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Research Letters

Overcoming biases of birds' research in the Caatinga

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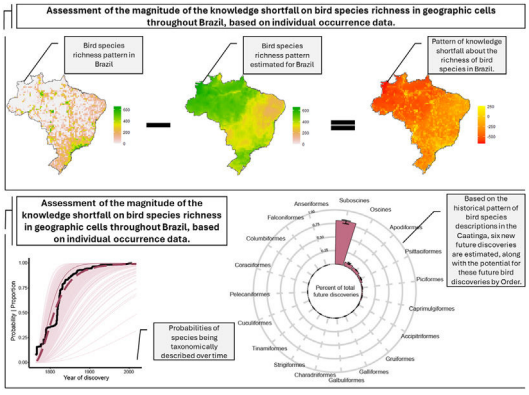
HIGHLIGHTS

- Biodiversity research in Brazil has claimed that the "Caatinga is poorly known", including for well-known groups like birds.
- Even if false, this narrative perpetuates nationwide biases and slows down regional research and conservation agendas.
- We show that the Caatinga bird diversity is as well- or better known than most ecosystems in Brazil.
- Biodiversity research in the Caatinga should stand as a model for many pressing ecological questions, such as climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

"The biodiversity of the Caatinga is poorly known" has been a mantra among studies on biodiversity in Brazil, including birds. However, species richness in semiarid regions is expected to be lower than that in other ecosystems, and studies in the Caatinga have increased in recent decades. Therefore, this narrative may not only reflect knowledge bias. Here, we gathered complementary datasets of bird assemblages from literature and an online database of the Caatinga and other phytogeographic domains in Brazil. We then employed novel spatial and temporal predictive statistics to address this question. We estimate that the Caatinga is only six species short of fully knowing its taxonomic diversity. We did find important spatial knowledge gaps regarding species distribution, but only higher than that of the Atlantic Forest. The species richness and distribution of Caatinga birds are as well-known as the Pampa and Pantanal and are better known than the Cerrado and the Amazon rainforest. Our findings challenge the notion that the Caatinga is the poorest known region regarding birds. Bird research in the region should focus on advancing a research and conservation agenda that enhances understanding of regional biodiversity and ecosystem dynamics while promoting ecological syntheses for tropical dry forests.

Introduction

Knowledge shortfalls of biodiversity – the lack of knowledge on the dimensions of organismal diversity – curb ecological understanding and conservation efforts. They mainly result from

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asymmetries in research investments and researchers' distribution, and when particular regions harbor a very high, hard-to-achieve species diversity (Hortal et al., 2015), such as tropical forests and coral reefs. Globally, this asymmetry roughly discriminates the Global North from the South (Tydecks et al., 2018) and produces many biases towards the latter. These include stereotyping, dependency on "advanced" regions, knowledge colonization, epistemic injustice when scientific contributions are underrated, and, ultimately, environmental injustice (Dempsey, 2015). Nevertheless, the drivers of research efforts on biodiversity are also regionally heterogeneous. Therefore, many types of common global biases are often reproduced on a regional scale (Hoveka et al., 2020). In Brazil, this asymmetry in biodiversity research is evident and discriminates the southern region from the northern regions, but with a reverse trend, with the northern region allegedly being a poorly known region (Santos et al., 2011; Oliveira et al., 2017).

The Caatinga, a seasonally dry tropical forest restricted to Brazil (Pennington et al., 2006), is notable in this context. While numerous research studies have contributed to its understanding, there is a prevalent claim of poor knowledge in the Caatinga. Indeed, biodiversity research investments and the pace of research in the Caatinga have historically lagged behind other regions of Brazil (Young, 2005; Santos et al., 2011). However, they have been leveraged over the last three decades (de Albuquerque et al., 2012). Currently, many synthesis studies have been consolidated (e.g., Leal et al., 2003; Silva et al., 2017), and new fronts in ecological and conservation research are underway (e.g., Leal, 2005; Tabarelli et al., 2017; Dória and Dobrovolski, 2021). Notably, advanced conservation programs are ongoing in the Caatinga, including efforts to reintroduce native animal species like the Spix's macaw (*Cyanopsitta spixii*), which is currently classified as Extinct in the Wild (BirdLife International, 2019).

Typical to this context are the birds, which have been the best-studied group among terrestrial vertebrates, including in Brazil. Until the 1820s, knowledge about Brazilian avifauna was rudimentary, mainly focused on cataloging attractive species (Pacheco, 2004). However, early ornithological endeavors already included species from the Brazilian Caatinga dry forest, with descriptions of native bird species like the red-cowled cardinal *Paroaria dominicana* (Linnaeus, 1758) and the campo troupial *Icterus jamacaii* (Gmelin, 1788). Bird surveys in the Caatinga accelerated in the mid-19th century (Pacheco, 2004). Despite being overlooked for much of the 20th century, the situation changed in the last 60 years (de Albuquerque et al., 2012). Presently, the Brazilian Caatinga dry forest is known to harbor approximately 554 bird species, including migratory and resident birds inhabiting diverse ecosystems, ranging from arid, open woodlands to lush tropical forests in wet forest enclaves (Silva et al., 2003; de Araujo and da Silva, 2017; de Araújo et al., 2022).

The lower bird species richness in the Caatinga, compared to other Brazilian ecosystems, is often attributed to limited knowledge from ornithological studies in the region (e.g., de Araujo and Rodrigues, 2011; Barnett et al., 2014; Kaminski et al., 2016; Pichorim et al., 2016; Brasileiro et al., 2017; Gonçalves et al., 2017a; de Azevedo-Júnior et al., 2023). However, this reduced species richness is expected from macroecological associations between bird species and environmental factors like climate and environmental productivity (Rahbek and Graves, 2001; Diniz-Filho and Bini, 2005), and the high aridity levels of the Caatinga is known to limit species richness (de Oliveira and Diniz-Filho, 2010). Moreover, some synthesis studies of the regional avifauna have been consolidated (Silva et al., 2003; de Araujo and da Silva, 2017). Thus, this narrative, often based on incomplete bibliographic coverage, may reflect a perception bias toward the Brazilian Caatinga, similar to that between the Global North and South. If this is the case, evaluating the actual state of knowledge shortfalls of birds from the Caatinga could help circumvent this bias and advance the region's research and conservation agendas (Lees et al., 2020; Soares et al., 2023).

This often-mentioned lack of knowledge about the diversity and distribution of bird species in the Caatinga falls under two main biodiversity shortfalls: the Linnaean and the Wallacean shortfalls (Hortal et al., 2015; de Araújo et al., 2022), which refers to ignorance about the species' existence and their geographical distribution, respectively (Lomolino, 2004; Hortal et al., 2015). Estimating these two knowledge shortfalls, primarily the Linnean, can provide a springboard to encourage assessments of other shortfalls that depend on knowing which and where the species are (Hortal et al., 2015). Knowing this knowledge bias may also offer a fairer perception of the Caatinga avifauna. Here, we address the Linnean and Wallacean shortfalls of birds in the Caatinga based on data from individual species' records and published articles on bird communities through novel spatial and temporal assessments. We identified under-sampled regions regarding bird species richness and composition and the possibilities for new bird species descriptions. We also employ a geostatistical approach to assess the observed and expected patterns of species richness in the Caatinga compared to other Brazilian phytogeographic domains.

Methods

Study area and data assembling

Brazil has six phytogeographic domains: Amazon Rainforest, Atlantic Rainforest, Cerrado, Caatinga, Pampa, and Pantanal (IBGE, 2022). We primarily focused on the Caatinga for temporal assessment but also compared the spatial pattern of bird knowledge with that of the other domains. The Caatinga, like other ecoregions, is an open ecological system (de Araujo et al., 2022), so we considered all bird species recorded within the Caatinga region (*sensu* IBGE, 2022) as a component of the regional species pool. However, other authors have used different definitions of the regional species pool, such as considering only allegedly resident species (e.g., de Araujo and da Silva, 2017; de Araujo et al., 2022) or those restricted to the deciduous xerophytic formation that predominates in the Caatinga (e.g., Lima, 2021). For all spatial analyses, we adopted a spatial resolution of 0.5°, recognized for its optimal balance between aggregation and detail in studies employing completeness metrics for biodiversity inventories (Sousa-Baena et al., 2014).

We assessed the sampling efforts applied by researchers in the inventories of bird communities in the Caatinga through literature searches and data extraction from relevant studies. In addition to the studies obtained, species occurrence data were obtained from the Global Biodiversity Information Facility (GBIF) and thoroughly cleaned. Linnean shortfall assessments involved time-to-event models predicting undiscovered bird species (Moura and Jetz, 2021), while Wallacean shortfalls were addressed by mapping sampling efforts and integrating them with species records. Furthermore, comparisons of knowledge shortfall magnitude on species richness between phytogeographic domains were made using Regression-Kriging (RK) interpolation techniques (Alves et al., 2020). All details on data acquisition, cleaning, and analysis procedures are available in the Supplementary material.

Statistical analyzes

We partitioned the values of knowledge shortfall (i.e., residuals between observed and estimated species richness from RK interpolation) within each phytogeographic domain in Brazil. The more negative the differences, the greater the scarcity of knowledge in bird richness patterns within each domain. Due to the absence of normality and homogeneity of residuals in the ANOVA model, we

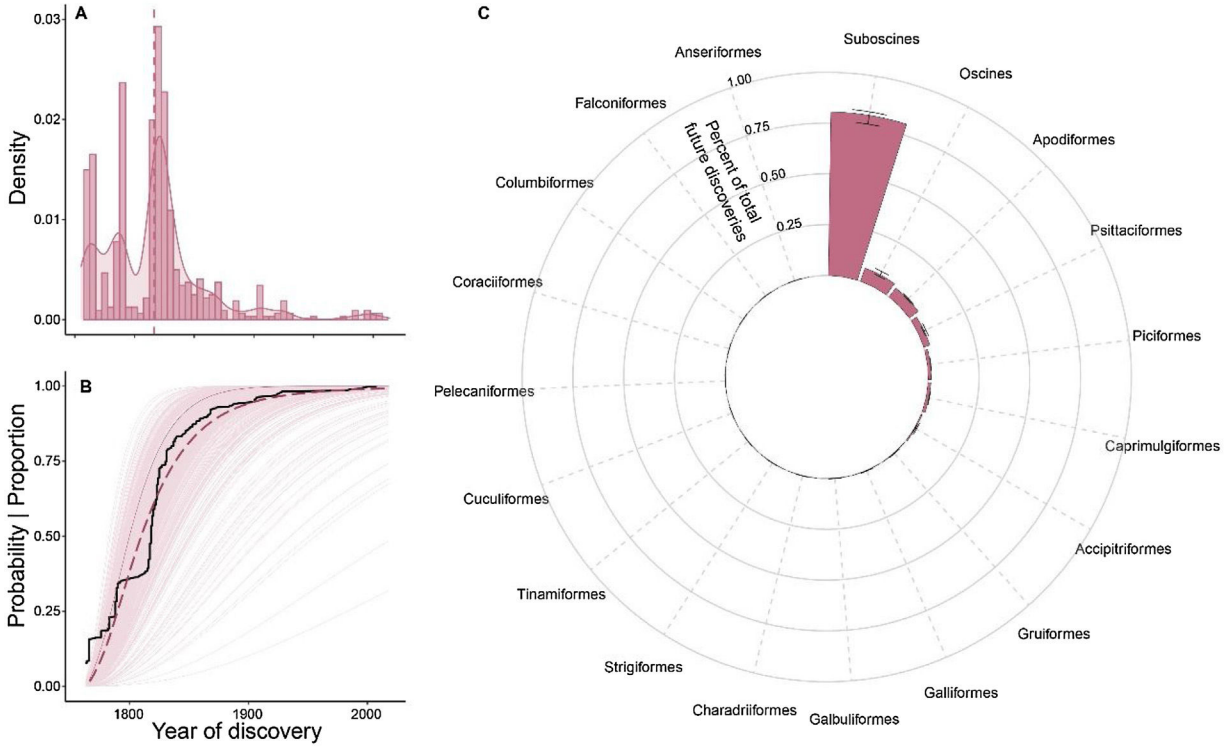

Fig. 1. Variation in observed and predicted discovery trends for birds in the Caatinga. A) Fluctuations in species descriptions over time are shown, with a dashed line marking the year when 50% of the known species were described. B) Time-to-event model-based predictions of the discovery probability for each species are depicted in light colors, with *Pitangus sulphuratus* as an example (colored dashed line). The black lines indicate the empirical cumulative growth of the described species. C) Potential for future bird discovery in the Caatinga. The heights of the bars represent the proportion of undiscovered species within each bird order, with error bars indicating a 95% confidence interval.

employed the Kruskal-Wallis test, followed by the Dunn post hoc test with Bonferroni correction. These tests were conducted for both raw residuals and residuals proportional to estimated species richness, as geographic cells with higher species richness require greater effort to achieve local knowledge completeness. We performed all procedures in the R environment (R Core Team, 2023) using the packages rgdal (Bivand et al., 2023), raster (Hijmans et al., 2023), KnowBR (Lobo et al., 2018), GGally (Schloerke et al., 2023), car (Fox et al., 2023), sp (Pebesma et al., 2023), automap (Hiemstra et al., 2009), and gstat (Pebesma and Graeler, 2023).

Results

We gathered 4,647,551 occurrences from GBIF for 1,843 species from Brazil, of which 149,509 (3.2% of the total) occurrences and 614 species (33%) were in the Caatinga. The bibliographic survey of community studies in the Caatinga yielded 74 studies that provided composition data from 217 sites. From the obtained species list, we excluded four considered invasive species (*Bubulcus ibis*, *Columba livia*, *Estrilda astrild*, and *Passer domesticus*) and 10 other species with native distributions remote from the Caatinga, strongly suggesting misidentification: *Agelasticus thilius*, *Cathartes melambrotus*, *Chaetura brachyura*, *Chloroceryle aenea*, *Chlorostilbon mellisugus*, *Empidonax alnorum*, *Phylloscartes ventralis*, *Picumnus exilis*, *Sclerurus mexicanus*, and *Thamnophilus punctatus*. The consolidated list had 648 species, with 34 species unique to academic studies and 109 exclusively from the GBIF database (Supplementary material).

Linnean and Wallacean shortfalls

Between 1750 and 1850, the number of species descriptions per year of bird occurring in the Caatinga saw a rapid increase, with a peak in descriptions between the 1820s and 1840s, followed by a slowdown until the 2000s (Fig. 1A and B). On average, the typical documentation year for bird species in the Caatinga region is 1818. This reflects the high probability of species description during that period, exemplified by the case of the great kiskadee *Pitangus sulphuratus* described in 1825. Our analysis suggests a low potential for new discoveries in the Caatinga based on the probabilities of species description for those already known. We estimate that only six new species occurring in the Caatinga are likely to be described in the future, with suboscines showing the highest likelihood of new descriptions, accounting for approximately 80% of the potential across all orders (Fig. 1C).

The sampling effort in academic studies varied widely, ranging from 2:45 to 12,600 h, focused on just 78 grid cells. In contrast, GBIF data covered 280 cells with at least one bird record, varying from 1 to 19,125 records. Sampling efforts from published studies were most concentrated in the central and northeastern portions of the Caatinga (Fig. 2A). However, the distribution of records in the GBIF database was more evenly spread across the entire area. Nevertheless, the distribution of cells with high record values resembles the sampling efforts found from published studies (Fig. 2B).

Comparison among phytogeographic domains

RK analysis revealed substantial knowledge gaps in the understanding of bird species richness in Brazil (Fig. 3). Many localities had no records (Fig. 3A) and only 77 cells had adequate inventory completeness (Supporting information Fig. S2B). The best model for the gradient of bird species richness in Brazil included the annual mean temperature, annual precipitation, and canopy height ($R^2 = 0.63$; Supporting information Table S1). The variogram model that best captured the pattern of species richness among the well-

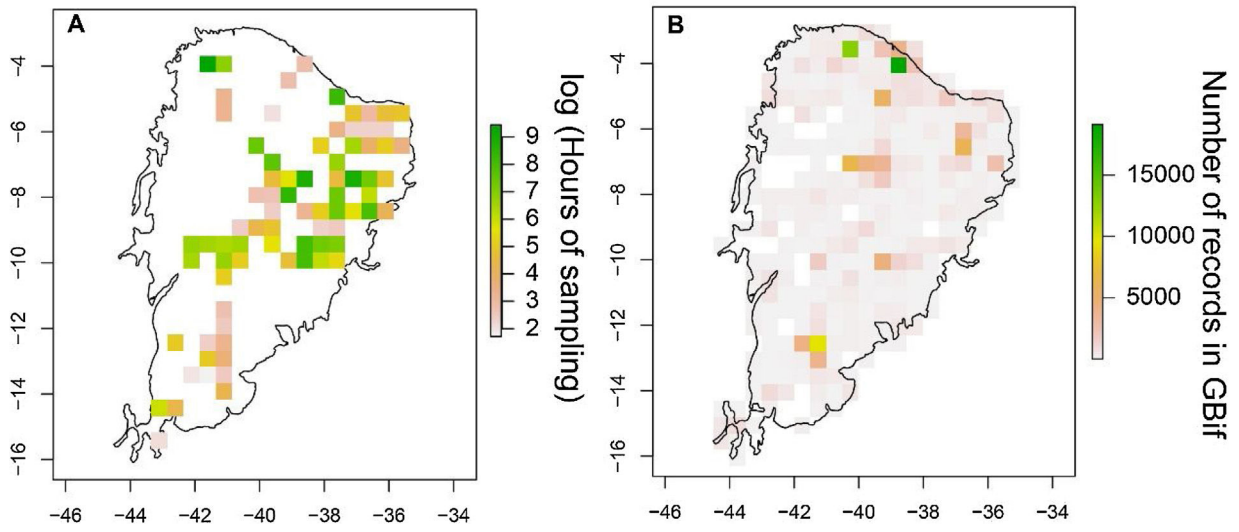

Fig. 2. A) Spatial distribution of the sampling effort in hours for inventories of bird communities in the Caatinga on a logarithmic scale. B) Spatial distribution of bird records in GBIF data.

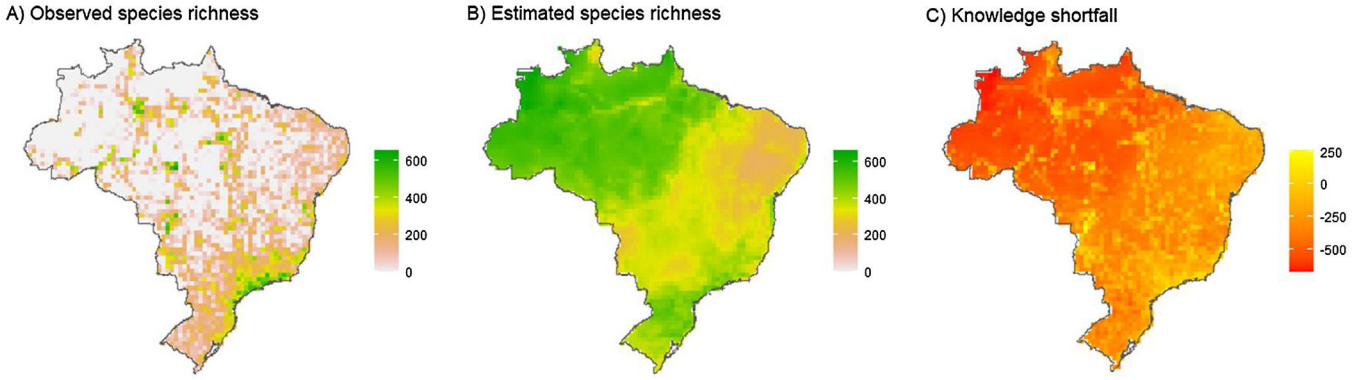

Fig. 3. Spatial data and results of regression-kriging applied to birds in Brazil.

sampled cells was the Matern model with Stein's parameterization (sill = 2908.61, range = 0.46, nugget = 594.03, kappa = 1.2).

The species richness gradient estimated from RK revealed an expected higher species richness in the Amazon and Atlantic rainforests (Fig. 3B). This richness gradually declines towards open formations in Brazil, particularly in the Caatinga in the northeastern region of Brazil. The differences between the observed richness and that estimated by RK highlight varying levels of knowledge shortfalls across Brazil. The Amazon region showed the highest levels of knowledge shortfall, while the Atlantic Forest in southeastern Brazil, the Pantanal, and the Caatinga appear to be relatively well known. The Caatinga showed a more uniform pattern of knowledge deficiencies (Fig. 3C).

We found that the Wallacean shortfall, given by the difference between observed and estimated richness through RK, was significantly different among phytogeographic domains, either without controlling for species richness (Kruskal-Wallis $\chi^2 = 1473.3$, df = 2, $p < 0.001$) or controlling for species richness (Kruskal-Wallis $\chi^2 = 753.96$, df = 5, p-value < 0.001). The level of knowledge shortfall was greater in the Amazon than elsewhere ($p < 0.001$; Fig. 4A,B). The lowest knowledge shortfalls were found for Atlantic Forest, Pantanal, and Caatinga, which did not differ significantly from each other ($p > 0.05$). Additionally, similarities were noted between the Atlantic Forest and Pampa ($z = 2.442$, $p > 0.05$), Pampa and Pantanal ($z = -2.207$, $p > 0.05$), and the Cerrado and Pampa ($z = -0.084$, $p > 0.05$). Knowledge shortfalls in the Caatinga were significantly lower than in the Cerrado ($z = 7.389$, $p < 0.001$) and Amazon ($z = 3.629$, $p < 0.001$; Fig. 4A). When comparing the values of residuals proportional to the estimated species richness, the Caatinga ranked second in terms of the lowest magnitude of shortfalls, along with the Pampa and Pantanal regions ($z = -1.864$, $p > 0.05$; $z = -0.603$, $p > 0.05$, respectively). However, Pampa and Pantanal did not differ from the Atlantic Forest ($z = 1.718$, $p > 0.05$; $z = 2.766$, $p > 0.05$, respectively), which exhibited the lowest shortfall values among the domains (Fig. 4B).

Discussion

We found that the Linnaean shortfall of birds in the Caatinga is approaching resolution, with an estimated potential discovery of six new species in the future, mainly belonging to the suboscines suborder. Suboscine birds comprise over 1,100 species, whereas Oscine is estimated to be approximately 4,000 (Tobias et al., 2012). Despite their lower species richness, suboscines have historically been underrepresented in studies compared to oscines, which are more conspicuous in temperate regions (Tobias et al., 2012). Therefore, a primary strategy to accelerate the description of unknown species is to focus future field surveys by Suboscine taxonomists in unsampled or undersampled regions (Oliveira et al., 2016; Lees et al., 2020). Of course, our finding of fair knowledge of birds owes to the fact that they are among the better-studied biological groups worldwide (Mora et al., 2011; Scheffers et al., 2012). This may not be true for other biological groups that may be indeed severely under-

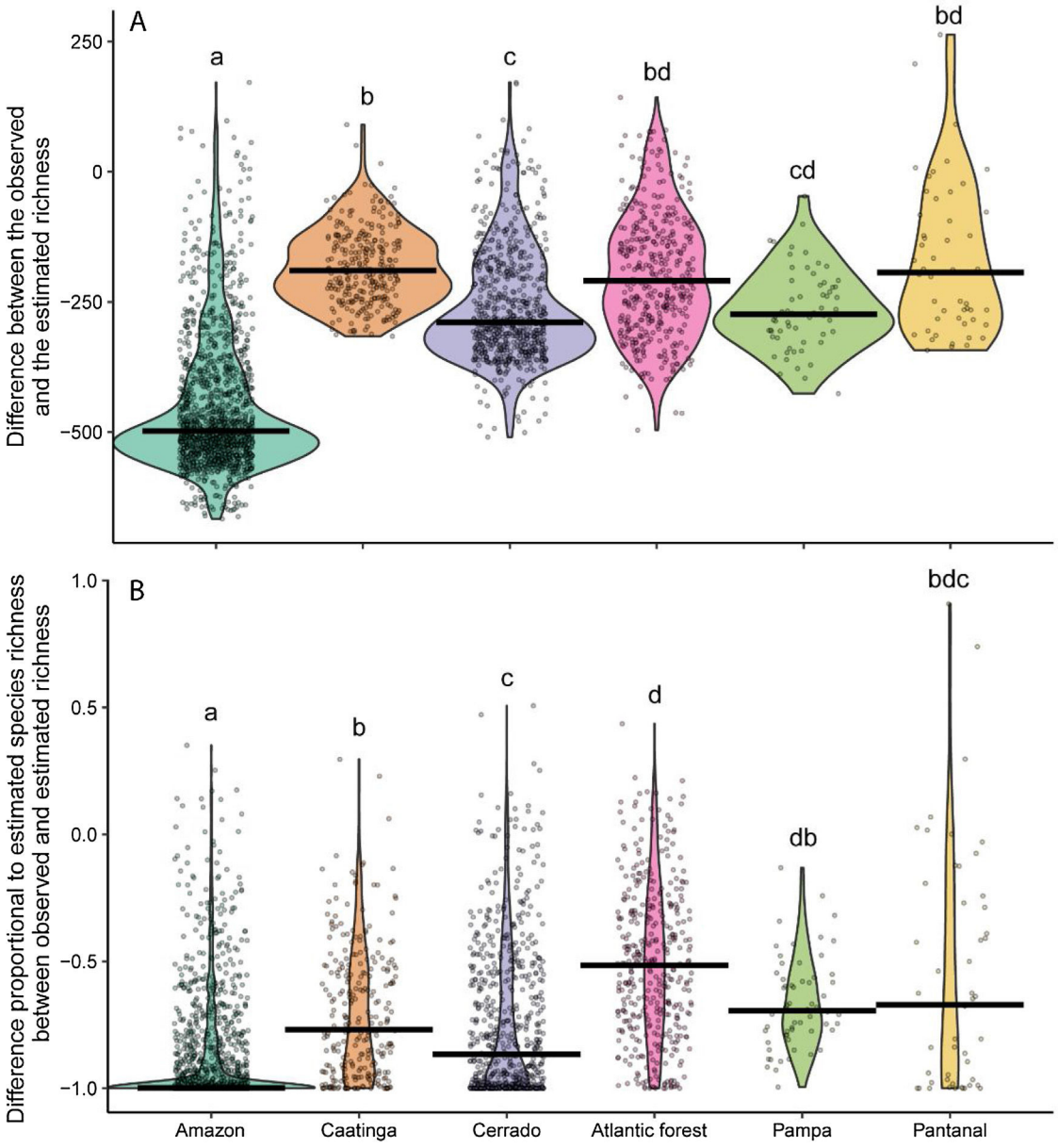

Fig. 4. Violin plots illustrating the distribution of Linnean knowledge shortfall across different phytogeographic domains in Brazil. In A, the raw residuals from regression-kriging, and in B, the value of the residuals is proportional to the estimated species richness. The horizontal black lines represent the median for each domain. Different letters above each violin plot indicate significant differences ($p < 0.05$, Dunn's post hoc test, with p adjusted by Bonferroni's method).

studied in the Caatinga, such as insects (e.g., Santos et al., 2011). However, a similar account of poor knowledge could be mistakenly reproduced for other terrestrial taxa that attain lower species richness under semiarid conditions.

Further than conducting field surveys, forwarding data integration and analysis is essential to address biodiversity knowledge gaps. This will require that data disclosure and sharing in studies within the Caatinga region be promoted (Turnhou and Boonman-Berson, 2011). For instance, having access to raw data from some studies (e.g., Gonçalves et al., 2017a, b; Costa et al., 2023) could have enhanced our estimates. Restrictions on data access undermine any scientific field and negatively affect society (Černe et al., 2013). In the case of birds from the Caatinga, it feeds back this seemingly unsupported narrative of poor knowledge, which precludes us from overcoming knowledge shortfalls, making the Caatinga avifauna an important model for biodiversity research, and ultimately furthering the conservation of regional biodiversity.

The persistence of undersampled or unsampled regions in the Caatinga indicates the need for further sampling efforts to overcome the Wallacean shortfall for birds. The spatial pattern of sampling efforts from bird community studies likely coincides with the distribution of university campuses or important protected areas, such as Vale do Catimbau, Boqueirão da Onça, and Chapada Diamantina National Parks, as generally expected (Meyer et al., 2015). Nevertheless, considering only the data available from GBIF, the level of Wallacean shortfall in the Caatinga is not the highest compared to other phytogeographic domains in Brazil. Indeed, its knowledge level regarding bird diversity and distribution ranked second, alongside the Pantanal and Pampa, surpassing that of the Cerrado and Amazon rainforest, and lagging behind the Atlantic Forest only. On the other hand, the proportion of records in the Caatinga (3.2%) is indeed much lower than that in other domains, considering that it comprises approximately 10% of the Brazilian territory (IBGE, 2022). However, its moderate completeness indi-

cates that its diversity can be grasped more rapidly than elsewhere in Brazil. In other words, the knowledge level is not a function solely of sampling effort but also of existing biodiversity (Magurran, 2004). At relatively lower levels of species richness, such as in the Caatinga, a lower sampling effort is required to attain fair completeness. Therefore, these findings challenge the prevailing claim of poor knowledge of bird diversity in the Caatinga compared with other ecosystems in Brazil.

Ecological research in the Caatinga has been historically undervalued and underfunded compared to other formations, particularly those near wealthier and denser populations, such as the Atlantic Forest in the southwestern region of Brazil (Young, 2005; Santos et al., 2011). However, the investments in the Caatinga, especially during the last 30 years (de Albuquerque et al., 2012), seem to have paid off in terms of accelerating the knowledge of the distribution and diversity of birds, as this and other studies (e.g., de Araujo and da Silva, 2017; de Araújo et al., 2022) have shown. However, rather than concluding that lower investment levels are adequate for the Caatinga, we advocate for recognizing it as an opportunity for increased investment in biodiversity research, spanning from primary surveys to advanced inquiries. For instance, the Caatinga birds can be a good model for investigations of ecological assemblages in tropical ecosystems because of the overall high knowledge of species taxonomy and a lower risk of species omission during surveys (Soares et al., 2023). Recently, de Araújo et al. (2022) advocated for a positive research agenda for the Caatinga that emphasizes filling other knowledge shortfalls of biodiversity and forging an eco-evolutionary understanding of how species cope with climate seasonality, climate change, and anthropocentric impacts on the ecosystem. Regarding the particular case of climate change, many tropical regions are expected to experience an increase in temperature and a reduction in annual precipitation (Malhi and Wright, 2004). Such conditions have shaped the Caatinga's ecologically and evolutionarily diverse avifauna for thousands of years (de Araujo and da Silva, 2017; Correia et al., 2020).

In summary, the bird richness in the Caatinga seems to be close to being fully known, and it can be attained if important knowledge gaps in some regions are overcome. Furthermore, the current level of knowledge is comparable to or higher than that of most other phytogeographic domains in Brazil. Therefore, we contend that the prevailing claim that bird diversity in the Caatinga is poorly known is unjustified, at best. This dominant perception, also reverberated by local researchers, reproduces many biases and should be surpassed. This should be replaced by a focus on addressing other knowledge shortfalls of biodiversity (Hortal et al., 2015; de Araújo et al., 2022; Soares et al., 2023), and a view that takes advantage of the ecological context of the Caatinga to advance its research agenda to boost the understanding of biodiversity dynamics, ecosystem functioning, and ultimately ecological syntheses in dry tropical ecosystems.

Author contributions

HSO: Conceptualization, Investigation, Methodology, Data Curation, Formal Analyses, Investigation, Writing-Original draft preparation. SFG: Conceptualization, Investigation, Methodology, Project Administration, Resources, Supervision, Writing-Original draft preparation.

Declaration of conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pecon.2024.09.001.

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