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Geographic ranges, richness patterns, and the effectiveness of conservation units on the protection of Brachycephalidae anurans in the Brazilian Atlantic Forest

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Abstract. Among vertebrates, the Atlantic Forest biodiversity hotspot supports a high diversity of anuran amphibians, many of them endemic species, such as the family Brachycephalidae. This family is constituted by two genera (*Brachycephalus* and *Ischnocnema*), which are highly dependent on the humid forest floor for the direct development of eggs (the larval phase is suppressed in these anurans). Then, the Brachycephalidae species are good bioindicators for forest integrity and biological models for biological conservation. In this study, we obtained occurrence records of all species of Brachycephalidae, generated their geographic ranges, and quantified how much of their ranges are protected within the Atlantic Forest conservation units. The distribution of *Brachycephalu*s species is concentrated in the central and southern parts of the Serra do Mar mountain chain, in the states of São Paulo and Paraná. The highest richness of *Ischnocnema* species is found in mountainous areas in the states of Espírito Santo, Rio de Janeiro, southern Minas Gerais, and eastern São Paulo. We found that about half of the Brachycephalidae species do not have at least 30% of their distributions covered by legally protected areas, and only ~30% of the species have most of their ranges inside protected areas. Considering the current scenario of the Atlantic Forest and the presence of highly endemic species living in limited geographic ranges, we believe that our results are useful to guide the elaboration of conservation proposals, such as the reassessment of the current spatial configuration of conservation units in the Atlantic Forest.

Keywords: amphibia, biodiversity hotspot, biogeography, geographic distribution, macroecology, protected areas.

The Atlantic Forest in South America is considered a biodiversity conservation hotspot due to its high species richness and endemism rates, while being simultaneously threatened by several human actions (Myers et al. 2000, Lips et al. 2005, Catenazzi 2015). Among a range of biological groups, anuran amphibians are distinguished for having the highest endemism rates (~77% of the 625 species are endemic to this region; Rossa-Feres et al. 2017), as well as other biological diversity metrics, such as functional and phylogenetic diversity (Haddad et al. 2013, Vasconcelos et al. 2019).

The family Brachycephalidae (including two genera: *Brachycephalus* and *Ischnocnema*) is endemic to the Atlantic Forest, some of them being officially designated as threatened species (Haddad et al. 2013, Frost 2024). *Brachycephalus* comprises 42 currently described species that are distributed from the northeast to southern Brazil, mainly along the Atlantic coast (Frost 2024). They are small (less than 2.5 cm long), brightly colored, diurnal organisms that inhabit microhabitats in the leaf litter, and depend on high air humidity of forested microhabitats for the direct development of the eggs, which takes place on the forest floor (Yeh 2002, Bornschein et al. 2016, and references therein). Despite having the same reproductive mode and occupying the same microhabitats as *Brachycephalus*, *Ischnocnema* species have a wider distributional range, some of them occurring in the northern region of Argentina and central Brazil (Haddad et al. 2013, Frost 2024). *Ischnocnema* has 39 species described and is considered a sister group of *Brachycephalus* (Canedo & Haddad 2012, Frost 2024).

In conservation biology, the concept of umbrella species is given to a taxon that has its area of occupancy or home range large enough to bring other species under protection as well (Barua 2011 and references therein). We may apply this concept to the Brachycephalidae family since these anurans are endemic to the Atlantic Forest, some of them being also included in the National Action Plan for the Conservation of Threatened Herpetofauna (Machado et al. 2021). Thus, due to the high association of these organisms with the forest environment, using the Brachycephalidae anurans as an umbrella group may be an interesting strategy for the conservation biogeography of Atlantic Forest anurans. In this study, we use the geographic occurrences of *Brachycephalus* and *Ischnocnema*, obtained from different sources, to generate their geographic ranges and to determine where, along the Atlantic Forest extension, the highest/lowest species richness of these two genera is located. Additionally, overlapping the obtained species geographic ranges over the extent of the network of Conservation Units in the Atlantic Forest, we perform GAP analyses to quantify how much of the extent of occurrence area of each species is effectively protected by legal conservation units (e.g., Terribile et al. 2018). Then, we can provide important information to assist conservation planners in reassessing the network of Conservation Units in the Atlantic Forest, considering the distribution of this endemic anuran family.

We surveyed the point occurrence records of each species of *Brachycephalus* and *Ischnocnema,* considering the species list and nomenclature up to December 2021 provided by Frost (2024). By setting this deadline, the number of *Brachycephalus* and *Ischnocnema* species considered here is 38 for each genus, thus totalizing 76 species of Brachycephalidae. The survey of occurrence records was performed separately for each species using two open-access digital databases: the Global Biodiversity Information Facility (e.g., GBIF 2021) and SpeciesLink (specieslink.net/search) databases up to December 2021. In addition, we also consulted the herpetological websites Amphibian Species of the World (Frost 2024) and AmphibiaWeb (2025) to check the updates in the geographic distribution of anuran species. Specifically, we looked for pertinent bibliographies for each species in these herpetological websites to obtain specific occurrence points of the respective species, including recent records, and to expand their geographic ranges. Subsequently, the point records of each species were checked to remove inaccurate occurrences and/or fix typing errors, which finally resulted in 239 occurrence records for *Brachycephalus* and 812 for *Ischnocnema* (Appendix 1 and 2 in Supplementary material available online).

The extent of occurrence maps of each species were built considering the occurrence points of the respective species. Specifically, the species distribution maps were generated in ArcGIS using the minimum convex polygon for species with three or more occurrence records (i.e., consideration of the minimum convex distance between two occurrence points; García-Roselló et al. 2015, Souza et al. 2022). For species with one or two occurrence records, we considered their distributions within an area of approximately 10 km diameter around the occurrence points (e.g., Vasconcelos et al. 2019). Subsequently, these distribution maps were overlaid onto a 10 x 10 km grid system along the Atlantic Forest, as considered by the definition of the Brazilian Ministry of Environment that covers 17 states predominantly located along the Atlantic coast, but also with a smaller area covering part of the Paraguay and Argentina (Fundação SOS Mata Atlântica & INPE. 2020). Then, presence/absence distribution matrices of *Brachycephalus* and *Ischnocnema* across the Atlantic Forest were generated for each genus using the package letsR in R (Vilela & Villalobos 2015). Further, we summed up the occurrence of each species into the Atlantic Forest grid system to obtain a final richness map of each genus.

We also built a map depicting the areas legally protected within the 10 km grid resolution along the Atlantic Forest. To do so, we overlapped a map from the World Database of Protected Areas (WDPA: UNEP-WCMC and IUCN 2021) onto the Atlantic Forest grid, so the grids that were at least 50% covered by any legally protected area were considered areas where anurans are presumably protected from anthropogenic actions (Figure 1) (see Lemes et al. 2014, Terribile et al. 2018).

Subsequently and separately for *Brachycephalus* and *Ischnocnema*, the polygons of each species were overlaid onto the Atlantic Forest grid system to quantify the distribution percentage of a given species that falls within the protected grids compared to its total extent of occurrence area. Specifically, we consider part of the distribution of a species "protected" when the respective part of its extent of occurrence coincides with the grids containing a protected area. Therefore, we assume that a species occurring in grids covered by a conservation unit may benefit from the associated legal protection (Lemes et al. 2014).

The highest species richness values of *Brachycephalus* (grid cells having up to seven species) are concentrated in the central and southern regions of the Serra do Mar mountain chains, in the states of São Paulo and Paraná, respectively (Figure 2). For *Ischnocnema*, the highest species richness values (grid cells having up to 11 species) are found in hillside areas in the states of Espírito Santo, Rio de Janeiro, southern Minas Gerais, and southeastern São Paulo (Figure 3).

Regarding the distributional representativeness of *Brachycephalus* species in legally preserved areas, 13 species occur entirely outside conservation areas, four species have up to 30% of their distributions in areas of Conservation Units, seven species have their distributions in Conservation Units between 30 and 50% of their ranges, and 14 species have the majority of their extent of distributions (more than 50%) occurring within the limits of Conservation Units (Figure 4). Three out of the last 14 species occur entirely within the Conservation Units (Figure 4).

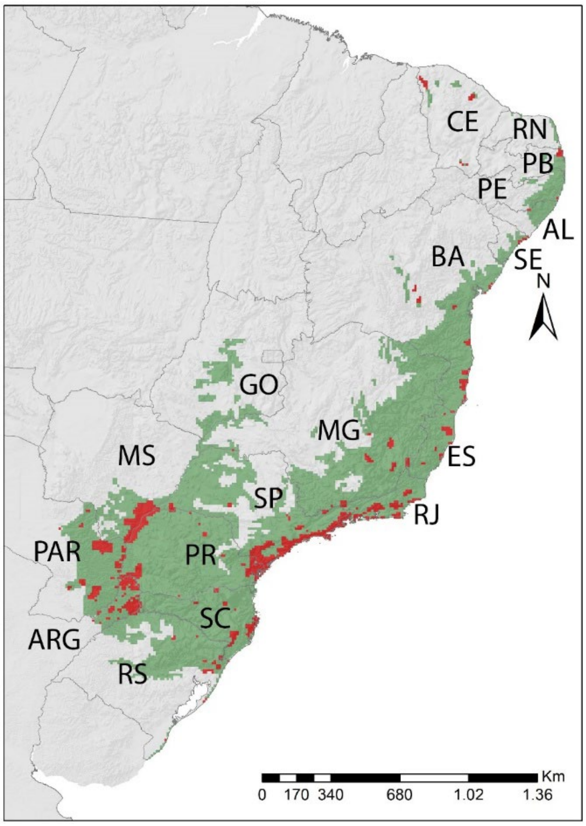

Figure 1. Atlantic Forest domain (green) and the protected areas designed by the network of Conservation Units according to the World Database of Protected Areas (see Methods). Abbreviations for the Brazilian states and surrounding countries: ARG = Argentina; PAR = Paraguay; AL = Alagoas; BA = Bahia; CE = Ceará; ES = Espírito Santo; GO = Goiás; MG = Minas Gerais; MS = Mato Grosso do Sul; PB = Paraíba; PE = Pernambuco; PR = Paraná; RJ = Rio de Janeiro; RN = Rio Grande do Norte; RS = Rio Grande do Sul; SE = Sergipe; SC = Santa Catarina; SP = São Paulo.

Regarding the *Ischnocnema* species, two are outside Conservation Units, 17 species have up to 30% of their ranges occurring in Conservation Units, nine species have 30% to 50% of their ranges within protected areas, and ten species have more than 50% of their distributional ranges within protected areas (Figure 5). Three out of the last ten species occur entirely within protected areas (Figure 5).

Our results indicate that the southeastern and southern Brazilian mountain chains support the highest species richness of the Brachycephalidae family in the Atlantic Forest, mainly associated with the Serra do Mar and Mantiqueira mountains (e.g., Pie et al. 2013). Specifically, species of the genus *Ischnocnema* are more diverse in the states of Espírito Santo, Rio de Janeiro, and São Paulo (southeastern Brazil). In contrast, species of *Brachycephalus* are more abundant in southeastern and southern Brazil (states of São Paulo and Paraná). The association of these two genera with mountainous areas of the Atlantic Forest is strongly related to geological processes that occurred in the early Cenozoic, 60 million years ago, responsible for uprising the Serra do Mar, thus generating a greater number of endemic species through allopatric speciation (Haddad et al. 2013, Benício et al. 2021). Additionally, a range of ecological interacting factors are also likely to influence on the non-homogeneous distribution of *Brachycephalus* and *Ischnocnema* throughout the Atlantic Forest, such as factors acting either at local (e.g., the vegetation structural characteristics, humidity conditions and depth of the leaf litter) or broad scales (e.g., the interplay between altitude and climatic variables that generates high levels of precipitation and decreased temperatures along the mountainous areas of the Atlantic Forest) (Giaretta et al. 1997, Van Sluys et al. 2007, Vasconcelos et al. 2010, 2014).

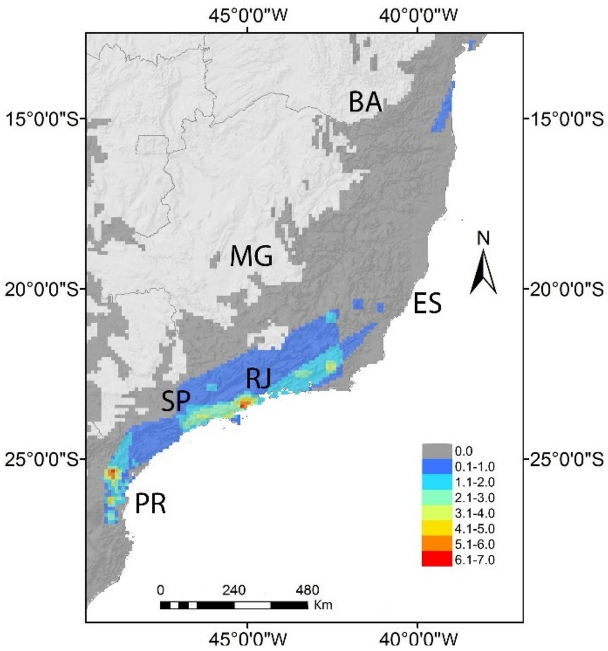

Figure 2. Map of the species' richness (i.e., the colorful blue-red gradient) for the genus *Brachycephalus*. Abbreviation for the Brazilian states: BA = Bahia; ES = Espírito Santo; MG = Minas Gerais; PR = Paraná; RJ = Rio de Janeiro; SP = São Paulo.

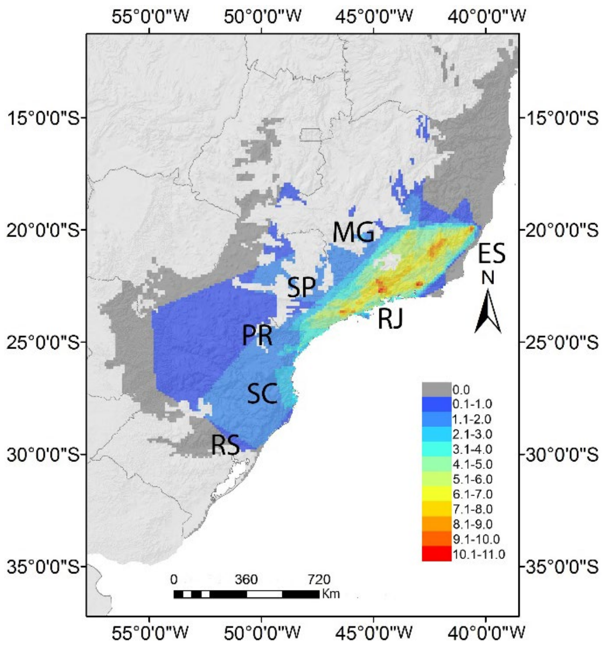

Figure 3. Map of the species richness (i.e., the colorful blue-red gradient) for the genus *Ischnocnema*. Abbreviation for the Brazilian states: ES = Espírito Santo; MG = Minas Gerais; PR = Paraná; RJ = Rio de Janeiro; RS = Rio Grande do Sul; SC = Santa Catarina; SP = São Paulo.

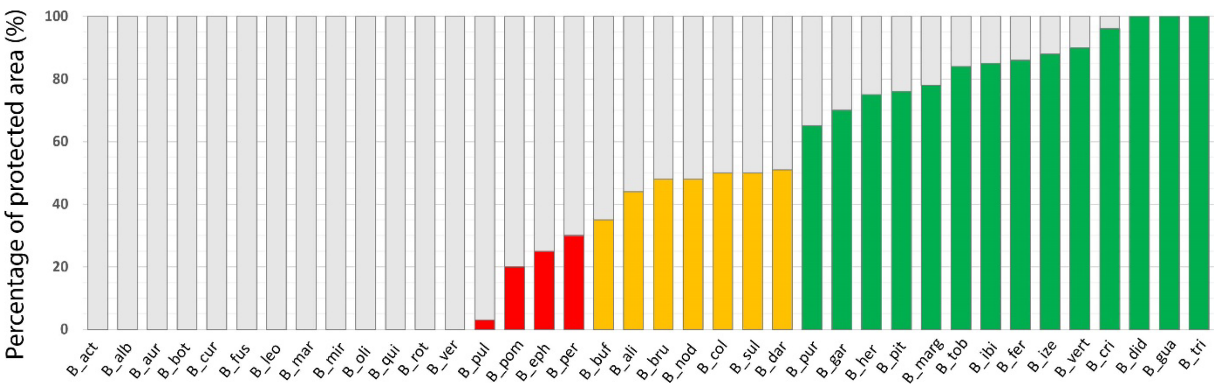

Figure 4. Percentage of protected area (Y axis) that encompasses the geographic range of each *Brachycephalus* species (X axis). Red: species with up to 30% of their ranges within protected areas; Yellow: species from 30-50% of their ranges within protected areas; Green: species with more than 50% of their ranges inside a protected area. Abbreviations for the species names: B_act = *B. actaeus*; B_alb = *B. albolineatus*; B_aur = *B. auroguttatus*; B_bot = *B. boticario*; B_cur = *B. curupira*; B_fus = *B. fuscolineatus*; B_leo = *B. leopardus*; B_mar = *B. mariaeterezae*; B_mir = *B. mirissimus*; B_oli = *B. olivaceus*; B_qui = *B. quiririensis*; B_rot = *B. rotenbergae*; B_ver = *B. verrucosus*; B_pul = *B. pulex*; B_pom = *B. pombali*; B_eph = *B. ephippium*; B_per = *B. pernix*; B_buf = *B. bufonoides*; B_ali = *B. alipioi*; B_bru = *B. brunneus*; B_nod = *B. nodoterga*; B_col = *B. coloratus*; B_sul = *B. sulfuratus*; B_dar = *B. darkside*; B_pur = *B. puri*; B_gar = *B. garbeanus*; B_her = *B. hermogenesi*; B_pit = *B. pitanga*; B_marg = *B. margaritatus*; B_tob = *B. toby*; B_ibi = *B. ibitinga*; B_fer = *B. ferruginus*; B_ize = *B. izecksohni*; B_vert = *B. vertebralis*; B_cri = *B. crispus*; B_did = *B. didactylus*; B_gua = *B. guarani*; B_tri = *B. tridactylus*.

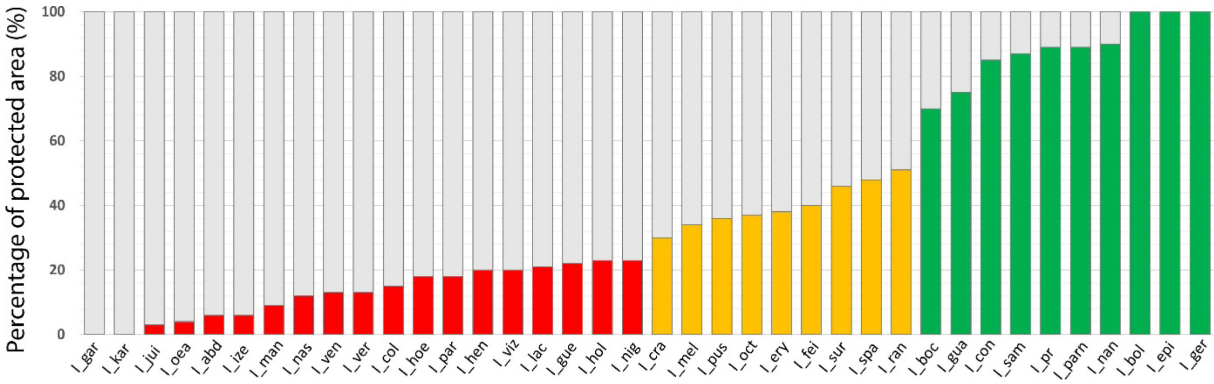

Figure 5. Percentage of protected area (Y axis) that encompasses the geographic range of each *Ischnocnema* species (X axis). Red: species with up to 30% of their ranges within protected areas; Yellow: species from 30-50% of their ranges within protected areas; Green: species with more than 50% of their ranges inside a protected area. Abbreviations for the species names: I_gar = *I. garciai*; I_kar = *I. karst*; I_oea = *I. oea*; I_abd = *I. abdita*; I_ize = *I. izecksohni*; I_man = *I. manezinho*; I_nas = *I. nasuta*; I_ven = *I. venancioi*; I_ver = *I. verrucosa*; I_col = *I. colibri*; I_hoe = *I. hoehnei*; I_par = *I. parva*; I_hen = *I. henselii*; I_viz = *I. vizottoi*; I_lac = *I. lactea*; I_gue = *I. guentheri*; I_hol = *I. holti*; I_nig = *I. nigriventris*; I_cra = *I. crassa*; I_mel = *I. melanopygia*; I_pus = *I. pusilla*; I_oct = *I. octavioi*; I_ery = *I. erythromera*; I_fei = *I. feioi*; I_sur = *I. surda*; I_spa = *I. spanios*; I_ran = *I. randorum*; I_boc = *I. bocaina*; I_gua = *I. gualteri*; I_con = *I. concolor*; I_sam = *I. sambaqui*; I_pr = *I. paranaensis*; I_parn = *I. parnaso*; I_nan = *I. nanahallux*; I_bol = *I. bolbodactyla*; I_epi = *I. epipeda*; I_ger = *I. gehrti*.

An important warning of our results is that almost half of the Brachycephalidae species (36 species: 47.37%) have a maximum of 30% of their geographic ranges encompassed by legally protected areas. Out of these 36 species, 15 are entirely outside Conservation Units. On the other hand, approximately 31% of all species (24 species) have most of their geographic ranges encompassed by protected areas (only six - 7.9% - of all species occur entirely within Conservation Units). Therefore, the current distributional configuration of the Conservation Units in the Atlantic Forest is not sufficient to protect most Brachycephalidae species. For instance, *Brachycephalus mirissimus*, *B. quiririensis*, *Ischnocnema garciai*, and *I. karst* are some examples of species that are on the National List of Endangered Species (MMA 2022) and do not have occurrence records in any protected areas, which in turn indicates that these species may be even more vulnerable to extinction.

As a highly threatened hotspot of biological conservation, the Atlantic Forest has only 30% of its remnants legally protected as conservation units; among them, only 9% are categorized as strictly protected (IUCN Categories I-IV) (Rezende et al. 2018). The remaining 70% of the Atlantic Forest is protected under different levels that, in practical situations, may allow anthropic interventions and even deforestation (Brasil 2012). Therefore, even species categorized as "least concern" are at risk because they are exposed to anthropogenic actions such as the reduction and loss of habitat quality in the Atlantic Forest, which in turn may lead to population declines (Ceballos et al. 2017). Considering that only 31.58% of the Brachycephalidae species (24 species) have most of their ranges inside a protected area, we consider that most of them are definitely exposed and vulnerable to endangering factors that are likely to lead them to become officially endangered in the upcoming years/decades. More worrying yet is the influence of synergist factors that are presumed to negatively affect the biological diversity, such as the effects of the current climate change (e.g., Pecl et al. 2017). Therefore, upcoming studies with different approaches using different metrics of conservation biogeography (ecological niche modeling, systematic conservation planning; Lemes et al. 2014, Terribile et al. 2018, Vasconcelos et al. 2018, Vasconcelos & Prado 2019) may assist in establishing urgent and effective conservation proposals for Brachycephalidae species and/or other biological groups that are endemic to the Atlantic Forest.

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