



Perspectives in ecology and conservation

Supported by the National Council for Scientific and Technological Development - CNPq

www.perspectecolconserv.com



Research Letters

Declining representation of imperiled Atlantic Forest birds in community-science datasets

Lucas Rodriguez Forti^{a,b}, Ana Passetti^b, Talita Oliveira^c, Juan Lima^d, Arthur Queiros^c, Maria Alice Dantas Ferreira Lopes^e, Judit K. Szabo^{f,*}

^a Departamento de Biociências, Universidade Federal Rural do Semi-Árido, Av. Francisco Mota, 572 – Bairro Costa e Silva, 59625-900 Mossoró, Rio Grande do Norte, Brazil

^b Programa de Pós-Graduação em Ecologia: Teoria, Aplicações e Valores, Instituto de Biologia, Universidade Federal da Bahia, Rua Barão de Jeremoabo, 668 – Campus de Ondina CEP: 40170-115 Salvador, Bahia, Brazil

^c Undergraduate Program in Ecology, Universidade Federal Rural do Semi-Árido, Av. Francisco Mota, 572 – Bairro Costa e Silva, 59625-900 Mossoró, Rio Grande do Norte, Brazil

^d Programa de Pós-Graduação em Ecologia e Conservação, Universidade Federal Rural do Semi-Árido, Av. Francisco Mota, 572 – Bairro Costa e Silva, 59625-900, Mossoró, Rio Grande do Norte, Brazil

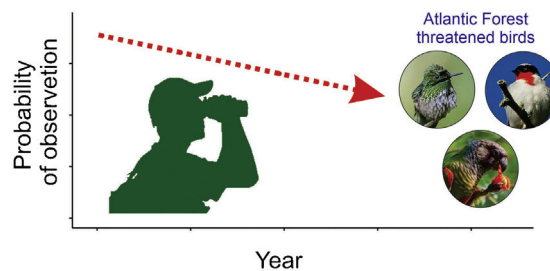
^e Undergraduate Program in Medicine Veterinary, Universidade Federal Rural do Semi-Árido, Av. Francisco Mota, 572 – Bairro Costa e Silva, 59625-900 Mossoró, Rio Grande do Norte, Brazil

^f College of Engineering, IT and Environment, Charles Darwin University, Casuarina, Northern Territory 0909, Australia

HIGHLIGHTS

- Bird species of the Atlantic Forest in Brazil are threatened and declining.
- Declines can lead to decreased detectability and fewer observations.
- We analyzed bird data from three citizen science platforms for 2000–2022.
- The representation of threatened and Near Threatened species decreased through time.
- We recommend future species-specific monitoring to fill survey gaps.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 8 April 2023

Accepted 13 February 2024

Available online xxx

Keywords:

Brazil
Community science
Extinction risk
Species occurrence data
Spatial distribution
Temporal patterns

ABSTRACT

While monitoring is essential for effective conservation, obtaining occurrence data is often challenging, time consuming and expensive. The Brazilian Atlantic Forest has a high number of threatened and endemic species that need effective and urgent conservation actions informed by sound monitoring data. Community (or citizen) science surveys can provide cost-effective data for large areas over extended time and these geocoded and time-stamped observations can deliver information on species of conservation interest. We provide a spatio-temporal analysis of Least Concern, Near Threatened and globally threatened Atlantic Forest endemic bird species from iNaturalist, eBird and WikiAves and analyze species according to their global trends. Together, these three datasets contained 838,880 unique observations of 218 species in 2000–2022, including 95 threatened and Near Threatened species. While the absolute number of observations of threatened and Near Threatened species increased annually, their proportion decreased compared to the total number of observations. Similarly, the proportion of observations of declining species decreased. Through time, the number of non-specialist birdwatchers could have increased, with the higher survey effort resulting in a higher proportion of common (i.e., more easily

* Corresponding author.

E-mail addresses: lucas.forti@yahoo.com.br (L.R. Forti), ana.mpassetti@outlook.com (A. Passetti), talitamonielly@gmail.com (T. Oliveira), juanemaze@hotmail.com (J. Lima), luanarthur00@gmail.com (A. Queiros), Alicedflopes.02@gmail.com (M.A. Lopes), judit.szabo@cdu.edu.au (J.K. Szabo).

<https://doi.org/10.1016/j.pecon.2024.02.001>

2530-0644/© 2024 Associação Brasileira de Ciência Ecológica e Conservação. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Please cite this article as: Forti, L.R. et al. Declining representation of imperiled Atlantic Forest birds in community-science datasets, Perspectives in Ecology and Conservation, <https://doi.org/10.1016/j.pecon.2024.02.001>

observed) species. However, this pattern can also reflect real trends, as most threatened and Near Threatened species were declining, leading to decreased detectability and relatively fewer observations, even with the same effort and skills. Decreasing and threatened species need special attention and targeted monitoring. In spite of the biases inherent in non-structured datasets and the difficulties of surveying rare species, community science can provide an effective warning system, and can improve monitoring of species at high risk of extinction.

Introduction

Datasets of species occurrences provide the basis for studies of spatial distribution and assessments of population trends (Chapman, 2005; Soberón and Townsend Peterson, 2009), fundamental to inform conservation actions (Robinson et al., 2018). Unfortunately, individual researchers are constrained by logistics and funding, which prevent data collection at broad spatial scales and longer time frames. As rare or threatened species usually occur at low densities and require large sampling effort (Green and Young, 1993), they are often underrepresented in datasets compared to locally abundant or widely distributed species (Martikainen and Kouki, 2003). Unlike traditional research, community (or citizen) science (CS) has produced large amounts of data at large scales, occasionally also providing information on threatened species (Bonney, 2021; Lloyd et al., 2020; Wilson et al., 2020). The effort devoted by CS has reduced the Wallacean shortfall, i.e., the lack of knowledge with regard to species distribution (Deacon et al., 2023; Hortal et al., 2015).

Worldwide, many datasets collected by CS feed into the largest global biodiversity database, the Global Biodiversity Information Facility (GBIF; Bonney, 2021; Callaghan et al., 2021). While spatial, temporal, and taxonomic biases are inherent to most CS datasets and they often only record presences (Di Cecco et al., 2021; Szabo et al., 2012a,b), statistical methods are becoming available to handle most of these issues (Bird et al., 2014; Jiménez et al., 2019; Szabo et al., 2010) and after cleaning and adjustments, the data can inform conservation decision making (Newman et al., 2017).

Birds are the best-represented taxonomic group in global biodiversity databases (Troutet et al., 2017). For instance, in October 2023, GBIF included over 1.7 million bird records, representing approximately 6% of all biodiversity data (<https://www.gbif.org/>). To illustrate the volume of information available with regard to birds, in the same month, eBird had over 630,000 occurrence lists of 1800 species for Brazil (<https://ebird.org/>) and the Brazilian WikiAves hosted over 4.5 million photos and nearly 270,000 sound recordings of 1961 species (<https://www.wikiaves.com.br/>). At the forefront of producing unstructured data, iNaturalist brings together a global community of over 2.8 million observers. This platform, formerly managed by the California Academy of Sciences and National Geographic and now a non-profit organization, has been serving as a barometer of CS activity virtually around the globe and at the time of writing this article, contained 323,000 observations of 1702 bird species for Brazil (<https://www.inaturalist.org/>). However, we need to mention here that these platforms use somewhat different taxonomy that need to be reconciled before directly comparing species diversity and numbers.

As a result of this high interest in birds, in countries that have a relatively high number of birdwatchers and low avian species richness, the coverage of bird species on these CS platforms is nearly complete. For example, for the United States, almost 90% of extant bird species reported from the country are represented by at least one record on iNaturalist (Di Cecco et al., 2021). However, the species most frequently recorded on iNaturalist tend to be common in urbanized and other human-modified habitats, as well as large and easily observed (Di Cecco et al., 2021). Overall, CS has produced contrasting data with regard to the representa-

tiveness of threatened species observations (Sánchez-Clavijo et al., 2021). For instance, in Western Australia, volunteer surveyors were more interested in recording rare bird species compared to common species, practically oversampling rare and “interesting” or “birdwatching trophy” species (Tulloch and Szabo, 2012). On the other hand, in Colombia, during the Covid-19 pandemic the number of visits to less disturbed areas decreased, leading to a decreasing number of observations of species of conservation interest compared to Least Concern species (Sánchez-Clavijo et al., 2021). Nevertheless, the decreasing number of rare or threatened species observations in remote and protected areas can be a worrying indicator of species declines (Barnes et al., 2015). Therefore, these patterns need to be assessed, if possible, using an independent dataset collected using structured surveys, as they can indicate real declines (Szabo et al., 2011).

Following BirdLife International's (2023) taxonomy, with 1816 species, Brazil has the third highest avian species diversity in the world, of which 257 species are endemic to the country. However, Brazil also ranks extremely high (second in the world) with regard to the number of species in danger of extinction (BirdLife International, 2023). The Atlantic Forest is the second largest tropical moist forest domain in South America after the Amazon and is considered a global biodiversity hotspot (Myers et al., 2000). This biome is home to over 800 bird species, 223 of which are endemic, a number that can further increase due to ongoing taxonomic revisions (Pizo and Tonetti, 2020). The three Endemic Bird Areas (Atlantic Forest lowlands and Atlantic Forest mountains and the Atlantic slope of Alagoas and Pernambuco) and 163 Important Bird and Biodiversity Areas in particular, hosts several endemic, restricted range and threatened taxa (Bencke et al., 2006). Most of these birds are threatened by habitat fragmentation and habitat loss, both ongoing and current (BirdLife International, 2023). In fact, over 92% of the original vegetation has been lost due to deforestation (Marques and Grelle, 2021). This level of habitat loss has led to a substantial extinction debt (Uezu and Metzger, 2016), which makes biodiversity surveys and the appropriate conservation actions particularly urgent (Szabo et al., 2011). The Atlantic Forest covers nearly 11,200,000 km² of the Brazilian territory, spreading from sea level to above 3000 m and containing a mosaic of ombrophilous, deciduous and semideciduous forests, mangroves, dunes and high-altitude meadows (Ribeiro et al., 2011). The Atlantic Forest displays complex vertical stratification, offering a variety of substrates and microhabitats for its highly diversified biota (Morellato et al., 2000). Unfortunately, its remaining biodiversity continues to face challenges related not only to habitat fragmentation but also global climate change (de Lima et al., 2020; SOS Mata Atlântica/INPE, 2018).

In Brazil, CS-collected data have been used to study migratory patterns of birds (Cunha et al., 2022; Guaraldo et al., 2022; Lees and Martin, 2015; Lopes and Schunck, 2022; Schubert et al., 2019), as well as general species distribution (Santos et al., 2021; Zulian et al., 2021), habitat use (Barbosa et al., 2021; Devenish et al., 2021), feeding behavior (de Souza et al., 2022), novel nesting behavior (Alexandrino et al., 2022) and species interactions (Bosenbecker et al., 2023). However, there is no specific information on the spatio-temporal patterns of imperiled bird species in CS-collected data in Brazil, which can restrict decision making for species protection.

Considering the importance of participatory monitoring in inform conservation actions, we aim to describe spatio-temporal patterns of globally threatened and Near Threatened Atlantic Forest endemic bird species based on observations collected by CS in the three most popular digital platforms hosting bird observations from Brazil. Based on the spatial data, we evaluate the representativeness of observations in urban, as well as protected areas. Using temporal data, we quantify the proportion of observations of threatened and Near Threatened (thereafter imperiled) species in relation to all species observed in 2000–2022. We also describe the monthly distribution of observations and observers. Finally, we discuss the representativeness of imperiled Atlantic Forest bird species in the dataset, providing recommendations and guidelines for future surveying efforts in partnership with the public to generate more robust datasets, in order to support conservation actions and to evaluate the effectiveness of past actions in the biome.

Materials and methods

Based on the list of Atlantic Forest endemic bird species in Vale et al. (2018), we compiled data from three CS platforms: (1) eBird (<https://ebird.org/home>), (2) WikiAves (<https://www.wikiaves.com.br/index.php>) and iNaturalist (<https://www.inaturalist.org/>). As eBird data are curated by experts, we used all observations, including species lists, while from the other two we used observations with audio and photo evidence. In order to use global threat status and trends, we adopted BirdLife International's taxonomy (BirdLife International, 2023), obtaining trends from BirdLife Data Zone manually (<http://datazone.birdlife.org/>) and global threat status from IUCN (<https://www.iucnredlist.org/>); which in turn is based on the Red List assessment conducted by BirdLife through the *rredlist* package (Chamberlain, 2020) of the program R version 4.0.5. (R Core Development Team, 2020). We used global threat status and trends from the assessment of 2020, as considering and recalculating the status and trends of these species at previous assessments (2000, 2004, 2008, 2012 and 2016) was outside the scope of this paper (see for instance Szabo et al. (2012a)). Nevertheless, since 1988, only 93 species have been downlisted globally to a lower Red List category due to a genuine improvement in status, while and 436 species have been uplisted (BirdLife International, 2022). In addition, status is calculated for 10 years or three generations, whichever is the longer (IUCN Standards and Petitions Committee, 2022). Therefore, we can calculate 10 years for passerines and a 4-to-7-year generation length is realistic for the non-passerine endemic species (e.g., 4.1 years for Solitary Tinamou *Tinamus solitarius* and Long-trained Nightjar *Macropsalis forcipata*, 4.6 years for Rufous-capped Motmot *Baryphthengus ruficapillus*, 4.7 years for Red-breasted Toucan *Ramphastos dicolorus* 5.9 years for White-collared Kite *Leptodon forbesi* and 7.4 years for Black-fronted Piping-Guan *Pipile jacutinga*; Bird et al., 2020). Considering the evaluation period and the fact that habitat loss and fragmentation continue in the Atlantic Forest (Pizo and Tonetti, 2020; Schnell et al., 2013), we are confident that our methods are conservative.

We formally requested raw data for the area of interest from eBird and iNaturalist and received them in csv format. As bulk download request was not available for WikiAves, we used the instant data scraper app (<https://webrobots.io/instantdata/>), adhering to the "fair use" principle. We only considered research grade observations from iNaturalist, i.e., those that were identified at the species level and reached a 2/3 consensus among the identifiers on the suggested species.

The raw dataset contained 1,204,210 observations, with 58.8% of the observations in eBird, 39.8% in WikiAves and 1.4% in iNaturalist. Based on the species, date and location, we removed data

points duplicated within and among the datasets and filtered observations to 2000–2022 using the distinct and filter functions in the *dplyr* R package (Wickham et al., 2022). Therefore, we excluded repeat observations of the same species from the same day and the same location, but treated observations of the same individual bird on different days as separate data points. We restricted the data to observations collected after January 1, 2000, because digital CS platforms became popular after this year (Mandeville et al., 2022), and to be able to use current threat and trend data, as discussed above. We also cleaned the data by deleting observations with missing coordinates and locations outside the limits of the Atlantic Forest using the clip tool in QGIS software version 3.16.9 (QGIS Development Team, 2021).

After removing duplicates and pre-2000 observations (approximately 30% of the data), we obtained a joint clean dataset of 838,880 observations of all Atlantic Forest endemic bird species for 2000–2022. Approximately 13.8% of these observations (115,582 data points) were of threatened and Near Threatened species. We used a fit test for Benford's Law to evaluate the distribution of digits on the number of observations among species to check data quality of the joint dataset based on sampling heterogeneity (Szabo et al., 2023). For this test, we adopted the Benford function of the *Benford analysis* package (Cinelli, 2014), and following standard practice, we used only species with more than 100 observations (Nigrini, 2012). We tested the fit of the data to the unimodal gamma binomial distribution model, which is considered the best model of species abundance distributions for real communities with many rare species (Ugland et al., 2007) and used the fit abundance function in the *gambin* package to estimate statistical parameters and to test the fit using the maximum likelihood method (Matthews et al., 2014).

We identified 493,186 bird observations (about 40% of the raw data) that had exact geographic coordinates, i.e., we excluded the entire WikiAves dataset from this analysis, as locations are only provided at the scale of municipality level, as well as observations with incorrect or missing location information from the other two datasets. Using the subset with valid coordinates, we overlaid bird observations with urban and non-urban areas (IBGE, 2015), as well as protected areas (Centro de Estudos da Metrópole, 2021) using QGIS. We defined protected areas as conservation units that are strictly protected (IUCN Categories I–IV) and sustainable use (IUCN Categories V and VI). The remaining vegetation cover (about 70% of the vegetation cover) is protected by other area-based conservation measures, which may allow intervention and deforestation in specific situations (Rezende et al., 2018). We created distribution maps of observations of Atlantic Forest bird species using QGIS.

We compared observed and expected numbers of observations by region based on the area of each region using a χ^2 goodness of fit through the *chisq* test function in R. Considering that we had four regions (no relevant habitat in the north; Fig. 1), we adjusted the p-value for 0.0125, as a result of Bonferroni correction (0.05/4). We repeated the same test for observations inside and outside protected areas.

We tested whether the numbers of observations of imperiled species and contributing observers on the platforms changed along years applying generalized linear models (glm) using the *glm* function in R. For this, we chose quasipoisson distribution, to avoid false positives due to overdispersion in the count data. We also tested whether the proportion of observations of imperiled species changed along the years in relation to the number of all species observations. Given the normal distribution of the data, here we applied *glm* of the Gaussian family. Similarly, we fitted two Gaussian *glm* to compare the proportion of observations of decreasing and stable species along the years (i.e., by dividing the number of observations of decreasing species by the sum of decreasing and stable for each year).

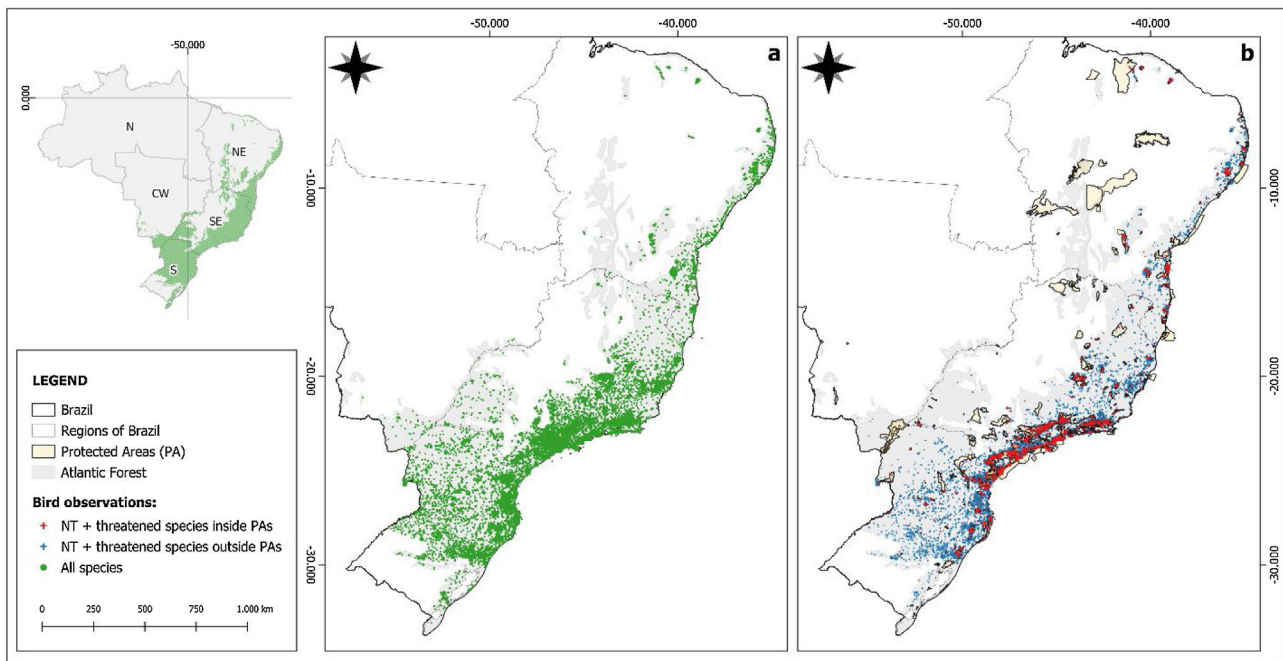


Fig. 1. (a) The distribution of endemic Atlantic Forest bird species observations from two popular community science platforms (eBird and iNaturalist) from 2000 to 2022; and (b) observations of threatened and Near Threatened species inside (red), and outside (blue) protected areas. The inset shows the five major regions of Brazil: N: north, NE: northeast, CW: central west, SE: southeast and S: south. Species threat status and taxonomy follows [BirdLife International \(2023\)](#).

To understand whether the diversity and abundance of imperiled species correlate with the annual number of observers on the platform, after visually checking the linearity of the data, we applied Spearman's correlation through the `corr.test` function of the `psych` package ([Revelle, 2022](#)). To test the seasonality in the number of observations of Atlantic Forest endemic birds, we used the Rayleigh test of uniformity based on the p -value using the `circular` package ([Agostinelli and Lund, 2023](#)) and visualized monthly and annual observation patterns using the `ggplot2` package ([Wickham, 2016](#)).

Results

General data description

The average number of observations per species was 3779, ranging from two sightings of the Alagoas Curassow (*Mitu mitu*) to 35,583 observations of the Ruby-crowned Tanager (*Tachyphonus coronatus*), which is a common, Least Concern species ([Table 1](#)). Eleven species had fewer than 100 observations, two of them classified as Least Concern. Among imperiled species, the ten most observed species accounted for 41% of the observations, and all of them were Near Threatened. Near Threatened species were represented in 9.4% of all (threatened + non-threatened species) observations, Vulnerable in 2.9%, Endangered in 1.3% and Critically Endangered species in 0.2% of observations.

The joint dataset had satisfactory heterogeneity, as it achieved marginally acceptable conformity to Benford's Law with regard to digit distribution of the number of observations per species (Mean Absolute Deviation (MAD) = 0.01468667; Distortion Factor: -1.158198 ; Mantissa Arc Test: $L2 = 0.0002087$; $df = 2$; $p = 0.9567$; $n = 212$). Even though over 44% of the species were imperiled (presumably rare), the data did not fit the gamma binomial model ($\alpha = 29.789$; $X^2 = 439.851$; $df = 13$; $p = 0.0000$).

Spatial distribution

Most of the observations of Atlantic Forest bird species were collected in the southern and south-eastern regions of the Atlantic Forest ([Fig. 1a](#)), while observations in the northeast were sparse. The number of observations was not proportionally distributed as expected based on the size of each region ($\chi^2 = 385,324$, $df = 3$, $p < 10^{-16}$). Similarly, imperiled species were not evenly distributed ([Fig. 1b](#)). Even though most observations (74.5%) were located outside protected areas, it was lower than expected based on the area of non-protected areas (91.7% of all Atlantic Forest) and this difference was significant ($\chi^2 = 382,532$, $df = 1$, $p < 2.2 \times 10^{-16}$).

Temporal distribution

Even though the observations of imperiled species increased annually (estimate = 0.1579, $t = 10.86$, $p = 4.52 \times 10^{-10}$, $n = 23$), their proportion in relation to all species observations (imperiled/all species records) decreased (estimate = -0.18379 , $t = -5.348$, $p = 2.65 \times 10^{-5}$, $n = 23$), remaining below 15% (average proportion between 2000 and 2022) in the last five years ([Fig. 2a](#) and [b](#)). After 2017, this proportion was below 13.8%, and in 2022 the proportion of imperiled species reached its lowest (12%) in the 21 years of our study. This pattern was maintained in spite of the increase in the number of birdwatchers on the platforms in the later years (estimate = 0.1469, $t = 9.942$, $p = 2.15 \times 10^{-9}$, $n = 23$; [Fig. 2c](#)). Species richness and the number of observations of Atlantic Forest bird species recorded annually on the platform was strongly correlated with the number of observers ([Table 2](#)). We also found that while the proportion of observations of declining species was decreasing through the years (estimate = -0.34384 , $t = -7.173$, $p = 4.52 \times 10^{-16}$, $N = 23$), the proportion of stable species observations was increasing (estimate = 0.34384, $t = 7.173$, $p = 4.52 \times 10^{-7}$, $n = 23$).

Bird species were observed more in October and November, with smaller peaks in observation in January, May and July ([Fig. 3](#)).

Table 1

Endemic bird species of the Brazilian Atlantic Forest based on Vale et al. (2018) with global threat status (IUCN 2022) and the number of observations (N) on three digital community science platforms based on data from 2000–2022; LC – Least Concern, NT – Near Threatened, VU – Vulnerable, EN – Endangered, CR – Critically Endangered, EW – Extinct in the Wild, EX – Extinct. The common name of declining species (165 species) is marked in bold and with unknown trend (11 species) in italics (BirdLife International, 2023). Note: we use BirdLife International taxonomy and nomenclature.

ID	Family	Scientific name	Common name	Threat status	N
1	Tinamidae	<i>Tinamus solitarius</i>	Solitary tinamou	NT	3327
2	Cracidae	<i>Pipile jacutinga</i>	Black-fronted piping-guan	EN	1408
3	Cracidae	<i>Ortalis araucuan</i>	White-bellied chachalaca	LC	1971
4	Cracidae	<i>Ortalis squamata</i>	Escaped chachalaca	LC	4437
5	Cracidae	<i>Crax blumenbachii</i>	Red-billed curassow	EN	554
6	Cracidae	<i>Mitu mitu</i>	Alagoas curassow	EW	2
7	Odontophoridae	<i>Odontophorus capueira</i>	Spot-winged wood-quail	LC	3168
8	Caprimulgidae	<i>Macropsalis forcipata</i>	Long-trained nightjar	LC	844
9	Trochilidae	<i>Ramphodon naevius</i>	Saw-billed hermit	LC	7657
10	Trochilidae	<i>Glaucis dohrnii</i>	Hook-billed hermit	VU	468
11	Trochilidae	<i>Phaethornis squalidus</i>	<i>Dusky-throated hermit</i>	LC	1984
12	Trochilidae	<i>Phaethornis idaliae</i>	Minute hermit	LC	800
13	Trochilidae	<i>Phaethornis eurynome</i>	Scale-throated hermit	LC	9546
14	Trochilidae	<i>Phaethornis malaris</i>	Great-billed hermit	LC	104
15	Trochilidae	<i>Lophornis chalybeus</i>	<i>Festive coquette</i>	NT	3993
16	Trochilidae	<i>Clytolaema rubricauda</i>	<i>Brazilian ruby</i>	LC	4023
17	Trochilidae	<i>Stephanoxis lalandi</i>	<i>Green-crowned plovercrest</i>	LC	2489
18	Trochilidae	<i>Stephanoxis loddigesii</i>	<i>Violet-crowned plovercrest</i>	LC	2487
19	Trochilidae	<i>Thalurania watertonii</i>	Long-tailed woodnymph	EN	716
20	Trochilidae	<i>Thalurania glaucopsis</i>	<i>Violet-capped woodnymph</i>	LC	30,893
21	Rallidae	<i>Aramides saracura</i>	Slaty-breasted wood-rail	LC	21,249
22	Accipitridae	<i>Leptodon forbesi</i>	White-collared kite	EN	333
23	Accipitridae	<i>Buteogallus lacernulatus</i>	White-necked hawk	VU	1841
24	Accipitridae	<i>Pseudastur polionotus</i>	Mantled hawk	NT	1720
25	Strigidae	<i>Megascops sanctaetatarinae</i>	Long-tufted screech-owl	LC	1296
26	Strigidae	<i>Megascops atricapilla</i>	<i>Black-capped screech-owl</i>	LC	1521
27	Strigidae	<i>Pulsatrix koeniswaldiana</i>	Tawny-browed Owl	LC	3827
28	Strigidae	<i>Strix hylophila</i>	Rusty-barred Owl	LC	2202
29	Strigidae	<i>Glaucidium minutissimum</i>	Least pygmy-owl	LC	1735
30	Trogonidae	<i>Trogon surrucura</i>	Southern Surucua Trogon	LC	8433
31	Momotidae	<i>Baryphthengus ruficapillus</i>	Rufous-capped motmot	LC	5809
32	Galbulidae	<i>Jacamaralcyon tridactyla</i>	Three-toed jacamar	NT	1161
33	Bucconidae	<i>Notharchus swainsoni</i>	<i>Buff-bellied puffbird</i>	LC	1365
34	Bucconidae	<i>Malacoptila striata</i>	Greater crescent-chested puffbird	LC	6572
35	Ramphastidae	<i>Ramphastos dicolorus</i>	Red-breasted toucan	LC	17,762
36	Ramphastidae	<i>Selenidera maculirostris</i>	Spot-billed toucanet	LC	4223
37	Ramphastidae	<i>Pteroglossus bailloni</i>	Saffron toucanet	NT	1725
38	Picidae	<i>Picumnus exilis</i>	Golden-spangled piculet	LC	1273
39	Picidae	<i>Picumnus temminckii</i>	<i>Ochre-collared piculet</i>	LC	10,963
40	Picidae	<i>Melanerpes flavifrons</i>	<i>Yellow-fronted woodpecker</i>	LC	9249
41	Picidae	<i>Veniliornis maculifrons</i>	<i>Yellow-eared woodpecker</i>	LC	1703
42	Picidae	<i>Campephilus robustus</i>	<i>Robust woodpecker</i>	LC	4911
43	Picidae	<i>Celeus galeatus</i>	Helmeted woodpecker	VU	335
44	Picidae	<i>Celeus tinnunculus</i>	Atlantic black-breasted woodpecker	VU	159
45	Picidae	<i>Piculus chrysochloros</i>	Golden-green woodpecker	LC	59
46	Picidae	<i>Piculus aurulentus</i>	Yellow-browed woodpecker	NT	5092
47	Psittacidae	<i>Touit melanonotus</i>	Brown-backed parrotlet	NT	640
48	Psittacidae	<i>Touit surdus</i>	Golden-tailed parrotlet	VU	860
49	Psittacidae	<i>Brotogeris tirica</i>	<i>Plain parakeet</i>	LC	34,619
50	Psittacidae	<i>Pionopsitta pileata</i>	Pileated parrot	LC	4045
51	Psittacidae	<i>Triclaria malachitacea</i>	Blue-bellied parrot	LC	1533
52	Psittacidae	<i>Pionus reichenowi</i>	Blue-breasted parrot	VU	267
53	Psittacidae	<i>Amazona vinacea</i>	Vinaceous-breasted amazon	EN	2863
54	Psittacidae	<i>Amazona pretrei</i>	<i>Red-spectacled amazon</i>	VU	882
55	Psittacidae	<i>Amazona rhodocorytha</i>	Red-browed amazon	VU	1313
56	Psittacidae	<i>Amazona brasiliensis</i>	<i>Red-tailed amazon</i>	NT	1204
57	Psittacidae	<i>Pyrrhura cruentata</i>	Ochre-marked parakeet	VU	887
58	Psittacidae	<i>Pyrrhura frontalis</i>	<i>Maroon-bellied parakeet</i>	LC	24,417
59	Psittacidae	<i>Pyrrhura griseipectus</i>	<i>Grey-breasted parakeet</i>	EN	635
60	Psittacidae	<i>Pyrrhura leucotis</i>	White-eared parakeet	VU	899
61	Thamnophilidae	<i>Hypoedaleus guttatus</i>	Spot-backed antshrike	LC	6559
62	Thamnophilidae	<i>Mackenziaena leachii</i>	Large-tailed antshrike	LC	3546
63	Thamnophilidae	<i>Mackenziaena severa</i>	<i>Tufted antshrike</i>	LC	4471
64	Thamnophilidae	<i>Biatas nigropectus</i>	White-bearded antshrike	VU	1245
65	Thamnophilidae	<i>Thamnophilus ambiguus</i>	<i>Sooretama slaty antshrike</i>	LC	1873
66	Thamnophilidae	<i>Rhopias gularis</i>	Star-throated antwren	LC	5203
67	Thamnophilidae	<i>Dysithamnus stictothorax</i>	Spot-breasted antvireo	NT	3938
68	Thamnophilidae	<i>Dysithamnus xanthopterus</i>	Rufous-backed antvireo	LC	1434
69	Thamnophilidae	<i>Dysithamnus plumbeus</i>	Plumbeous antvireo	VU	353
70	Thamnophilidae	<i>Myrmotherula axillaris</i>	White-flanked antwren	LC	1213
71	Thamnophilidae	<i>Myrmotherula minor</i>	Salvadori's antwren	VU	659
72	Thamnophilidae	<i>Myrmotherula urosticta</i>	Band-tailed antwren	VU	446
73	Thamnophilidae	<i>Myrmotherula unicolor</i>	Unicolored antwren	NT	3364

Table 1 (Continued)

ID	Family	Scientific name	Common name	Threat status	N
74	Thamnophilidae	<i>Myrmotherula snowi</i>	Alagoas antwren	CR	102
75	Thamnophilidae	<i>Herpsilochmus pileatus</i>	Bahia antwren	VU	624
76	Thamnophilidae	<i>Formicivora erythronotos</i>	Black-hooded antwren	EN	488
77	Thamnophilidae	<i>Formicivora serrana</i>	Serra antwren	LC	1487
78	Thamnophilidae	<i>Formicivora paludicola</i>	Marsh antwren	CR	350
79	Thamnophilidae	<i>Formicivora acutirostris</i>	Parana antwren	NT	898
80	Thamnophilidae	<i>Drymophila ferruginea</i>	Ferruginous antbird	LC	7324
81	Thamnophilidae	<i>Drymophila rubricollis</i>	Bertoni's antbird	LC	2242
82	Thamnophilidae	<i>Drymophila genei</i>	Rufous-tailed antbird	LC	1667
83	Thamnophilidae	<i>Drymophila ochropyga</i>	Ochre-rumped antbird	NT	1879
84	Thamnophilidae	<i>Drymophila malura</i>	Dusky-tailed antbird	LC	3715
85	Thamnophilidae	<i>Drymophila squamata</i>	Scaled antbird	LC	5064
86	Thamnophilidae	<i>Terenura sicki</i>	Orange-bellied antwren	CR	289
87	Thamnophilidae	<i>Terenura maculata</i>	Streak-capped antwren	LC	4982
88	Thamnophilidae	<i>Cercomacra brasiliana</i>	Rio de Janeiro antbird	NT	598
89	Thamnophilidae	<i>Pyriglena atra</i>	Fringe-backed fire-eye	EN	243
90	Thamnophilidae	<i>Pyriglena leucoptera</i>	White-shouldered fire-eye	LC	11,675
91	Thamnophilidae	<i>Rhopornis ardesiacus</i>	Slender antbird	EN	528
92	Thamnophilidae	<i>Myrmoderus ruficauda</i>	Scalloped antbird	EN	571
93	Thamnophilidae	<i>Myrmoderus loricatus</i>	White-bibbed antbird	LC	1720
94	Thamnophilidae	<i>Myrmoderus squamosus</i>	Squamate Antbird	LC	5380
95	Conopophagidae	<i>Conopophaga melanops</i>	Black-cheeked gnatcatcher	LC	6585
96	Conopophagidae	<i>Conopophaga cearae</i>	Ceara gnatcatcher	NT	710
97	Grallariidae	<i>Hylopezus nattereri</i>	Speckle-breasted antpitta	LC	681
98	Rhinocryptidae	<i>Psilorhamphus guttatus</i>	Spotted bamboo-wren	LC	1535
99	Rhinocryptidae	<i>Merulaxis ater</i>	Slaty bristlefront	LC	2188
100	Rhinocryptidae	<i>Merulaxis stresemanni</i>	Stresemann's bristlefront	CR	57
101	Rhinocryptidae	<i>Eleoscytalopus psychopompus</i>	Bahia tapaculo	EN	127
102	Rhinocryptidae	<i>Eleoscytalopus indigoticus</i>	White-breasted tapaculo	LC	3571
103	Rhinocryptidae	<i>Scytalopus gonzagai</i>	Boa Nova tapaculo	EN	9
104	Rhinocryptidae	<i>Scytalopus speluncae</i>	Mouse-colored tapaculo	LC	3057
105	Rhinocryptidae	<i>Scytalopus diamantinensis</i>	Diamantina tapaculo	EN	105
106	Rhinocryptidae	<i>Scytalopus petrophilus</i>	Rock tapaculo	LC	537
107	Rhinocryptidae	<i>Scytalopus pachecoi</i>	Planalto tapaculo	LC	510
108	Rhinocryptidae	<i>Scytalopus iraiensis</i>	Marsh tapaculo	EN	198
109	Formicariidae	<i>Chamaeza meruloides</i>	Cryptic antthrush	LC	2424
110	Formicariidae	<i>Chamaeza ruficauda</i>	Rufous-tailed antthrush	LC	1780
111	Furnariidae	<i>Sclerurus cearensis</i>	Ceara leaf-tosser	VU	165
112	Furnariidae	<i>Sclerurus scansor</i>	Rufous-breasted leaf-tosser	LC	4279
113	Furnariidae	<i>Dendrocincla turdina</i>	Plain-winged woodcreeper	LC	6540
114	Furnariidae	<i>Xiphorhynchus fuscus</i>	Lesser woodcreeper	LC	10,401
115	Furnariidae	<i>Xiphorhynchus atlanticus</i>	Atlantic woodcreeper	VU	790
116	Furnariidae	<i>Campylorhamphus falcularius</i>	Black-billed Scythebill	LC	2579
117	Furnariidae	<i>Lepidocolaptes squamatus</i>	Scaled woodcreeper	LC	3940
118	Furnariidae	<i>Lepidocolaptes falcinellus</i>	Scalloped woodcreeper	LC	4479
119	Furnariidae	<i>Cinclodes pabsti</i>	Long-tailed cinclodes	NT	1275
120	Furnariidae	<i>Anabazenops fuscus</i>	White-collared foliage-gleaner	LC	3976
121	Furnariidae	<i>Cichlocolaptes leucophrus</i>	Pale-browed treehunter	LC	2710
122	Furnariidae	<i>Heliobletus contaminatus</i>	Sharp-billed treehunter	LC	1512
123	Furnariidae	<i>Philydor atricapillus</i>	Black-capped foliage-gleaner	LC	5525
124	Furnariidae	<i>Anabacerthia amaurotis</i>	White-browed foliage-gleaner	NT	1539
125	Furnariidae	<i>Anabacerthia lichtensteini</i>	Ochre-breasted foliage-gleaner	LC	2804
126	Furnariidae	<i>Clibanornis dendrocolaptooides</i>	Canebrake groundcreeper	LC	855
127	Furnariidae	<i>Automolus lammi</i>	Pernambuco Foliage-gleaner	EN	230
128	Furnariidae	<i>Automolus leucophthalmus</i>	White-eyed foliage-gleaner	LC	8375
129	Furnariidae	<i>Leptasthenura striolata</i>	Striolated tit-spinetail	LC	993
130	Furnariidae	<i>Leptasthenura setaria</i>	Araucaria tit-spinetail	NT	4866
131	Furnariidae	<i>Phacellodomus erythrophthalmus</i>	Orange-eyed thornbird	LC	4006
132	Furnariidae	<i>Phacellodomus ferrugineigula</i>	Orange-breasted thornbird	LC	3410
133	Furnariidae	<i>Asthenes moreirae</i>	Itatiaia spinetail	LC	1031
134	Furnariidae	<i>Acrobatornis fonseci</i>	Pink-legged graveteiro	VU	234
135	Furnariidae	<i>Thripophaga macroura</i>	Striated softtail	VU	583
136	Furnariidae	<i>Cranioleuca obsoleta</i>	Olive spinetail	LC	3288
137	Furnariidae	<i>Cranioleuca pallida</i>	Pallid spinetail	LC	10,153
138	Furnariidae	<i>Synallaxis cinerea</i>	Bahia spinetail	NT	448
139	Furnariidae	<i>Synallaxis infuscata</i>	Pinto's spinetail	EN	109
140	Furnariidae	<i>Synallaxis ruficapilla</i>	Rufous-capped spinetail	LC	13,720
141	Tyrannidae	<i>Phyllomyias virescens</i>	Greenish tyrannulet	LC	1946
142	Tyrannidae	<i>Phyllomyias griseicapilla</i>	Grey-capped tyrannulet	NT	4138
143	Tyrannidae	<i>Phylloscartes kronei</i>	Restinga tyrannulet	LC	1751
144	Tyrannidae	<i>Phylloscartes beckeri</i>	Bahia tyrannulet	EN	237
145	Tyrannidae	<i>Phylloscartes ceciliae</i>	Alagoas tyrannulet	CR	339
146	Tyrannidae	<i>Phylloscartes paulista</i>	Sao Paulo tyrannulet	NT	1441
147	Tyrannidae	<i>Phylloscartes oustaleti</i>	Oustalet's tyrannulet	NT	1890
148	Tyrannidae	<i>Phylloscartes difficilis</i>	Serra do mar tyrannulet	LC	700
149	Tyrannidae	<i>Phylloscartes sylviolus</i>	Bay-ringed tyrannulet	NT	1001
150	Tyrannidae	<i>Myiornis auricularis</i>	Eared pygmy-tyrant	LC	7675

Table 1 (Continued)

ID	Family	Scientific name	Common name	Threat status	N
151	Tyrannidae	<i>Hemitriccus diops</i>	Drab-breasted bamboo-tyrant	LC	3138
152	Tyrannidae	<i>Hemitriccus obsoletus</i>	Brown-breasted bamboo-tyrant	LC	1603
153	Tyrannidae	<i>Hemitriccus orbitatus</i>	Eye-ringed tody-tyrant	NT	3256
154	Tyrannidae	<i>Hemitriccus nidipendulus</i>	Hangnest tody-tyrant	LC	4478
155	Tyrannidae	<i>Hemitriccus mirandae</i>	Buff-breasted tody-tyrant	VU	541
156	Tyrannidae	<i>Hemitriccus kaempferi</i>	Kaempfer's tody-tyrant	VU	683
157	Tyrannidae	<i>Hemitriccus furcatus</i>	Fork-tailed tody-tyrant	VU	1431
158	Tyrannidae	<i>Todirostrum poliocephalum</i>	Yellow-lored tody-flycatcher	LC	18,110
159	Tyrannidae	<i>Platyrrhynchus leucoryphus</i>	Russet-winged spadebill	VU	487
160	Tyrannidae	<i>Onychorhynchus swainsoni</i>	Atlantic royal flycatcher	VU	765
161	Tyrannidae	<i>Knipolegus nigerrimus</i>	Velvet black-tyrant	LC	5281
162	Tyrannidae	<i>Muscipipra vetula</i>	Shear-tailed grey tyrant	LC	3475
163	Tyrannidae	<i>Attila rufus</i>	Grey-hooded attila	LC	10,287
164	Tyrannidae	<i>Piprites pileata</i>	Black-capped piprites	NT	1312
165	Cotingidae	<i>Carpornis cucullata</i>	Hooded berryeater	LC	4600
166	Cotingidae	<i>Carpornis melanocephala</i>	Black-headed berryeater	NT	1223
167	Cotingidae	<i>Phibalura flavirostris</i>	Swallow-tailed cotinga	LC	1715
168	Cotingidae	<i>Cotinga maculata</i>	Banded cotinga	CR	257
169	Cotingidae	<i>Lipaugus lanioides</i>	Cinnamon-vented piha	LC	1669
170	Cotingidae	<i>Lipaugus ater</i>	Black-and-gold cotinga	LC	1642
171	Cotingidae	<i>Lipaugus conditus</i>	Grey-winged cotinga	VU	262
172	Cotingidae	<i>Procnias nudicollis</i>	Bare-throated bellbird	NT	7788
173	Cotingidae	<i>Xipholena atropurpurea</i>	White-winged cotinga	VU	701
174	Pipridae	<i>Neopelma aurifrons</i>	Wied's tyrant-manakin	NT	327
175	Pipridae	<i>Neopelma chrysolophum</i>	Serra do Mar tyrant-manakin	LC	2188
176	Pipridae	<i>Antilophia bokermanni</i>	Araripe manakin	CR	7
177	Pipridae	<i>Chiroxiphia caudata</i>	Blue manakin	LC	26,382
178	Pipridae	<i>Illicura militaris</i>	Pin-tailed manakin	LC	7292
179	Pipridae	<i>Machaeropterus regulus</i>	Kinglet manakin	LC	997
180	Tityridae	<i>Schiffornis virescens</i>	Greenish schiffornis	LC	8586
181	Tityridae	<i>Iodopleura pipra</i>	Buff-throated purpletuft	EN	1341
182	Tityridae	<i>Laniisoma elegans</i>	Elegant mourner	NT	330
183	Vireonidae	<i>Hylophilus poicilotis</i>	Rufous-crowned greenlet	LC	7960
184	Corvidae	<i>Cyanocorax coeruleus</i>	Azure jay	NT	7582
185	Poliptilidae	<i>Poliptila lactea</i>	Creamy-bellied gnatcatcher	NT	331
186	Thraupidae	<i>Nemosia rourei</i>	Cherry-throated tanager	CR	147
187	Thraupidae	<i>Orchesticus abeillei</i>	Brown tanager	NT	1804
188	Thraupidae	<i>Hemithraupis ruficapilla</i>	Rufous-headed tanager	LC	10,180
189	Thraupidae	<i>Haplospiza unicolor</i>	Uniform Finch	LC	3948
190	Thraupidae	<i>Tachyphonus coronatus</i>	Ruby-crowned tanager	LC	35,583
191	Thraupidae	<i>Ramphocelus bresilius</i>	Brazilian tanager	LC	21,613
192	Thraupidae	<i>Dacnis nigripes</i>	Black-legged dacnis	NT	1239
193	Thraupidae	<i>Sporophila falcirostris</i>	Temminck's seedeater	VU	1157
194	Thraupidae	<i>Sporophila frontalis</i>	Buffy-fronted seedeater	VU	2049
195	Thraupidae	<i>Saltator maxillosus</i>	<i>Thick-billed saltator</i>	LC	2935
196	Thraupidae	<i>Saltator fuliginosus</i>	<i>Black-throated grosbeak</i>	LC	4827
197	Thraupidae	<i>Castanozoster thoracicus</i>	Bay-chested warbling-finch	LC	1978
198	Thraupidae	<i>Thlypopsis pyrrhocoma</i>	Chestnut-headed tanager	LC	2298
199	Thraupidae	<i>Microspingus lateralis</i>	Buff-breasted warbling-finch	LC	3726
200	Thraupidae	<i>Tangara cyanoptera</i>	Azure-shouldered tanager	NT	3316
201	Thraupidae	<i>Tangara brasiliensis</i>	White-bellied tanager	LC	827
202	Thraupidae	<i>Tangara peruviana</i>	Black-backed tanager	VU	1912
203	Thraupidae	<i>Tangara cyanomelas</i>	Silvery-breasted tanager	LC	465
204	Thraupidae	<i>Tangara seledon</i>	Green-headed tanager	LC	21,755
205	Thraupidae	<i>Tangara fastuosa</i>	Seven-colored tanager	VU	964
206	Thraupidae	<i>Tangara cyanocephala</i>	Red-necked tanager	LC	13,062
207	Thraupidae	<i>Tangara desmaresti</i>	Brassy-breasted tanager	LC	8705
208	Thraupidae	<i>Tangara cyanoventris</i>	Gilt-edged tanager	LC	6928
209	Thraupidae	<i>Tangara ornata</i>	Golden-chevroned tanager	LC	6297
210	Mitrospingidae	<i>Orthogonys chloricterus</i>	Olive-green tanager	LC	5418
211	Passerellidae	<i>Arremon semitorquatus</i>	Half-collared sparrow	LC	2873
212	Icteridae	<i>Anumara forbesi</i>	Forbes's blackbird	VU	288
213	Fringillidae	<i>Euphonia chalybea</i>	Green-throated euphonia	NT	2811
214	Fringillidae	<i>Euphonia pectoralis</i>	Chestnut-bellied euphonia	LC	14,946
215	Tyrannidae	<i>Pogonotriccus eximius</i>	Southern bristle-tyrant	NT	893
216	Tyrannidae	<i>Mionectes rufiventris</i>	Grey-hooded flycatcher	LC	7262

This pattern on the number of observations was considered syn-chronic ($\rho = 0.0369$, and $p < 0.01$; $n = 838,880$).

Discussion

We saw a general increase in the number of bird observers and bird observation in 2000–2022, reflecting an increasing interest

in citizen science in Brazil. The marginally acceptable conformity to Benford's Law of the joint dataset suggests that the number of observations had satisfactory heterogeneity, which is evidence for the proportional real abundance of each species. In spite of this, the data did not fit the gamma binomial distribution model, potentially because of the relatively high number of observations of imperiled (and therefore presumably rare) species. In total, 79 species had

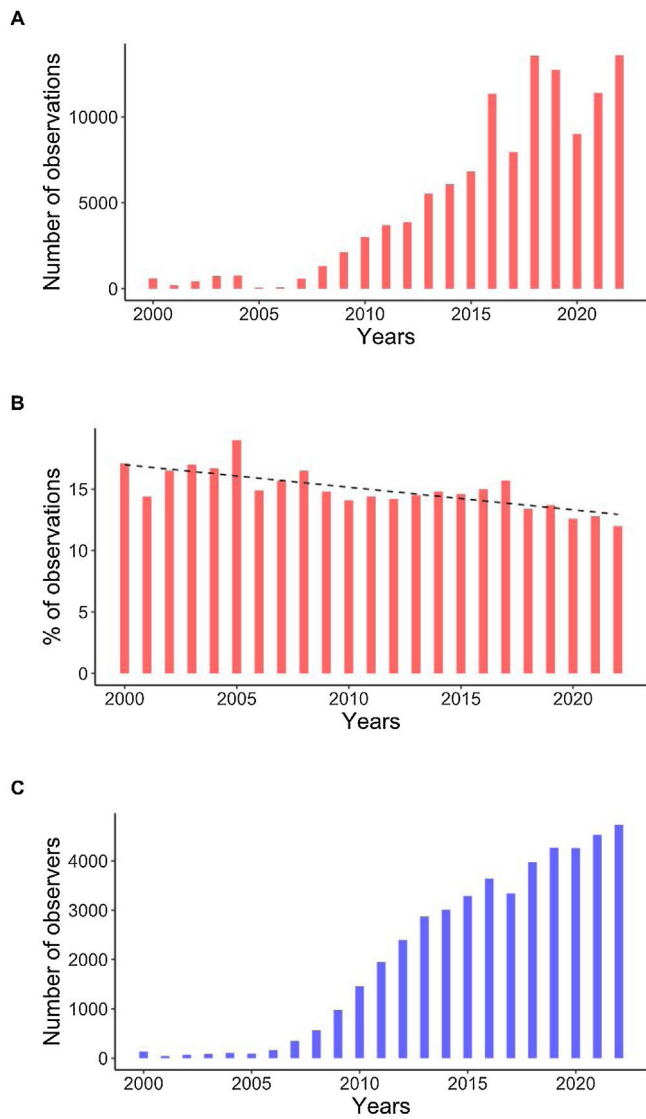


Fig. 2. The number (a) and the proportion (b) of observations of threatened and Near Threatened bird species in the Brazilian Atlantic Forest compiled by community scientists and (c) number of observers that submitted observations of birds from the Brazilian Atlantic Forest in 2000–2022; the dashed line in b is the trend line from a smooth linear model.

Table 2

Matrix with Spearman rank correlation coefficients ($n = 23$) for the correlations between threatened and Near Threatened species richness, number of observations of endemic species and the number of observers each year in the interval between 2000 and 2022. All correlations were $p < 0.01$, but exact p-values could not be calculated.

	Richness	Number of observers each year	Number of observations of endemic species
Richness	–	0.84	0.87
Number of observers each year	–	–	0.95
Number of observations of endemic species	–	–	–

2000–10,000 observations, while only eight species, all Least Concern, had over 20,000 observations (Table 1). Given this pattern, our results reveal that imperiled Atlantic Forest bird species with decreasing populations are relatively often recorded by CS.

Five species, including the Near Threatened Bare-throated Bellbird (*Procnias nudicollis*) and Azure Jay (*Cyanocorax coeruleus*) had

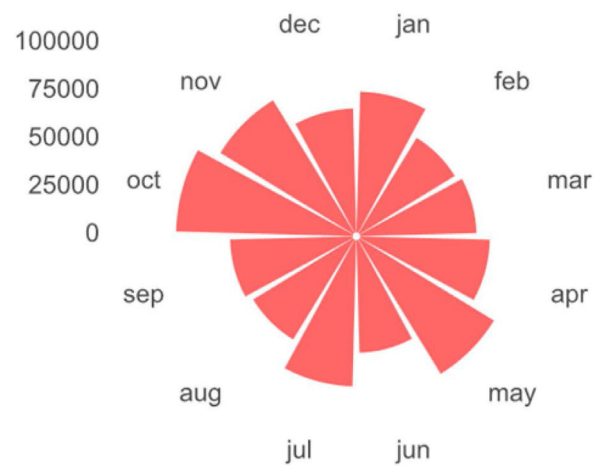


Fig. 3. Monthly distribution of observations of endemic species from the Brazilian Atlantic Forest based on three community science platforms in 2000–2022.

over 4000 observations, both of them being relatively large, attractive birds that are easy to detect when present and vocalizing and are sought after by birdwatchers. These characteristics are similar to those preferred by birdwatchers in South Australia (Szabo et al., 2011). We assume that on all three platforms, many observers are experienced birdwatchers who focus on finding desired species to complete their personal list of observed birds, similar to a type of observer identified in Western Australia by Tulloch and Szabo (2012). Nevertheless, populations of Critically Endangered species, which are by definition extremely rare, are restricted to small remnant patches of native vegetation. These remote habitats are usually beyond the reach of most observers using these CS platforms. Two Critically Endangered species, Stresemann’s Bristlefront (*Merulaxis stresemanni*) and Alagoas Antwren (*Myrmotherula snowi*), were represented by a total of 57 and 102 observations, respectively, on the three platforms in 2000–2022. In fact, Stresemann’s Bristlefront is only known to persist in one forest patch (Lees and Pimm, 2015). Similar to the results of Barbosa et al. (2021), most observations were concentrated in areas of high human population density, i.e., in southern and south-eastern Brazil. In 2020 and 2021, restrictions imposed by the pandemic also limited the movement of bird observers to areas closer to urban centers (Sánchez-Clavijo et al., 2021) and the number of observations in protected areas declined globally compared to pre-pandemic levels (Qiao et al., 2023). This convenience sampling can inflate the number of observations of Least Concern and urban-tolerant species compared to those restricted to particular habitats, usually found within protected areas. Our results confirm this pattern and demonstrate that the probability of observing a threatened or Near Threatened species is much higher (98.5%) outside urban areas. Unfortunately, strictly protected areas only cover 9% of the Atlantic Forest (Rezende et al., 2018), which could explain the relatively high number of observations of imperiled bird outside protected areas. This pattern does not confirm with bird observations made by CS in Australia (Barnes et al., 2015). In addition, many threatened and Near Threatened species use habitats outside protected areas for feeding and reproduction, which raises an important question about prioritizing areas for monitoring and conservation.

Even more worrying is the proportional decline of imperiled species observations in 2000–2022 compared to all bird observations in the Atlantic Forest. We assume that the number of generalist observers (i.e., non-bird specialist in the case of iNaturalist or non-threatened species specialist on the other two platforms) has grown throughout the years, leading to a relatively large increase in the number of observations of common species and

simultaneously decreasing the relative number of observations of rare species, some of which are threatened or Near Threatened. This hypothesis is supported by the correlations between species richness, the number of observations of imperiled species and the number of observers that are active on the platforms each year. However, real population declines also result in lower reporting rates, which is a cause for concern, particularly in the case of globally threatened species. These kinds of declines are more pronounced when we consider the increase in the number of observers on all three CS platforms. In fact, 67% of threatened and Near Threatened bird species observed on the platform show declining population trends and a further 5% have unknown trends (BirdLife International, 2023).

Two endemic species listed as Critically Endangered that are present on the list of Vale et al. (2018) and were absent from the CS dataset: Purple-winged Ground-Dove (*Claravis geoffroyi*; Columbidae) last seen in 2007 and Kinglet Calyptura (*Calyptura cristata*; Tyrannidae) seen only once in 1996 within the last century – both had a high probability of being globally extinct (Butchart et al., 2018; Lees et al., 2021; Lees and Pimm, 2015). The third missing species, Pernambuco Pygmy-Owl (*Glaucidium mooreorum*; Strigidae) was last seen in 2004 and is listed as Critically Endangered (Possibly Extinct) by BirdLife International (2023). On the other hand, there were a few records of two Furnariidae species in the CS datasets, one observation of the Cryptic Treehunter (*Cichocolaptes mazarbarnetti*) in 2001 and 26 observations of the Alagoas Foliage-gleaner (*Philydor novaesi*), which was last seen in 2011, and is also possibly extinct (Butchart et al., 2018; Lees and Pimm, 2015). The joint dataset also contained two observations of the Alagoas curassow, a species listed as Extinct in the Wild by IUCN, possibly of individuals reintroduced in 2019 (Francisco et al., 2021).

The negative trend in the proportion of observations of threatened and Near Threatened species is worrying and needs to be confirmed by focused analysis of targeted studies. Most observations of imperiled species occurred before the beginning of the austral summer (Jones and Carvalho, 2002). Arthropod abundance in the Atlantic Forest is highest during the wet season, in December, while fruit availability is highest in April–June (Develey and Peres, 2000), which in turn increases bird activity and thereby detection rates. For many forest birds, the breeding season ends in December–January (Sick, 1997), when the number of individuals is augmented by fledglings, and this can explain a small peak of observations in January. The Atlantic Forest also receives a handful of Neotropical migrants during this period (Moreira-Lima, 2013) and some austral migrants (Lees and Martin, 2015). Another explanation is that the general public is also on holiday during this time, so they have more time to observe birds. The other peak in sightings of imperiled species occurred in May and July, possibly explained by the weather, as conditions are more favorable for observers (i.e., dryer and cooler) to visit more remote areas of the Atlantic Forest. Observers in unstructured surveys are known to have a preference for weekends, holidays and fair weather (Knape et al., 2022).

The interannual variability in climatic conditions can also affect the number of birds present and CS effort, as El Niño years bring extreme conditions that manifest in longer periods of drought in some regions and higher temperature with torrential rainfalls in others (Costa et al., 2021). The 2015–16 El Niño event resulted in extended drought in the Atlantic Forest of the northeast (Gateau-Rey et al., 2018), possibly affecting the number of birds observed in this region as well as CS effort. Measures to combat the Covid-19 pandemic may have affected the activities of observers, which can explain the lower number of observations of imperiled species in 2020 and 2021 compared to the previous two years. Even though the pandemic has brought some positive changes to nature conservation (Forti et al., 2020), most of its

effects were negative (Gibbons et al., 2022). However, the relatively high number of observers in 2020–21 (Fig. 2c) demonstrates the resilience of community scientists that engaged in birdwatching even during these difficult times. Even if the number of surveys remained the same during these two years, the spatial patterns could have changed. In Colombia, observers submitted more data from modified than from natural landscapes as a result of lockdowns and other travel restrictions (Sánchez-Clavijo et al., 2021). Thus, hard-to-reach sites, such as remote protected areas, where there is a higher probability of observing certain rare species, have presumably received fewer CS surveys. This could explain the high number of records we identified outside protected areas, since many protected areas limited the number of visitors and, therefore tourist activities related to birdwatching were negatively affected in 2020–22 (Spenceley et al., 2021). Nevertheless, protected areas represent only 9% of the remaining natural vegetation of the Atlantic Forest in Brazil, with over 90% being on private land (Rezende et al., 2018).

Based on our results, more effort should be directed to remote areas of the Atlantic Forest to improve species coverage and thereby provide more data to inform biodiversity conservation. Expeditions to specific locations targeting species of conservation concern should be encouraged by CS platforms, protocols should be provided to minimize the risks presented to birds by tourist activities. We recommend targeted surveys for imperiled species to fill knowledge gaps for decision making. The central corridor of the Atlantic Forest is one of the areas that potentially needs a larger sampling effort to increase its representation on the platforms, as this alone could help to create a more robust dataset of Atlantic Forest biodiversity.

Conclusions

Considering the increasing pressures for landscape modification and the consequences of climate change on the Atlantic Forest (de Lima et al., 2020; SOS Mata Atlântica/INPE, 2018), there is an ever-increasing need to understand the biodiversity of this threatened biome. There are also ongoing restoration (Rezende et al., 2018) and refaunation (Galetti et al., 2017) efforts and further opportunities to be taken advantage of in the future in this global biodiversity hotspot. Community science can offer an ideal tool to monitor and document (hopefully positive) changes in the number and abundance of threatened species and to fully understand changes in functional diversity and species-specific responses to active restoration (Melo et al., 2020; Uezu and Metzger, 2016).

Developing a reliable monitoring system is a crucial challenge in the conservation of Atlantic Forest biodiversity, as conservation prioritization depends on the availability of such data. While CS data have influenced conservation decisions in other parts of the world (Fontaine et al., 2022; Fraisl et al., 2020), the lack of understanding of biases often prevents the use of this approach to derive reliable population trends (Bayraktarov et al., 2019). Here we provided the first exploration of CS data for a large number of Atlantic Forest endemic bird species considering two decades and multiple data sources. Even considering the biases inherent in CS data and the difficulties of surveying, it has proved to be an exceptional tool to reduce the Wallacean shortfall (La Sorte and Somveille, 2019; Lees and Martin, 2015), and to bring a new perspective to monitor species facing extinction and their responses to management actions.

Conflict of interest

The authors declare no conflicts of interest.

Availability of data

The raw data for this study are available at <https://zenodo.org/records/10044588>.

Acknowledgements

We appreciate the work of thousands of community scientists who share species occurrence data on digital platforms and therefore made this study possible. We thank Anderson Sandro and Gabriel Bonfa, two community scientists from iNaturalist who gave us permission to use their photographs in the graphical abstract. Arthur Queiros (grant number 127626/2022-0) and Talita Oliveira, (grant number 135165/2022-9) were financed by the Institutional Scientific Initiation Scholarship Program (Programa Institucional de Bolsas de Iniciação Científica; PIBIC), provided by the Coordination for the Improvement of Higher Education Personnel (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior; CAPES), while Juan Lima received financial support (grant number 88887.687023/2022-00) from the Postgraduate Program in Ecology and Conservation (Programa de Pós Graduação em Ecologia e Conservação) supported by CAPES. We are grateful to Darius Pukenis Tubelis, two anonymous reviewers and the handling editor for their constructive comments on previous versions of this manuscript.

References

- Agostinelli, C., Lund, U., <https://CRAN.R-project.org/package=circular>, 2023. (Accessed 26 October 2023).
- Alexandrino, Eduardo R., et al., 2022. Urban southern house wren (*Troglodytes aedon musculus*) nesting in apparently unsuitable human-made structures: Is it worth it? *Ornitol. Neotrop.* 33 (1), 44–52.
- Barbosa, Karlla Vanessade Camargo, et al., 2021. The contribution of citizen science to research on migratory and urban birds in Brazil. *Ornithol. Res.* 29, 1–11.
- Barnes, Megan, et al., 2015. Evaluating protected area effectiveness using bird lists in the Australian Wet Tropics. *Divers. Distrib.* 21, 368–378.
- Bayraktarov, E., Ehmke, G., O'Connor, J., Burns, E.L., Nguyen, H.A., McRae, L., Possingham, H.P., Lindenmayer, D.B., 2019. Do big unstructured biodiversity data mean more knowledge? *Front. Ecol. Evol.* 6, 239.
- Bencke, Glayson A., et al., 2006. Áreas Importantes para a Conservação das Aves no Brasil, Parte I – Estados do Domínio da Mata Atlântica. *SAVE Brasil*.
- Bird, Tomas J., et al., 2014. Statistical solutions for error and bias in global citizen science datasets. *Biol. Conserv.* 173, 144–154.
- Bird, J.P., Martin, R., Akçakaya, H.R., Gilroy, J.J., Burfield, I.J., Garnett, S.T., Symes, A.J., Taylor, J., Şekercioglu, Ç.H., Butchart, S.H.M., 2020. Generation lengths of the world's birds and their implications for extinction risk. *Conserv. Biol.* 34 (5), 1252–1261.
- BirdLife International, 2022. The Status of the World's Birds has Deteriorated in Recent Decades. (Accessed 26 October 2023) <http://www.birdlife.org/>.
- BirdLife International, 2023. BirdLife Data Zone. (Accessed 26 October 2023) <http://datazone.birdlife.org/>.
- Bonney, Rick, 2021. Expanding the impact of citizen science. *BioScience* 71 (5), 448–451.
- Bosenbecker, C., Anselmo, P.A., Andreoli, R.Z., Shimizu, G.H., Oliveira, P.E., Maruyama, P.K., 2023. Contrasting nation-wide citizen science and expert collected data on hummingbird-plant interactions. *Perspect. Ecol. Conserv.* 21, 164–171, <http://dx.doi.org/10.1016/j.pecon.2023.03.004>.
- Butchart, Stuart H.M., et al., 2018. Which bird species have gone extinct? A novel quantitative classification approach. *Biol. Conserv.* 227, 9–18.
- Callaghan, Corey T., et al., 2021. Three frontiers for the future of biodiversity research using citizen science data. *BioScience* 71 (1), 55–63.
- Centro de Estudos da Metrópole, <https://centrodametropole.fflch.usp.br/pt-br/node/9991>, 2021, <http://dx.doi.org/10.55881/CEM.db.unc001>, (Accessed 10 September 2022).
- Chamberlain, Scott, <https://CRAN.R-project.org/package=rredlist>, 2020.
- Chapman, A.D., 2005. *Uses of Primary Species-Occurrence Data, Version 1.0. Report for the Global Biodiversity Information Facility, Copenhagen*.
- Cinelli, C., <https://www.rdocumentation.org/packages/benford.analysis/versions/0.1.5>, 2014.
- Costa, M.d.S., Oliveira-Júnior, J.F.d., dos Santos, P.J., Correia Filho, W.L.F., Gois, G.D., Cavalcante Blanco, C.J., Teodoro, P.E., Silva Junior, C.A.d., Barros Santiago, D.d., Souza, E.d.O., Jardim, A.M.d.R.F., 2021. Rainfall extremes and drought in northeast Brazil and its relationship with El Niño–Southern Oscillation. *Int. J. Climatol.* 41, E2111–E2135, <http://dx.doi.org/10.1002/joc.6835>.
- Cunha, Filipe C.R., Lopes, Leonardo Esteves, Selezneva, Antonina, 2022. Revealing migration schedule and potential breeding grounds of lined seedeaters using citizen science data. *Emu* 122 (3–4), 167–175.
- de Lima, Renato A.F., et al., 2020. The erosion of biodiversity and biomass in the Atlantic Forest biodiversity hotspot. *Nat. Commun.* 11 (1), 1–16.
- de Souza, Eletra, et al., 2022. Ophiophagy in Brazilian birds: a contribution from a collaborative platform of citizen science. *Ornithol. Res.* 30, 15–24.
- Deacon, C., Govender, S., Samways, M.J., 2023. Overcoming biases and identifying opportunities for citizen science to contribute more to global macroinvertebrate conservation. *Biodivers. Conserv.* 32, 1789–1806, <http://dx.doi.org/10.1007/s10531-023-02595-x>.
- Develey, Pedro Ferreira, Peres, Carlos Augusto, 2000. Resource seasonality and the structure of mixed species bird flocks in a coastal Atlantic forest of southeastern Brazil. *J. Trop. Ecology* 16, 33–53.
- Devenish, Christian, et al., 2021. Multi-decadal land use impacts across the vast range of an iconic threatened species. *Divers. Distrib.* 27, 2218–2230.
- Di Cecco, Grace J., et al., 2021. Observing the observers: how participants contribute data to iNaturalist and implications for biodiversity science. *BioScience* 71 (11), 1179–1188.
- Fontaine, A., Simard, A., Brunet, N., Elliott, K.H., 2022. Scientific contributions of citizen science applied to rare or threatened animals. *Conserv. Biol.*, e13976, <http://dx.doi.org/10.1111/cobi.13976>.
- Forti, Lucas R., et al., 2020. Ecological inheritance for a post COVID-19 world. *Biodivers. Conserv.* 29, 3491–3494.
- Fraisl, D., Campbell, J., See, L., Wehn, U., Wardlaw, J., Gold, M., Moorthy, I., Arias, R., Piera, J., Oliver, J.L., Masó, J., Penker, M., Fritz, S., 2020. Mapping citizen science contributions to the UN sustainable development goals. *Sustainability Sci.* 15, 1735–1751, <http://dx.doi.org/10.1007/s11625-020-00833-7>.
- Francisco, Mercival Roberto, et al., 2021. Recovered after an extreme bottleneck and saved by ex situ management: lessons from the Alagoas curassow (*Pauxi mitu* [Linnaeus, 1766]; Aves, Galliformes, Cracidae). *Zoo Biol.* 40 (1), 76–78.
- Galetti, Mauro, et al., 2017. Reversing defaunation by trophic rewilding in empty forests. *Biotropica* 1, 5–8.
- Gateau-Rey, L., Tanner, E.V.J., Rapidel, B., Marelli, J., Royaert, S., 2018. Climate change could threaten cocoa production: effects of 2015–16 El Niño-related drought on cocoa agroforests in Bahia, Brazil. *PLoS One* 13 (7), e0200454, <http://dx.doi.org/10.1371/journal.pone.0200454>.
- Gibbons, David W., et al., 2022. The relative importance of COVID-19 pandemic impacts on biodiversity conservation globally. *Conserv. Biol.* 36 (1), e13781.
- Green, Roger H., Young, Richard C., 1993. Sampling to detect rare species. *Ecol. Appl.* 3 (2), 351–356.
- Guaraldo, André de Camargo, Bczuska, Juliane Coimbra, Manica, Lilian Tonelli, 2022. *Turdus flavipes* altitudinal migration in the Atlantic Forest the yellow-legged thrush is a partial altitudinal migrant in the Atlantic Forest. *Avian Biol. Res.* 15 (3), 117–124.
- Hortal, J., de Bello, F., Diniz-Filho, J.A.F., Lewinsohn, T.M., Lobo, J.M., Ladle, R.J., 2015. Seven shortfalls that beset large-scale knowledge of biodiversity. *Annu. Rev. Ecol. Evol. Syst.* 46, 523–549.
- IBGE, <https://www.ibge.gov.br/geociencias/cartas-e-mapas/redes-geograficas/15789-areas-urbanizadas.html?=&t=acesso-ao-produto>, 2015. (Accessed 10 September 2022).
- IUCN, <https://www.iucnredlist.org>, 2022. (Accessed 1 September 2022).
- IUCN Standards and Petitions Committee, Downloaded from <https://www.iucnredlist.org/documents/RedListGuidelines.pdf>, 2022.
- Jiménez, Manuel, Triguero, Isaac, John, Robert, 2019. Handling uncertainty in citizen science data: towards an improved amateur-based large-scale classification. *Inf. Sci.* 479, 301–320.
- Jones, Charles, Carvalho, Leila M.V., 2002. Active and break phases in the South American monsoon system. *J. Clim.* 15 (8), 905–914.
- Knape, J., Coulson, S.J., van der Wal, R., Arlt, D., 2022. Temporal trends in opportunistic citizen science reports across multiple taxa. *Ambio* 51, 183–198.
- La Sorte, Frank A., Somveille, Marius, 2019. Survey completeness of a global citizen-science database of bird occurrence. *Ecography* 42, 1–10.
- Lees, Alexander C., Martin, Robert W., 2015. Exposing hidden endemism in a neotropical forest raptor using citizen science. *Ibis* 157, 103–114.
- Lees, Alexander C., Pimm, Stuart L., 2015. Species, extinct before we know them? *Curr. Biol.* 25 (5), 177–180.
- Lees, Alexander C., et al., 2021. Assessing the extinction probability of the purple-winged ground dove, an enigmatic bamboo specialist. *Front. Ecol. Evol.* 9, 624959.
- Lloyd, Thomas J., et al., 2020. Estimating the spatial coverage of citizen science for monitoring threatened species. *Global Ecol. Conserv.* 23, e01048.
- Lopes, Leonardo Esteves, Schunck, Fabio, 2022. Unravelling the migratory patterns of the rufous-tailed attila within the neotropics using citizen science and traditional data sources. *Ornithol. Res.* 30, 87–98.
- Mandeville, Caitlin P., Nilsen, Erlend B., Finstad, Anders G., 2022. Spatial distribution of biodiversity citizen science in a natural area depends on area accessibility and differs from other recreational area use. *Ecol. Solut. Evid.* 3, e12185.
- Marques, Marcia C.M., Grelle, Carlos Eduardo Viveiros, 2021. The Atlantic Forest: History, Biodiversity, Threats and Opportunities of the Mega-Diverse Forest. *Springer Nature*.
- Martikainen, Petri, Kouki, Jari, 2003. Sampling the rarest: threatened beetles in boreal forest biodiversity inventories. *Biodivers. Conserv.* 12, 1815–1831.

- Matthews, Thomas J., et al., 2014. The gambin model provides a superior fit to species abundance distributions with a single free parameter: evidence, implementation and interpretation. *Ecography* 37 (10), 1002–1011.
- Melo, Marcos Antônio, da Silva, Marco Aurélio G., Piratelli, Augusto João, 2020. Improvement of vegetation structure enhances bird functional traits and habitat resilience in an area of ongoing restoration in the Atlantic Forest. *An. Acad. Bras. Cienc.* 92 (Suppl. 2), e20191241.
- Moreira-Lima, Luciano, 2013. *Aves Da Mata Atlântica: Riqueza, Composição, Status, Endemismos E Conservação*. Universidade de São Paulo.
- Morellato, L., Patricia, C., Haddad, C.Élio Fernando Baptista, 2000. Introduction: the Brazilian Atlantic Forest. *Biotropica* 32 (4b), 786–792.
- Myers, N., Mittermeier, R.A., Mittermeier, C.G., Da Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. *Nature* 403 (6772), 853–858.
- Newman, Gregory J., et al., 2017. Leveraging the power of place in citizen science for effective conservation decision making. *Biol. Conserv.* 208, 55–64.
- Nigrini, M.J., 2012. *Benford's Law: Applications for Forensic Accounting, Auditing, and Fraud Detection*. John Wiley & Sons.
- Pizo, M.A., Tonetti, V.R., 2020. Living in a fragmented world: birds in the Atlantic Forest. *Ornithol Appl* 122, 1–14, <http://dx.doi.org/10.1093/condor/duaa023>.
- QGIS Development Team, 2021. QGIS Geographic Information System. Open Source Geospatial Foundation Project. <http://qgis.osgeo.org>.
- Qiao, Huijie, Orr, Michael, Yang, Qinmin, Zhan, Xiangjiang, Lei, Fumin, Hughes, Alice C., 2023. Global birdwatching data reveal uneven consequences of the COVID-19 pandemic. *Biol. Conserv.* 288, 110351, <http://dx.doi.org/10.1016/j.biocon.2023.110351>.
- R Core Development Team, URL: <http://www.R-project.org/>, 2020.
- Revelle, W., <https://CRAN.R-project.org/package=psych>, 2022., Version 2.2.9.
- Rezende, C.L., et al., 2018. From hotspot to hopespot: an opportunity for the Brazilian Atlantic Forest. *Perspect. Ecol. Conserv.* 16, 208–214.
- Ribeiro, Milton Cezar, et al., 2011. The Brazilian Atlantic Forest: a shrinking biodiversity hotspot. In: Zachos, F.E., Habel, J.C. (Eds.), *Biodiversity Hotspots*. Springer, Berlin, Heidelberg, pp. 405–434.
- Robinson, Natasha M., et al., 2018. How to ensure threatened species monitoring leads to threatened species conservation. *Ecol. Manage. Restor.* 19 (3), 222–229.
- Sánchez-Clavijo, Lina María, et al., 2021. Differential reporting of biodiversity in two citizen science platforms during COVID-19 lockdown in Colombia. *Biol. Conserv.* 256, 109077.
- Santos, Clarissa O., et al., 2021. Distribution and migration phenology of purple martins (*Progne subis*) in Brazil. *Ornithol. Res.* 29, 213–222.
- Schnell, J.K., Harris, G.M., Pimm, S.L., Russell, G.J., 2013. Quantitative analysis of forest fragmentation in the Atlantic Forest reveals more threatened bird species than the current red list. *PLoS One* 8 (5), e65357, <http://dx.doi.org/10.1371/journal.pone.0065357>.
- Schubert, Stephanie Caroline, Manica, Lilian Tonelli, De Camargo Guaraldo, André, 2019. Revealing the potential of a huge citizen-science platform to study bird migration. *Emu* 119 (4), 364–373.
- Sick, H., 1997. *Ornitologia Brasileira*. Editora Nova Fronteira, Rio de Janeiro.
- Soberón, Jorge, Townsend Peterson, A., 2009. Monitoring biodiversity loss with primary species-occurrence data: toward national-level indicators for the 2010 target of the convention on biological diversity. *AMBIO* 38 (1), 29–34.
- SOS Mata Atlântica/INPE, 2018. *Atlas Dos Remanescentes Florestais Da Mata Atlântica: Período 2016–2017 – Relatório Técnico*. SOS Mata Atlântica/INPE, São Paulo.
- Spenceley, Anna, et al., 2021. Tourism in protected and conserved areas amid the COVID-19 pandemic. *PARKS* 27, 103–118.
- Szabo, Judit K., et al., 2010. Regional avian species declines estimated from volunteer-collected long-term data using list length analysis. *Ecol. Appl.* 20 (8), 2157–2169.
- Szabo, Judit K., et al., 2011. Paying the extinction debt: woodland birds in the Mount Lofty Ranges, South Australia. *Emu* 111 (1), 59–70.
- Szabo, J.K., Butchart, S.H.M., Possingham, H.P., Garnett, S.T., 2012a. Adapting global biodiversity indicators to the national scale: a Red List Index for Australian birds. *Biol. Conserv.* 148, 61–68, <http://dx.doi.org/10.1016/j.biocon.2012.01.062>.
- Szabo, Judit K., Fuller, Richard A., Possingham, Hugh P., 2012b. A comparison of estimates of relative abundance from a weakly structured mass-participation bird atlas survey and a robustly designed monitoring scheme. *Ibis* 154, 468–479.
- Szabo, Judit K., Forti, Lucas Rodriguez, Callaghan, Corey T., 2023. Large biodiversity datasets conform to Benford's law: implications for assessing sampling heterogeneity. *Biol. Conserv.* 280, 109982.
- Troudet, Julien, et al., 2017. Taxonomic bias in biodiversity data and societal preferences. *Sci. Rep.* 7, 9132.
- Tulloch, Ayesha, Szabo, Judit K., 2012. A behavioural ecology approach to understand volunteer surveying for citizen science datasets. *Emu* 112, 313–325.
- Uezu, Alexandre, Metzger, Jean Paul, 2016. Time-lag in responses of birds to Atlantic Forest fragmentation: restoration opportunity and urgency. *PLoS ONE* 11 (1), e0147909.
- Ugland, Karl I., et al., 2007. Modelling dimensionality in species abundance distributions: description and evaluation of the Gambin model. *Evol. Ecol. Res.* 9, 313–324.
- Vale, Mariana M., et al., 2018. Endemic birds of the Atlantic Forest: traits, conservation status, and patterns of biodiversity. *J. Field Ornithol.* 89 (3), 193–206.
- Wickham, Hadley, 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York.
- Wickham, Hadley, et al., <https://CRAN.R-project.org/package=dplyr>, 2022., (Accessed 20 January, 2023).
- Wilson, Joseph S., et al., 2020. More eyes on the prize: an observation of a very rare, threatened species of philippine bumble bee, *Bombus irisanensis*, on iNaturalist and the importance of citizen science in conservation biology. *J. Insect Conserv.* 24, 727–729.
- Zulian, Viviane, Miller, David A.W., Ferraz, Gonçalo, 2021. Integrating citizen-science and planned-survey data improves species distribution estimates. *Divers. Distrib.* 27, 2498–2509.