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Risk of bird electrocution in power lines: a framework for prioritizing species and areas for conservation and impact mitigation

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Abstract

Electrocution on power lines is an important human-related cause of bird mortality and an important conservation issue worldwide. Besides impacts on bird populations, electrocutions cause power outages, resulting in damage to power line network integrity. However, there is a general lack of knowledge on the risk of bird electrocution, especially in developing countries. Generating information over large scales without resorting to local mortality data can be useful for the development of regional management strategies, particularly in countries where electrocution is poorly documented. Here, we developed a framework to model the risk of bird electrocution as an interaction between the species-specific exposure to power lines (pole density within a species distribution range) and susceptibility (morphological and behavioral traits associated with electrocution hazards). We applied this framework to Brazil, identifying 283 species that face a risk of electrocution, of which 38 were classified as higher risk, mostly raptors (76%). The Pantanal (a large wetland biome) concentrates the greatest cumulative susceptibility due to the high number of species vulnerable to electrocution (i.e. large species using power lines for perching or nesting), while the Atlantic Forest region has a higher risk for electrocution, due to the spatial overlap between the presence of vulnerable species and high exposure to power lines. Furthermore, our study identified spatial patterns of bird electrocution, highlighting priority areas for electrocution susceptibility and electrocution risk to be further investigated, and where measures to mitigate bird electrocutions should be applied on new and existing power lines. Our framework allows a preliminary assessment aimed at identifying areas of higher risk of electrocution, to highlight species vulnerable to this threat and to improve power line routing. This approach can be replicated to other understudied areas of the world where the same information is available.

Introduction

Access to electricity is essential to meet basic human needs, boost economic growth and foster development. Today, almost all regions of the globe are crossed by transmission networks, which are continually expanding to underserved regions (Jenkins, Smallie & Diamond, 2010). However, despite their benefits to humans, power lines can pose a serious threat to birds by causing direct mortality due to collision with wires and electrocution (Bernardino *et al*., 2018; Biasotto & Kindel, 2018; D'Amico *et al*., 2018). Such mortality can have negative effects on population dynamics and demography, thus potentially affecting the persistence of species over time. Population-level impacts caused by power lines have been demonstrated, for example, for the Cape vulture *Gyps coprotheres* (Boshoff *et al*., 2011), Bonelli's eagle *Aquila fasciata* (Hernández-Matías *et al*., 2015) and Ludwig's bustard *Neotis ludwigii* (Shaw *et al*., 2015), and for a number of other raptor species as reviewed by Slater, Dwyer & Murgatroyd (2020). Bird electrocutions may also affect human populations, as they can cause power outages (Burgio, Rubega & Sustaita, 2014; Reed *et al*., 2014) and wildfire ignitions (Guil *et al*., 2018), resulting in economic losses for companies and customers (Maricato *et al*., 2016). Thus, assessing the risk of bird electrocution is relevant from both biodiversity conservation and economic perspective.

Identifying both species and areas most prone to electrocution events is essential to mitigate the impacts of existing power lines and to improve the planning of new energy corridors. However, the systematic collection of bird-electrocution data along power lines has been primarily performed at a local scale, and mainly for the identification of high-risk structures (Tintó, Real & Mañosa, 2010; Guil *et al*., 2011; Dixon *et al*., 2017). Upscaling these surveys from the local scale to larger management areas (at the regional or country level) can be difficult to achieve due to the high amount of resources and time required. The alternative of multiple surveys conducted on a local scale, if not coordinated, may fail to identify where mitigation and conservation efforts are most needed by overlooking areas and species with higher electrocution risk (Dwyer *et al*., 2016). Therefore, generating sound information at large scales without performing extensive fieldwork would be highly useful for identifying those areas where to develop site-based management strategies (D'Amico *et al*., 2019). This can be particularly important in countries where electrocution events are poorly documented and where power line grids are expanding rapidly (Eccleston & Harness, 2018).

Here, we suggest a framework for an initial risk assessment, at a large scale, using already available data on bird species and power line networks. The framework is based on the combination of two types of species-specific information, namely exposure to power lines and susceptibility to electrocution which, when combined, provide an integrated measure of the electrocution risk (Fig. 1). Exposure is defined as the likelihood for the individuals of a target species to encounter an electric pole and is assumed to increase proportionally with increasing pole density (Dwyer *et al*., 2016). That is, when a species inhabits a geographic range with a high pole density, that species has high overall exposure, and consequently the probability of electrocution occurring increases (Dwyer *et al*., 2020). Species susceptibility to electrocution is mainly influenced by intrinsic behavioral and morphological traits (Bevanger, 1998; Janss, 2000). Birds using power line structures as poles and wires for perching (Prather & Messmer, 2010) and nesting (Morelli *et al*., 2014; Moreira *et al*., 2018) are supposed to be more susceptible. Susceptibility also increases with body size (Dwyer *et al*., 2015), as electrocution occurs when a bird simultaneously touches two-phase conductors or one conductor and a ground wire device on a pole (Janss, 2000). Similar frameworks estimating risk as a combination of exposure and susceptibility have been previously proposed to address other impacts related to linear infrastructures, such as roadkills (Visintin, van der Ree & McCarthy, 2016; Morelli, Benedetti & Delgado, 2020) and collision with power lines (D'Amico *et al*., 2019).

Our framework allows a preliminary assessment of potential electrocution risk for whole bird communities over broad geographic scales (regional to continental, but potentially also applicable at a global scale). We applied this framework to Brazil, the largest megadiverse country, and for which no specific study or standardized assessment of bird electrocution has been conducted to date. With rare exceptions, bird electrocution has been largely neglected in the Neotropics (Galmes *et al*., 2017). In Brazil, all information consists of a few published casualty records and some anecdotal reports available in the scientific or gray literature. However, the country has a high species richness in taxonomic or functional groups known to be affected by electrocutions elsewhere, and there is no reason to suspect that such casualties do not occur in a similar way in Brazil. Electrocution also represents a threat to mammals, a group for which fatality events are far better documented in Brazil (Lokschin *et al*., 2007; Correa *et al*., 2018). Together, this evidence suggests that bird electrocution, although currently underreported, is a real issue that potentially affects many species in Brazil. Therefore, it is necessary to increase our ability to understand potential electrocution risk patterns across Brazilian regions. Here, we aimed to answer the following questions: (1) How is the overall bird susceptibility to electrocution spatially distributed? (2) How is the potential overall risk of bird electrocution spatially distributed? (3) Which species may face a higher risk of electrocution and, therefore, should receive special attention for conservation and mitigation?

Materials and methods

Study area

Brazil has a large land area (>8.5 M km^2), about half of South America. Both human population growth and urbanization rates are unevenly distributed across the country and demand an extensive and growing energy network (MME, 2019). Thousands of kilometers of power lines traverse the six Brazilian biomes (Fig. 2), regions with distinct environments defined according to the prevailing climate and vegetation type: Amazon (tropical rainforests), Atlantic Forest (coastal rainforests), Caatinga (seasonally dry forests), Cerrado (tropical savannas), Pampa (subtropical/temperate grasslands) and Pantanal (tropical wetlands) (IBGE, 2019). This environmental heterogeneity affords an exceptional diversity of birds, accounting for almost 20% of the world's bird species richness (Jetz, Thomas & Joy, 2012).

Power line information

We used the georeferenced database on the distribution of poles at the country level (updated through November 2018)

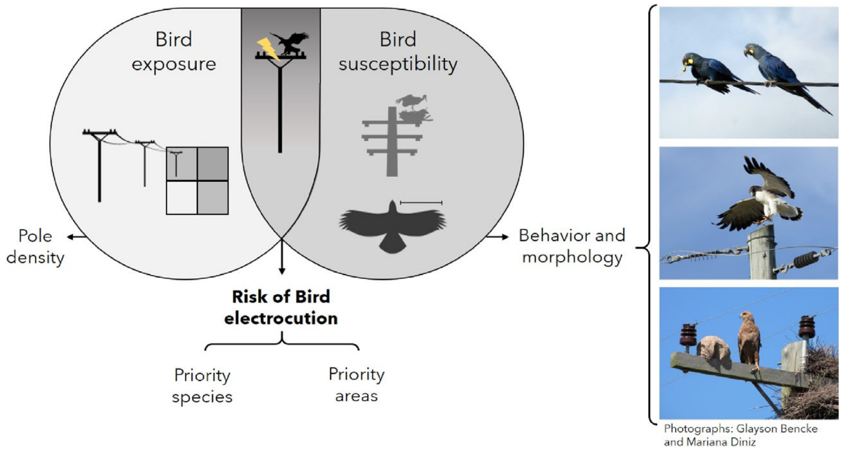

Figure 1 A general framework to assess the risk of bird electrocutions. Exposure is measured as the density of electrical infrastructure within the species distribution and susceptibility is related to the morphological and behavioral traits associated with a higher risk of electrocution. This approach allows identifying species and areas with higher electrocution risk.

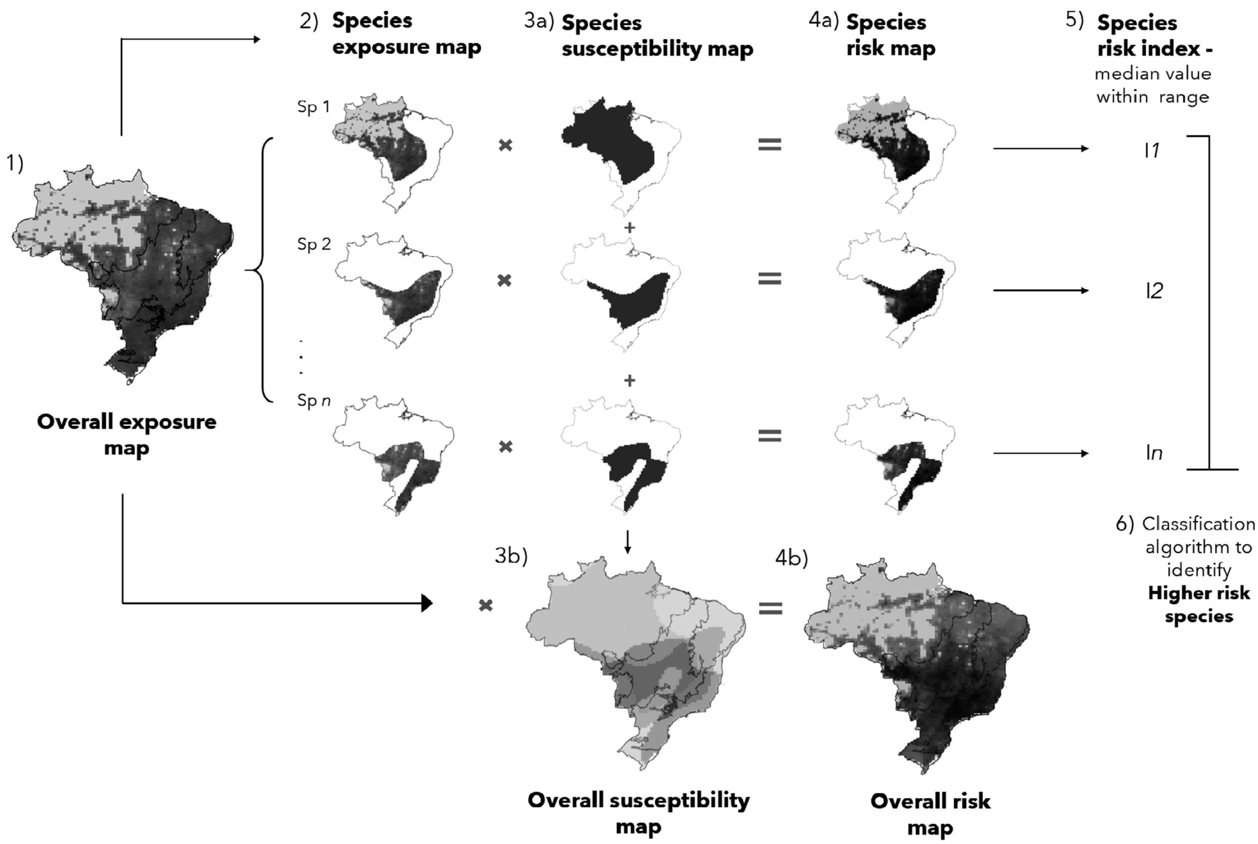

Figure 2 Workflow to identify target species and areas for bird electrocution prevention/control in eight steps. (1) Identification of geographic areas with high pole density – overall exposure map. (2) Obtaining species-specific exposure maps by overlaying the species distribution areas with the overall exposure map. (3a) Insertion of the wing-length value in the raster maps of the species distribution to generate the species-specific susceptibility maps. (3b) Cumulative map of susceptibility by summing up all species-specific susceptibility maps. (4a) Species risk maps obtained by multiplying species-specific susceptibility and exposure maps. (4b) Identification of areas with higher risk of bird electrocution by multiplying the overall exposure and overall susceptibility maps. (5) Extraction of median value within species risk maps. (6) Identification of higher-risk species.

available from the Brazilian Electricity Regulatory Agency (ANEEL). We selected structures from medium-voltage power lines (1–44 kV, n = 30 665 490 poles) as these are the most likely to cause bird electrocutions, because the distance between the electrical components (wire-wire and pole-wire) matches the wingspan of several bird species (APLIC, 2006; Lehman, Kennedy & Savidge, 2007; Eccleston & Harness, 2018). Throughout the text, we apply the term 'pole' to designate all the structures used to support medium-voltage power lines in Brazil, regardless of their material or specific configuration, as there is no information available that allows us to explicitly distinguish between the different structures (such as wood poles or pylons).

Bird species information

We used the spatial data available from BirdLife International and Handbook of the Birds of the World (www.birdlife.org/datazone; BirdLife v10, 2017) to obtain georeferenced polygons corresponding to the geographic range of each species. We excluded marine, insular, extinct and vagrant species according to the latest checklist of Brazilian birds published by the Brazilian Ornithological Records Committee – CBRO (de Piacentini, 2015). We reconciled the BirdLife and CBRO datasets for taxonomic inconsistencies (e.g. use of different scientific names for the same species or the adoption of divergent species limits for certain taxa). Whenever a species in BirdLife was treated as two or more distinct species on the CBRO checklist, we treated them as a single species in our analyses. This resulted in a working list of 1668 regularly occurring continental species (87% of the Brazilian species).

Wingspan is often selected as an indicator of morphological susceptibility to electrocution in birds (Bevanger, 1998), but it is not available for most Brazilian species. We used wing length as a proxy because this measure often represents the overall body size better than other univariate traits (e.g. Wiklund, 1996), and because it correlates well with wingspan in a wide variety of bird groups (see Supporting Information, Figure S1). For the species for which we could not obtain accurate wing-length data in the literature (n = 30, all passerines), we estimated missing values using a linear model relating 'wing length' ~ 'body length' (see Supporting Information, Figure S2).

To assess the behavioral susceptibility to electrocution, we classified each species according to its use of poles and wires for perching or nesting. First, we searched for evidence of perching or nesting on cables and poles in the online photographic archive of Brazilian birds WikiAves (www.wikiaves.com.br). This citizen-science platform currently encompasses over 3 million photographic records of Brazilian birds from all over the country. For each species, photographs were inspected until unequivocal evidence of perching and/or nesting on poles or wires was found (if any). This meant that, to be accepted, a record had to clearly show one or more individuals of the species perched on a power wire or pole, or with an active nest built on a pole or its associated structures (transformers, cable supports, etc.). To facilitate the search for images of nesting behavior, we filtered photographs with content 'nest' or main actions 'incubating', 'caring for/feeding offspring' or 'building nest' using the website built-in advanced search tool. For species poorly represented in the WikiAves database (e.g. rare or restricted-range species) and lacking evidence of the use of power line structures, the potential for perching/nesting on poles or wires was assessed by one of us (G.A.B) based on his extensive field experience with Brazilian birds and using evidence accumulated for phylogenetically related species sharing similar behavior and habitat preferences.

Modeling framework and analysis

The framework here proposed allows obtaining independent and complementary maps of susceptibility, exposure and risk as defined in Fig. 1. We used raster information with the same extent (Brazilian territory) and a 50 × 50 km resolution (n = 3419 cells). This resolution is suitable for our purposes since 76% of the 98 Brazilian energy companies manage areas larger than 2500 km² (equivalent to our pixel of 50 × 50 km). In addition, this resolution is recommended for continental or broad-scale analysis (Hawkins, Rueda & Rodríguez, 2008). Therefore, it can be assumed as an appropriate scale for regional mitigation planning and management. We conducted the analyses at the biome level because each Brazilian biome contains a distinct bird assemblage and has unique drivers affecting biodiversity (Souza *et al*., 2020). These drivers (land-use and land-cover changes) directly influence the rates of urbanization and expansion of the energy network. There are also several legal and conservation planning instruments that have been developed and/or are applied at the biome level and need to be complied by energy companies. The delimitation of Brazilian biomes followed IBGE (2019).

We started by building an overall exposure map based on the electricity pole distribution at the country level (see Power line information section), described as the density of medium voltage poles per unit area (50 × 50 km grid cell or km²) (Fig. 2, step 1). The value of pole density was log transformed to reduce the importance of the few cells containing very large urban areas and correspondingly very high pole densities. We derived species-specific exposure maps (Fig. 2, step 2) for the subset of behaviorally susceptible species (i.e. those species identified as using cables and/or poles; see Bird species information section) by clipping the overall exposure map with the polygon of distribution of each species.

Similarly, we built species-specific susceptibility maps (Fig. 2, step 3A) by using the wing length (in mm) as a susceptibility indicator and assigning this value to each pixel of each individual species map. We then obtained the overall susceptibility map for Brazil by summing all species-specific susceptibility maps (Fig. 2, step 3B). We chose to work with the cumulative susceptibility because we assume that all species using power line structures have some risk of electrocution, even the small ones. Thus, this metric indicates the accumulated susceptibility for each pixel, considering only those species that use power line structures. From this overall susceptibility map, we estimated the median value of susceptibility for each biome.

Using these information layers, we further derived species-specific maps of electrocution risk by multiplying the species morphological susceptibility (i.e. wing length) and exposure maps (Fig. 2, step 4A). To obtain the map of overall electrocution risk in Brazil (Fig. 2, step 4B), we multiplied the overall exposure map by the overall susceptibility map, from which we also extracted the median risk for each biome. The species-specific maps of electrocution risk were used to rank species according to their median risk (within their respective distribution ranges) (Fig. 2, step 5). To identify the subset of species potentially most affected by electrocution (i.e. with higher median risk values), we split the ranking into different classes using the method proposed by Jiang (2013) for data with heavy-tailed distributions. The method partitions the class intervals and so establishes the number of classes through an iterative multistep approach. The first step splits data values around the mean into two parts (head and tail); the next step splits the above-average values again into head and tail by the new mean, and so on until the head values are no longer heavy-tailed. Each mean corresponds to the upper limit of a class. This approach resulted in three classes, interpreted by us as species with 'higher', 'intermediate' and 'lower' electrocution risk, respectively (Fig. 2, step 6). We used this objective classification to reduce arbitrariness in the assignment of classes, as we do not have data to establish a clear relationship between risk level and priority level, which should ideally be defined on a local or case-by-case basis. We considered higher-risk species to be of greatest concern for conservation and mitigation actions at the national scale.

Finally, the overall exposure map, the species-specific maps, and the final susceptibility map were normalized to 0–1 values according to the minimum and maximum values in each map, with 0 being assigned to the grid cells with the lowest observed value and 1 to the grid cells with the highest observed value. This facilitates comparisons since all maps are on the same scale and ensured that the values of the input maps (exposure and susceptibility) had equal weights when multiplied to produce the risk map. We performed all spatial analyses in R environment (R Core Team, 2020) and the R packages 'sf' (Pebesma, 2018), 'fasterize' (Ross, Sumner & Al, 2020), 'raster' (Hijmans & van Etten, 2020), 'classInt' (Bivand, 2020) and 'rgdal' (Bivand *et al.*, 2020). Map layouts were made using ArcGIS 10.3 (ESRI, 2015).

Results

Pole density across the country ranged from 0 to 260 poles/km^2 (Table 1). Extensive areas in the Amazon (more than half of the biome's land surface) and Pantanal, and a few areas in the Cerrado, had very low pole densities (Fig. 3a). The Atlantic Forest, Pampa, Caatinga and the rest of the Cerrado had considerably higher and more homogeneous pole densities (Fig. 3a).

Table 1 Pole density of medium voltage power lines (1–44 kV) in the six Brazilian biomes. Biomes are arranged by the median pole density

Biome	Range pole density/km²	Mean (±SD) pole density/km²	Median pole density/km²
Atlantic forest	0.5–259.8	13.1 ± 19.8	9.7
Pampa	0.5–68.3	6.0 ± 7.8	4.5
Caatinga	0.1–25	4.4 ± 3.3	3.6
Cerrado	0.0–63.8	3.8 ± 4.7	2.6
Pantanal	0.0–5.4	0.6 ± 1.0	0.1
Amazon	0.0–48.4	0.8 ± 2.3	0.0

We found direct evidence of the use of power lines for perching and/or nesting for 242 bird species, and we further identified another 41 species that potentially use power line structures, totaling 283 species (Supporting Information, Table S1). Pantanal was the biome with the highest cumulative bird susceptibility to electrocution (Fig. 3b). Some areas of Cerrado adjacent to Pantanal also showed high cumulative susceptibility (Fig. 3b). At the other extreme, the Amazon showed the lowest median of cumulative susceptibility (Fig. 3b). The overall pattern does not change when only species with direct evidence of the use of power line structures are included in the analyses (242 species) (see Supporting Information, Figure S3). The Atlantic Forest showed the highest electrocution risk (median values), followed in order by Cerrado, Pantanal, Pampa, Caatinga and Amazon (Fig. 4).

We identified 38 species with higher electrocution risk (13% of the analyzed species) (Fig. 5), having a median risk ranging between 0.25 and 0.57. Most of the higher risk species were raptors (76%). The three species with the highest risk values were the jabiru *Jabiru mycteria* (a very large stork), the black-chested buzzard-eagle *Geranoetus melanoleucus* and the crowned eagle *Urubitinga coronata*. The risk within each species range was highly variable across species, but some species such as the black-chested buzzard-eagle and the crowned eagle had a small interquartile range over high-risk values, denoting a high pole density across their entire distribution ranges (Fig. 5). Of the remaining species, 51 were classified as 'intermediate risk' (18%; 0.10–0.25) and 194 as 'lower risk' (67%; 0.00–0.10) (Supporting Information, Figure S4).

Discussion

Electrocution is probably one of the main causes of human-induced bird mortality (Loss, Will & Marra, 2015; Slater *et al.*, 2020), but for many regions in the world, there is still no information on the extent of this impact. We provided a framework that allows a preliminary assessment of the spatial distribution of bird exposure and susceptibility, which combined provide the potential risk of electrocution. The framework is based on available information, including the

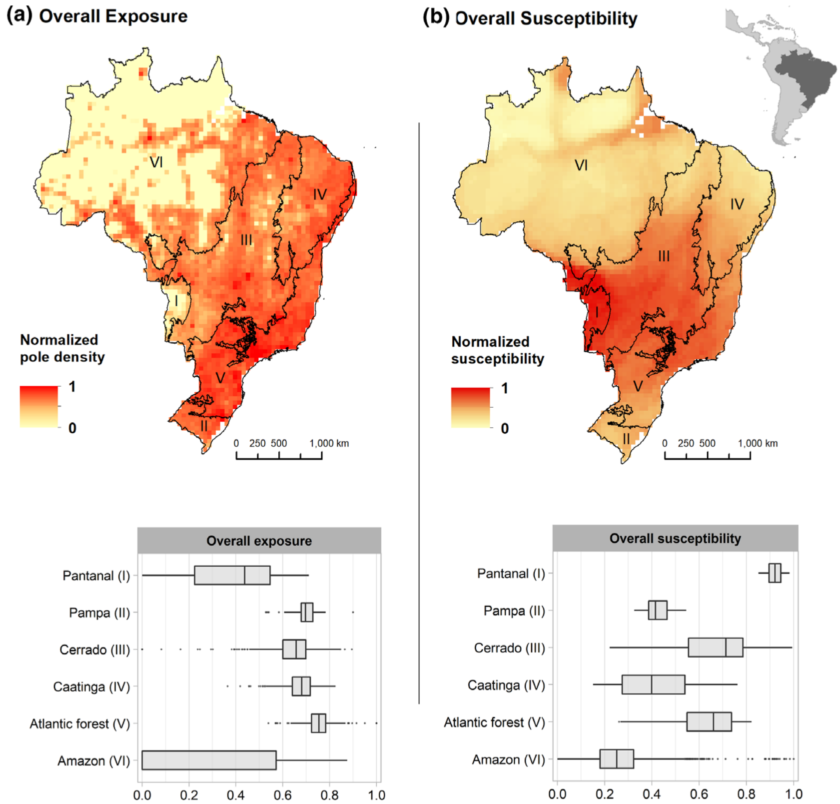

Figure 3 Summary results for exposure and susceptibility to electrocution, for 283 species with behavioral characteristics associated with a higher risk of electrocution: (a) overall exposure map based on pole density of medium voltage power lines (1–44 kV) (raw values of pole density were log transformed to reduce the high relative weight of a few areas in the Atlantic Forest, (see Table 1); (b) overall susceptibility map based on distribution area and wing length. In both panels, pixel values were normalized to a 0–1 scale. Boxplots represent the interquartile range (IQR; box), the median (vertical bar), the 1.5 × IQR interval (whiskers) and the outliers (dots).

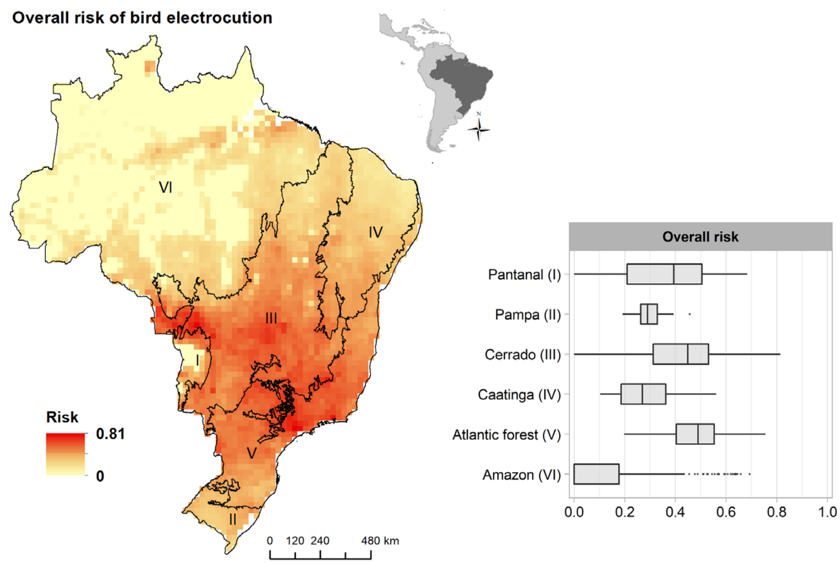

Figure 4 Overall risk of bird electrocution relating power pole density to bird susceptibility map. Boxplots represent the interquartile range (IQR; box), the median (vertical bar), the 1.5 × IQR interval (whiskers) and the outliers (dots).

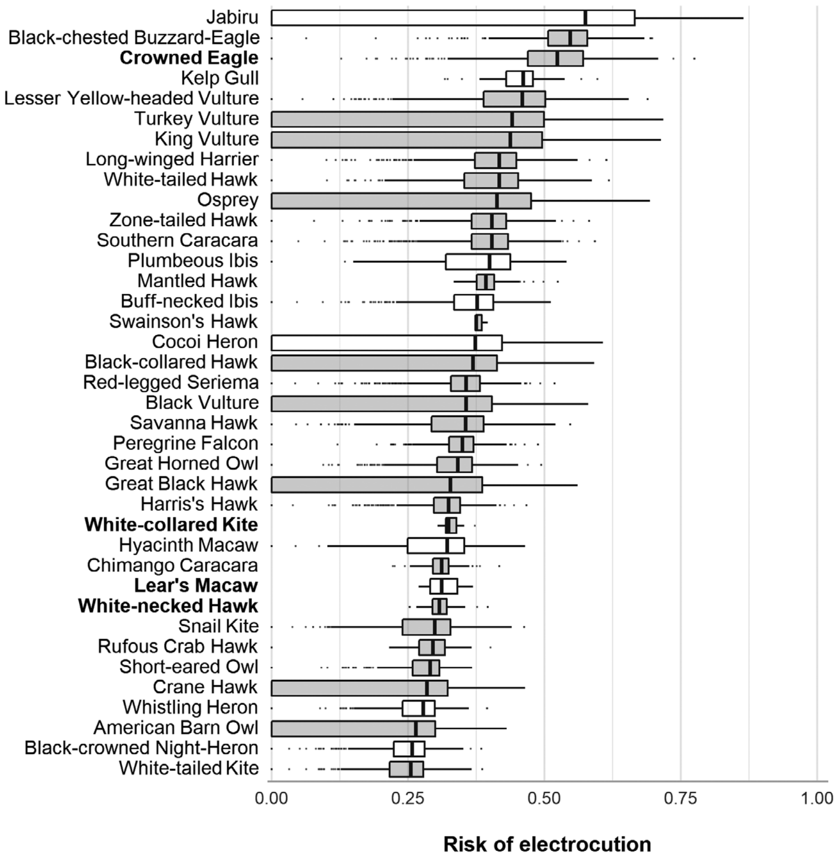

Figure 5 Variation in electrocution risk for 38 bird species with higher risk of electrocution. Boxplots represent the interquartile range (IQR; box), the median (vertical bar), the 1.5 × IQR interval (whiskers) and the outliers (dots). Gray boxes represent raptor species. Common names in bold represent globally threatened species according to the IUCN Red List of Threatened Species (BirdLife International, 2021).

density of electrical infrastructures within a species' range, and morphological and behavioral traits associated with a higher risk of electrocution.

The application of the framework to Brazil indicated the Atlantic Forest as the biome with the highest risk of bird electrocution, a condition resulting from a high pole density combined with a high number of susceptible species occurring therein. The Atlantic Forest concentrates more than 60% of the Brazilian human population (Scarano & Ceotto, 2015), so it is not surprising that it has the highest pole density (Ribeiro *et al*., 2009). The most cost-effective method to reduce bird electrocution in areas that already accommodate such a dense electrical network is the adoption of mitigation measures in strategic sites, including the retrofitting of wood poles (Dwyer, Harness & Eccleston, 2017) or pylons (Chevallier *et al*., 2015; Dixon et al., 2019) whose design poses a risk of electrocution. In areas classified as higher risk, under our framework, such as the Atlantic Forest, a more focused investigation can be applied to search for data on fatalities or power system failures assigned to electrocutions and to evaluate the relationship between landscape composition and electrocution events (e.g. Hernández-Matías *et al*., 2020). The pole location and configuration are important in determining the risk of mortality at the local scale (Mojica *et al*., 2018) and to inform the best mitigation interventions. Our approach indicates where electric companies and conservation biologists can focus their attention to perform detailed assessments aimed at identifying high-risk poles. For example, it is known that a combination of high pole density, prey abundance and few natural perches can increase electrocution risk for some raptor species (Pérez-García *et al*., 2011).

Our results also showed that the Pantanal and surrounding areas concentrate the highest cumulative susceptibility (i.e. the highest concentration of species vulnerable to electrocution). Although this biome and the Amazon currently experience high rates of agricultural expansion, they still have relatively few energy infrastructures (Souza *et al*., 2020), including power lines. However, the Pantanal can become a central area for future projects of infrastructure expansion that will connect the Amazon to central Brazilian regions (Hyde, Bohlman & Valle, 2018; Vilela *et al*., 2020). Our results indicate that the routing of new transmission lines through the Pantanal can lead to a significant increase in the risk of electrocution for susceptible species. Consequently, we recommend that these new facilities are carefully planned and, if it is not possible to avoid the most sensitive areas, the new power lines should at least be built with appropriate mitigation measures and considering the behavior and morphology of the most susceptible species.

Thirty-eight bird species were ranked as higher risk of electrocution in our study. Specific guidelines for protection against electrocution should be delineated for these species, which should further receive special attention during the environmental licensing of new power lines. We found that birds of prey predominate among our higher risk species. In particular, the globally threatened crowned eagle, white-collared kite *Leptodon forbesi* and white-necked hawk *Amadonastur lacernulatus* are of special concern because the electrocution of even a few individuals can potentially cause serious population-level impacts. Raptors are top predators and are well known for using cables and poles to perch (Slater *et al*., 2020). Overall, they have a delayed maturity, low fertility rates and smaller population sizes, thus electrocution events may have severe implications for their population dynamics and persistence over time (Eccleston & Harness, 2018; De Pascalis *et al*., 2020; Slater *et al*., 2020). In our ranking, the black-chested buzzard-eagle and the endangered crowned eagle occupied the top positions. These results are in line with studies performed in neighboring semiarid areas of central Argentina, where the former species accounts for numerous electrocution records (Ibarra & De Lucca, 2015) and the latter has been shown to be disproportionately affected by electrocution considering its low population density (Galmes *et al*., 2017; Sarasola, Galmes & Watts, 2020).

Likewise, parrots (order Psittaciformes), represented in our higher-risk class by the endangered lear's macaw *Anodorhynchus leari* and hyacinth macaw *Anodorhynchus hyacinthinus*, stand out for their curiosity and social behavior when interacting with power line structures (Seibert, 2006). They often peck the structures and interact closely with pole elements like jumpers and energized wires, and most commonly in small flocks. Galmes *et al*. (2017) reported two of the three species of parrots in Argentina as victims of electrocution, suggesting that this is indeed an important mortality factor for this group, at least in certain regions. In general, parrots are long-lived birds, and many species have naturally restricted ranges and are threatened with extinction (Berkunsky *et al*., 2017). We strongly recommend that particular attention be paid to these threatened macaws and parrots, for example by carefully considering the pole design to be used, ideally tailored for both raptors and for this group, since measures to mitigate the electrocution of raptors may not be sufficient or suitable for parrots.

Further developments of the framework

We acknowledge some limitations of our framework and reinforce that it should be considered a first approach to identify regions and species that need more attention and should be targeted for a more in-depth data collection process. We highlight some features that could be refined to improve the effectiveness of the framework.

First, some authors argue that the use of pole density as a single surrogate for bird exposure to electrocution can compromise the results because this approach ignores habitat availability and configuration in hazard pole arrangement (Pérez-García *et al*., 2017; Hernández-Lambraño, Sánchez-Agudo & Carbonell, 2018). In our study, we used pole density as a proxy for exposure to electrocution because there is no systematic information on electrocution hazards for any part of the Brazilian territory (and for many other countries), thus preventing approaches that identify the most problematic pole configurations. Yet, it has been shown that the probability of electrocution increases with pole density (Guil *et al*., 2011, 2015; Dwyer *et al*., 2020). We strongly recommended that future replications of our framework include information about pole/pylon configuration whenever available, in order to refine the electrocution risk as it is influenced by grounding, pole and crossarms material, conductor and wire arrangement, insulators, exposed jumpers and other technical elements (Tintó *et al*., 2010; Dwyer *et al*., 2017).

Second, the use of the wing length and perching/nesting behaviors as the sole predictors of susceptibility may seem reductionist. These traits, however, can be easily obtained, allowing a preliminary assessment of a vast pool of species as ours, similarly to previous approaches that looked at the risk of bird collision with wires and wind turbines (Beston *et al*., 2016; Santangeli *et al*., 2018; D'Amico *et al*., 2019). Our framework also does not integrate information on species abundance, or species-specific patterns of frequency and temporal use of the infrastructures. Resident species, for example, can have higher temporal exposure to poles than migratory species. On the other hand, a migratory species that spends its non-breeding period in low-risk areas might at least theoretically be significantly affected if it passes through high-risk areas during migration. While the inclusion of such information would greatly improve the ability to identify higher risk areas at finer resolutions or with larger confidence, we currently have no information about these species' traits. However, this information may be available at smaller scales or for some target species or groups.

Third, although we have explicitly indicated species that should receive special attention, we recommend caution when interpreting the terms 'intermediate' and 'lower' risk, as our rating provides a value that can only be used for comparisons within our species pool. All 283 species analyzed face some risk of electrocution, due to their use of energy structures. Some smaller species, despite their size, show gregarious nesting behavior or build bulky nests of sticks. The monk parakeet *Myiopsitta monachus*, for example builds large communal nests that greatly increase the risk of electrocution and power outages (Burgio *et al*., 2014).

Fourth, we were unable to verify or validate our results because bird electrocutions are under-reported and understudied in Brazil. We hope that our results will stimulate hypothesis testing and encourage electrocution surveys aimed at higher-risk areas and species to further improve the framework. Finally, the grid resolution used here is rather coarse for mitigation planning and routing at local scales. For example, it is not appropriate to indicate the most suitable corridors for new power lines or to identify specific poles to be mitigated. However, our spatial scale is applicable for planning the expansion of the energy network, especially in countries where there is a long distance between the power plants and the main energy-consuming regions, such as Brazil (Cardoso Júnior, Magrini & da Hora, 2014). The outcomes of our framework can be 'fine-tuned' following a systematic process of data refinement. The bird distribution and pole configuration databases are key elements to be improved for fine-scale studies.

Conclusion

Our framework allows recognizing target regions and species to receive special attention in bird electrocution assessments, fostering win-win situations that will simultaneously prevent bird fatalities and power outages. We recommend refining the scale in higher-risk regions and for higher-risk species. The method proposed here can be replicated in any geographic area of the world where bird electrocutions are poorly studied and where information on birds and power lines is available.

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Authors' contributions

Conception and design were conducted by LB, FM, MD, AK and FA. Data collection was performed by LB and GAB. Data preparation and analysis were performed by LB and FA. The first draft of the paper was written by LB. All authors commented and critically reviewed this and subsequent versions of the paper. All authors read and approved the final paper.

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Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Linear regression model relating wingspan (dependent variable) and wing length (independent variable) for 129 species of Brazilian birds belonging to 36 taxonomic families.

Figure S2. Linear model relating bird wing length ~ body length measures.

Figure S3. Map of electrocution susceptibility for 242 species of Brazilian birds that had their use of poles or wires for perching or nesting confirmed by examination of WikiAves photographs.

Figure S4. Classes and class intervals of bird electrocution risk as defined by the application of the clustering algorithm scheme of Jiang (2013) for data with a heavy-tailed distribution.

Table S1. Information on susceptibility and risk of electrocution for 283 Brazilian bird species.