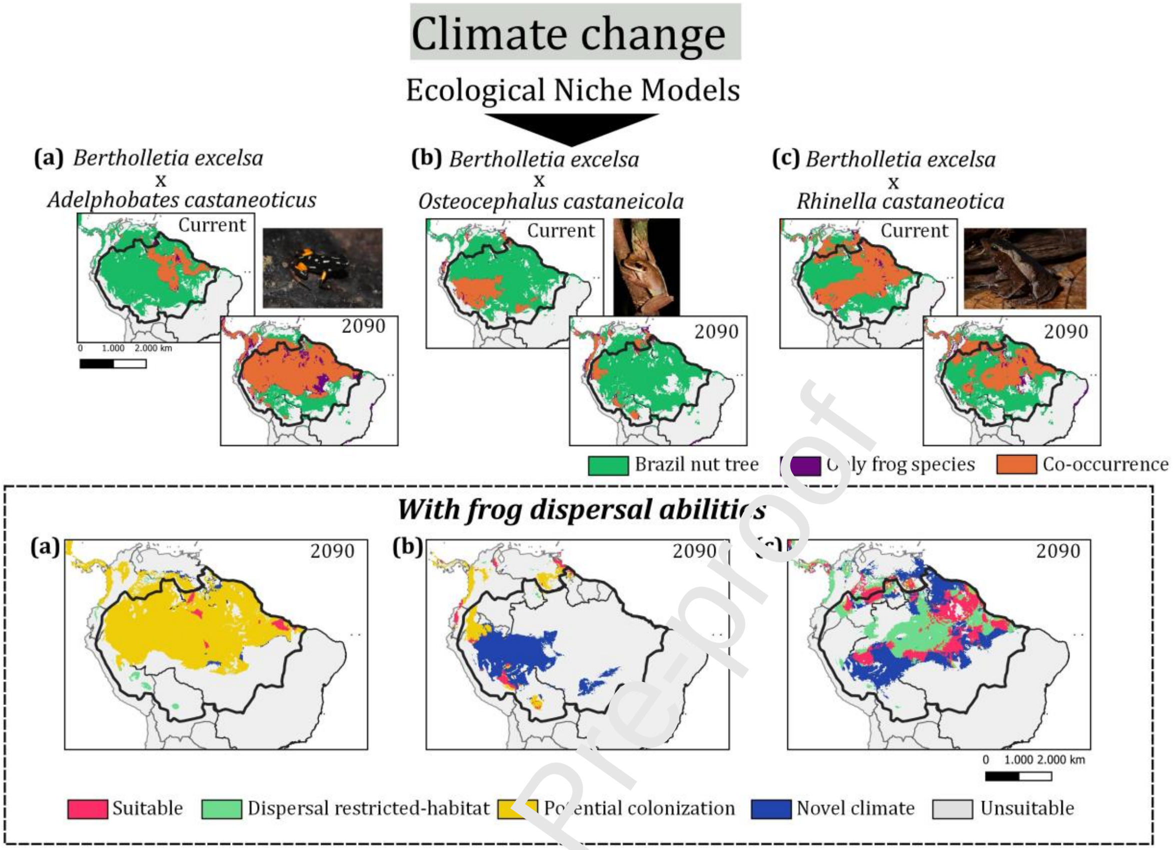
Conceptualization, P.L., F.G.B.; Data curation, P.L.; Formal analysis, P.L., F.G.B.; Methodology, P.L., F.G.B., B.N.; Writing-original draft, P.L.; Writing-review and editing, P.L. in coordination with P.L.,F.G.B., B.N., M.B.A. All authors have read and agreed to the published version of the manuscript.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract



Highlights

- We mapped the distribution of the Brazil nut and three commensalist frog species.
- Climate change will lead to changes in overlapping territory for studied species.
- Including dispersal limitation in simulations reduced the frogs' suitable habitat.
- Integrating dispersal constraints on future projections to make the models more realistic.