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RESEARCH ARTICLE

Mapping priority areas to mitigate the risk of electrocution of range-restricted bird species

Larissa D. Biasotto[1,2] | Andreas Kindel[2,3] | Erica C. Pacífico[4,5,6] | Thiago Filadelfo[5] | Fernanda R. Paschotto[5,7] | Gabriela R. Favoretto[5] | Antônio Emanuel E. A. Sousa[8] | Aldicir Scariot[9] | Fernando Ascensão[10]

[1]BirdLife International, Cambridge, UK; [2]Núcleo de Ecologia de Rodovias e Ferrovias, Departamento de Ecologia, Universidade Federal do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil; [3]Programa de Pós-graduação em Ecologia, Universidade Federal do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil; [4]Seção de Aves do Museu de Zoologia da Universidade de São Paulo, São Paulo, Brazil; [5]Lear's Macaw Research and Conservation Group, Bahia, Brazil; [6]Department of Animal Biology, State University of Campinas, São Paulo, Brazil; [7]Movement Ecology Laboratory, Department of Ecology, Postgraduate Program in Ecology, University of São Paulo, São Paulo, Brazil; [8]The Brazilian National Center for Bird Conservation and Research, Floresta, Paraíba, Brazil; [9]Ecology and Conservation Laboratory, Embrapa Genetic Resources and Biotechnology, Brasília, Distrito Federal, Brazil and [10]cE3c—Centre for Ecology, Evolution and Environmental Changes & CHANGE—Global Change and Sustainability Institute, Lisbon, Portugal

Correspondence
Larissa D. Biasotto
Email: larissa.biasotto@birdlife.org

Andreas Kindel
Email: andreaskindel@gmail.com

Erica C. Pacífico
Email: ericapacifico81@gmail.com

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Abstract

1. Power line electrocution is a major threat to bird conservation, particularly for some endangered species. While various mitigation measures have been developed to reduce electrocutions, there is limited information on how to prioritize their implementation for maximum cost-effectiveness. This gap is especially pronounced in remote, understudied areas and for species with restricted ranges, where systematic data is often lacking. Without such prioritization, financial resources risk being poorly allocated, potentially undermining conservation efforts. Cost-effective assessments are, therefore, essential to identify high-risk areas and guide mitigation efforts to where they will have the greatest impact.
2. We propose a framework to identify high-risk electrocution areas for prioritizing mitigation efforts. Our approach integrates the species' potential activity areas with the energy infrastructure hazard surface to produce a risk map, validated against known electrocution records. Additionally, we perform a cost–benefit analysis to determine the number of pylons that would need retrofitting to achieve specific reductions in electrocution events. As a case study, we used Lear's macaw, a range-restricted and endemic species from the Brazilian Caatinga, to illustrate the applicability of our framework.
3. For Lear's macaw, electrocution risk was unevenly distributed across the study area, with the central and southern portions of the energy grid identified as priorities for mitigation. Validation procedures confirmed that the risk map accurately represents electrocution risk. Our cost–benefit analysis revealed that retrofitting

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10% of pylons (approximately 37,000) could reduce known electrocution events by 80%.

4. *Synthesis and applications*. Our study proposes a framework to identify areas with higher electrocution risk, which can be used even in data-scarce regions or adapted to a multi-species assessment context. This approach can support proactive strategies for energy companies with an initial assessment identifying areas to avoid installing new power lines, evaluating sites for implementing mitigation reactive strategies, with optimal cost–benefit relation and guiding conservation projects by highlighting areas requiring in-depth investigation of electrocution risks and their impact on population dynamics.

KEYWORDS
bird conservation, cost–benefit analysis, energy grid, parrots, power lines, pylon retrofitting

1 | INTRODUCTION

The advancement of human development, driven by the need for reliable and widely accessible energy, is leading to the expansion of energy networks (Arderne et al., 2020). This expansion is set to accelerate in the coming years, especially in developing regions, with the International Energy Agency projecting that by 2040 over 80 million km of power lines—roughly equivalent to the current global grid length—will need to be installed or upgraded worldwide (IEA, 2023). Despite the expected benefits for humans, this grid expansion is anticipated to have significant impacts on biodiversity, most notably through bird collisions and electrocutions (Biasotto & Kindel, 2018; D'Amico et al., 2018). While the impacts of collisions have been more widely addressed in dedicated research, the description and mitigation of electrocution effects remain comparatively understudied, particularly for taxa other than raptors (Bernardino et al., 2018; Biasotto et al., 2021). Yet, electrocution on powerlines is expected to pose a serious threat to numerous species across biodiversity-rich regions (Ahmad & Zhang, 2020; Guil & Pérez-García, 2022; Rebolo-Ifrán et al., 2023). For some species, such as Bonelli's eagle (*Aquila fasciata*), even a few events of electrocution could deplete local populations (Hernández-Matías et al., 2015). Moreover, electrocution may cause extensive economic costs, such as power outages (Burgio et al., 2014), bushfires ignitions (Barnes et al., 2022; Guil et al., 2018) damage to energy infrastructure (Tena et al., 2010). Thus, identifying areas with a higher likelihood of bird electrocutions is essential, not only for biodiversity conservation but also from an economic perspective, especially in the context of the expected increase in the global grid development.

Bird electrocution generally occurs when an individual touches simultaneously two-phase conductors or a conductor and a grounded structure (Bevanger, 1994, 1998; Martín et al., 2022). For this reason, larger birds with larger wingspans are the most affected (Biasotto et al., 2021). For example, the populations of the Cape vulture (*Gyps coprotheres*) inhabiting areas with higher electrocution rates are significantly more vulnerable to extinction than other populations (Boshoff et al., 2011). However, other conditions may make birds more prone to electrocution (Biasotto et al., 2021). The type of pylons (e.g. different number of energy phases) used by different bird species may be a critical factor contributing to their varying susceptibility to electrocution. Likewise, species that spend extended periods on pylons, routinely nest there, or frequently interact with electrical components may face a higher risk of electrocution. A paradigmatic example is the psittacids, which are particularly vulnerable due to their unique behavioural traits and tendency to use pylons for perching and resting, and for playing and engaging in social interactions.

To mitigate the impact of electrocution, it is necessary to direct resources where they are most needed, that is, select grid section areas with a higher likelihood of electrocutions (Hernández-Matías et al., 2020; Tintó et al., 2010). However, mapping electrocution risk for species with small population sizes and restricted ranges (often the case of high conservation concern species) presents an added difficulty, particularly in remote and understudied areas (Hernández-Lambraño et al., 2018; Pérez-García et al., 2017). Additionally, mitigation efforts are typically applied to grid sections where electrocutions have already been recorded, reflecting a bottom-up approach (see Dwyer et al., 2020). However, fatality records are likely underestimated due to biases in carcass persistence and survey efficiency (Barrientos et al., 2018), and because data sources—including citizen science contributions—are neither randomly nor systematically distributed across space and time (Bernardino et al., 2020; Borner et al., 2017). This lack of information exacerbates the problem by limiting decision-makers' awareness of electrocution risks and further hindering the identification of high-risk areas where targeted mitigation could be most effective. Therefore, the key challenge is predicting where electrocutions are most likely to occur, especially for species of conservation concern and regions with limited or scarce data.

We propose a top-down framework to assess electrocution risk and identify priority areas for mitigation (Figure 1). Our approach

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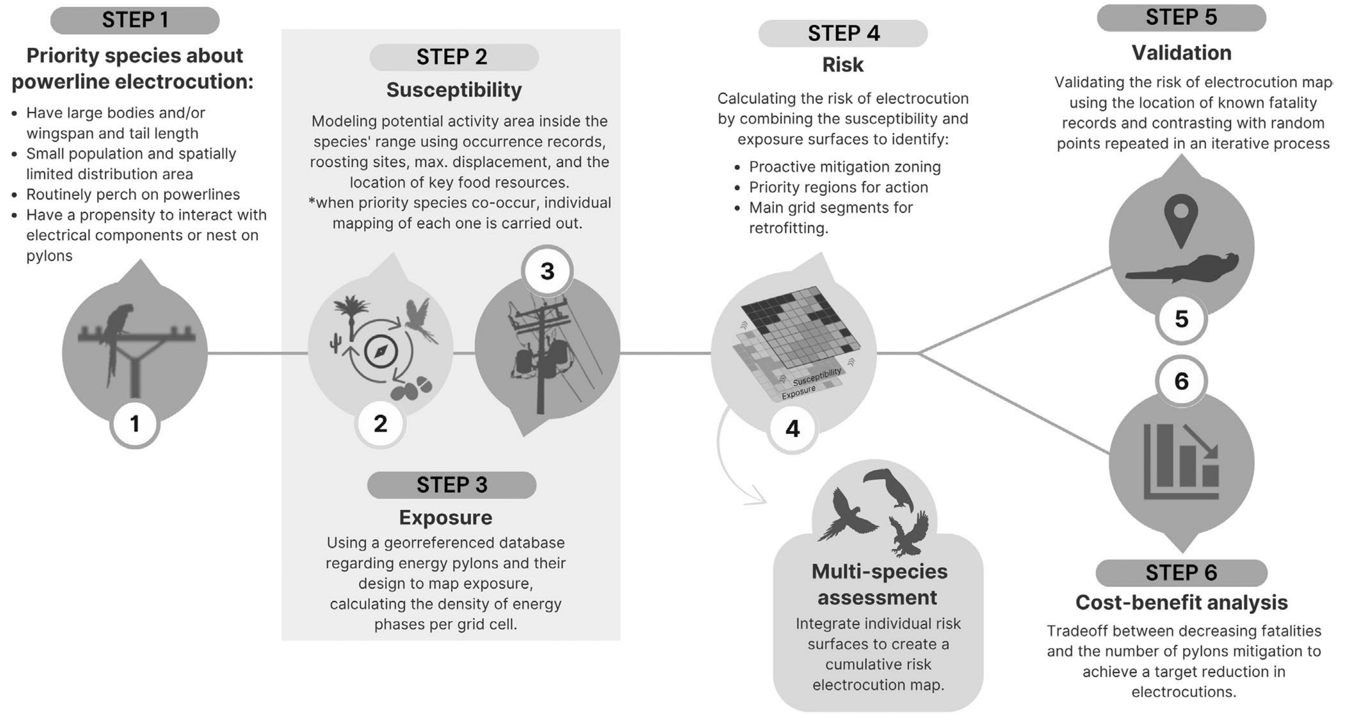

FIGURE 1 Workflow illustrating the top-down approach for identifying priority mitigation areas to reduce bird electrocution. The process begins with the prior identification of priority species (STEP 1), followed by modelling the species' potential activity area to generate a susceptibility surface (STEP 2). Next, the pole density within the species' range or planning territory is mapped to represent exposure (STEP 3). The risk of electrocution surface is then created by combining susceptibility and exposure (STEP 4) and validated using known fatality records (STEP 5). Finally, a cost–benefit analysis is conducted to compare the effectiveness of different levels of pylon mitigation in reducing electrocutions (STEP 6). Although not executed in this study, when multiple priority species co-occur, this framework can be adapted for a multi-species assessment by individually modelling the potential activity areas (STEP 2) and integrating the resulting surfaces after STEP 4.

is grounded in previous research and operates under the premise that the risk of a species being affected by linear infrastructure stems from the interplay between the species' exposure to such infrastructure and their susceptibility to its impacts (Ascensão et al., 2022; Biasotto et al., 2021; Visintin et al., 2016). We further assumed that, within a given area, the risk of electrocution increases with the amount of time birds spend there (e.g. foraging). In this framework, the first step (see Figure 1) is to select the focal species. Here, we apply the framework to the psittacid Lear's macaw (*Anodorhynchus leari*), a threatened species that routinely interacts with power pylons but for which limited spatial data are available. Based on previous research, we considered that Lear's macaw activity is intimately related to the distribution of its main food resource, the licuri palm *Syagrus coronata*, and within proximity to roosts (Biasotto et al., 2022). As such, we generated a map of the potential activity area for the Lear's macaw, using the best available data on observation records, roosting sites, maximum displacement distances and the distribution of licuri palm (STEP 2). This activity layer (susceptibility) was then overlaid with pylon density data representing the exposure (STEP 3) to assess the potential electrocution risk (STEP 4). We then validated the predicted electrocution risk across the study area using locations where Lear's macaw electrocutions had been previously documented (STEP 5). We further conducted a cost–benefit analysis to determine the number of pylons needing mitigation to achieve different levels of reduction in electrocution events and allow for the identification of a target level (STEP 6). While our study focuses on Lear's macaw as a case study, the framework we propose is inherently scalable and adaptable. Specifically, it can be extended to multiple species by integrating species-specific susceptibility surfaces (derived from activity ranges or habitat models) into a composite, multi-species risk surface.

Our framework allows transitioning from broad-scale assessments that identify priority species (see Biasotto et al., 2021) and general electrocution risks to more targeted mitigation planning for a particular management unit of interest (e.g. species range, jurisdictional limits and energy companies grid). The resulting risk map information can help pinpoint areas where mitigation measures, such as pylon retrofitting, are most urgently needed. By focusing on the most hazardous sections of the grid, we can enhance cost-effectiveness, avoiding the need to address larger but less critical areas. As such, this study can serve as a model for proactive mitigation zoning, providing a framework that can be adapted to protect other species at risk of electrocution and contribute to safeguarding their populations.

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2 | METHODS

2.1 | The focal species—Lear's macaw

The Lear's macaw is a large-bodied parrot, endemic to Brazil's Caatinga Ecoregion and classified as globally endangered (Biasotto et al., 2022; HBW and BirdLife International, 2024). The species' primary population is located in the Raso da Catarina region (see Figure 2a) and seems to have been increasing (Barbosa & Tella, 2019). Another isolated small population has been dependent on a reintroduction project to persist at the Boqueirão da Onça area (BDO), 230 km west of the Raso da Catarina region (E. C. Pacifico, T. Filadelfo, F. R. Paschotto, G. Favoretto & T. S. Andrade, unpubl. data).

The population persistence of Lear's macaw remains at risk due to the loss of nesting sites and foraging habitats, which pose serious threats to its long-term survival (Pacífico, 2020). In particular, land use changes have reduced the availability of the licuri palm (Matt Becc.), whose fruits are a crucial food source for the species (de Lima et al., 2023; Silva-Neto et al., 2012). Additionally, electrocution is suspected to pose a severe threat, potentially undermining ongoing conservation efforts aimed at the recovery of this species (Biasotto et al., 2022). Electrocutions have been reported for the species since 2005; it seems to be increasing (Biasotto et al., 2022). Observations suggest that electrocutions primarily occur on pylons located within or near licuri palm patches, as the macaws often use power line structures to rest and feed after collecting fruits (Biasotto et al., 2022) (see Figure 2). Furthermore, this species often exhibits intense social behaviours on these structures, including probing and pecking various pylon components. Due to the scarcity of tall trees in the Caatinga shrubby-dominated vegetation (da Silva et al., 2017), the macaws possibly choose power lines as their highest perch for surveillance. Observations have documented over 40 individuals simultaneously perched on cables near a single pole. This interaction was recognized as a new and worrisome threat to Lear's macaw, making the pylon retrofit an urgent action for species conservation (Biasotto et al., 2022; ICMBio No 1.546, 2024).

2.2 | Study area

Our study region encompasses the Raso da Catarina region area, hosting the single largest population of Lear's macaw (Figure 2a), where the electrocution records have been registered. This region is characterized by semi-arid vegetation comprising a mosaic of different woody plant densities (da Silva et al., 2017). The Caatinga has a high interannual variability in rainfall, and droughts in the area can last for years. Yet, this region is threatened mainly

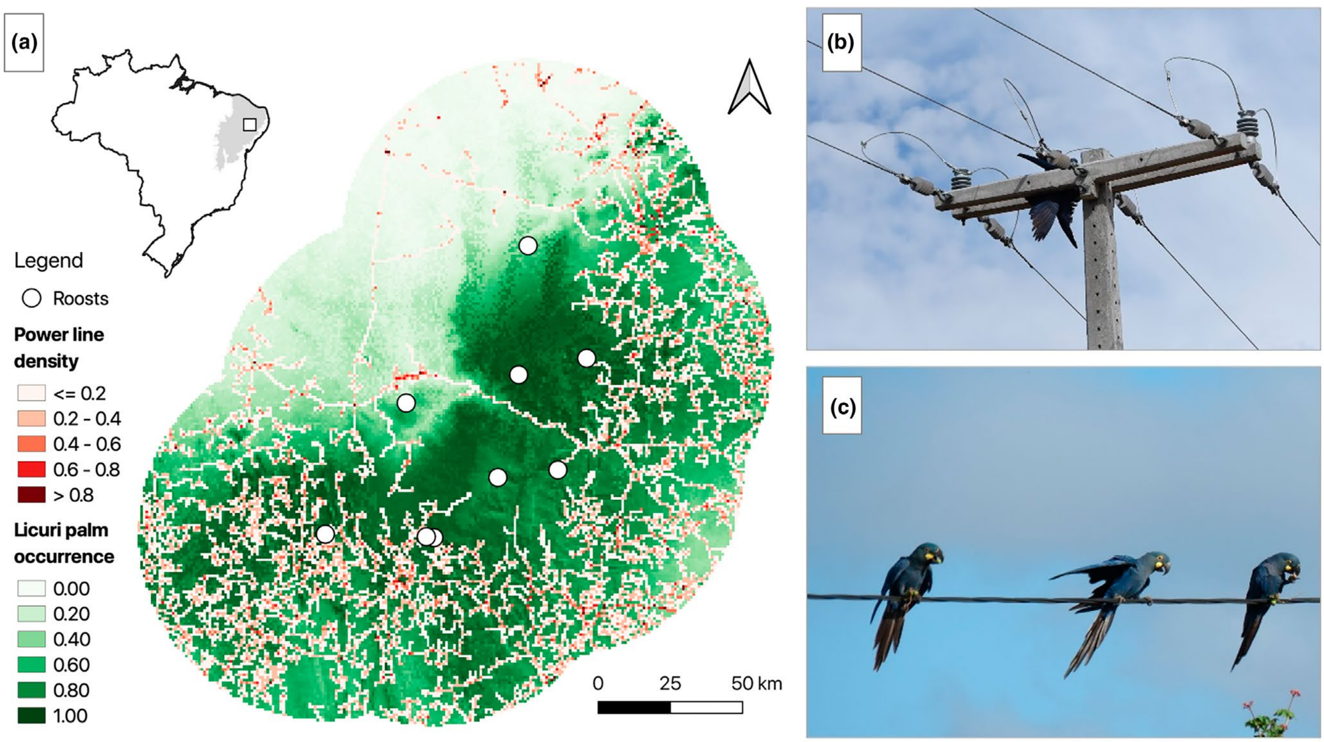

FIGURE 2 (a) Location of the study area where we assessed the risk of electrocution for Lear's macaw (*Anodorhynchus leari*), corresponding to the Raso da Catarina region (square in the inset) within the Brazilian Caatinga (light grey area). Within the study area, the background shows the probability of occurrence of licuri palm (*Syagrus coronata*) (obtained from de Lima et al., 2020) as a green gradient. Power line phase density is shown in red gradient. White circles represent Lear's macaw roost sites. (b) Example of a medium-voltage pylon (<13.9 kV) with an electrocuted individual of Lear's macaw (© Thiago Filadelfo). (c) A group of Lear's macaws perching on electric cables while feeding on licuri palm fruits (© Mariana Diniz).

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by the expansion of agriculture, farming and illegal charcoal production, experiencing intensive land use changes that have led to desertification in different areas (Acosta Salvatierra et al., 2017; Schulz et al., 2018). We defined the study area as the region within 65 km of known roosting sites (Figure 2a). This distance was chosen because it represents the maximum daily movement documented in the National Action Plan for the Conservation of the Lear's macaw (ICMBio, 2012) and aligns with the furthest occurrence point from the nearest roosting site in our dataset (see below).

2.3 | Data collection

For Lear's macaw occurrence, we used the information from the ongoing population monitoring carried out by Lear's Macaw Research and Conservation Group and the Chico Mendes Institute for Biodiversity Conservation (CEMAVE–ICMBio). This initiative has mapped 1712 sights of Lear's macaw (live observations), as well as the location of nine known communal roosting sites (Figure 2a). Until this date, a conservation plan has also compiled data on Lear's macaw potential electrocutions, collected opportunistically between 2005 and 2022, totalling 78 individuals. These records are primarily reported by local citizens, which sometimes leads to uncertainty regarding the exact location of each casualty. Therefore, we used 63 fatality events with a reported location accuracy of less than 100 m, as we considered these records to have low uncertainty about the electrocution site (considering the resolution to be used in analyses, 1 × 1 km, see below).

The distribution of licuri palm was obtained from de Lima et al. (2020), who modelled the potential distribution of this palm tree using climatic and topographic variables. This model demonstrated a very good predictive performance for both training and test data, with low omission error and significantly better-than-random test point predictions ($p > 0.01$); an AUC value above 0.9 indicated a strong fit between predicted distribution and presence points; and external validation also showed high sensitivity and accuracy, with a TSS value of 0.56, confirming performance above random (de Lima et al., 2020). Although the model's relatively low resolution (1 × 1 km) may limit more detailed spatial analysis, it provides the best available data on licuri palm occurrence. Given the importance of licuri palm fruit as a key resource for Lear's macaw, we chose to use this model to predict macaw occurrence. Consequently, the resolution of subsequent analyses aligns with this layer (1 × 1 km) (Figure 2a).

As for power line information, we utilized the georeferenced database provided by the Brazilian Electricity Regulatory Agency (ANEEL) of medium-voltage infrastructures (<13.9 kV), totalling 243,285 pylons within our study area (Figure 2b). These voltage levels were selected as they are the most associated with bird electrocutions (Eccleston & Harness, 2018). In these lines, the distances between electrified components (such as cable-cable, pole-cable, jumper-cable and transformers-cable) of the considered distribution grid are typically smaller than or equivalent to the wingspan and body measures of Lear's macaw (wingspan ~100 cm, wing length ~38 cm and tail length ~40 cm—Tobias et al. (2022); and body length ~75 cm—Sick et al., 1987). For each pylon, we obtained the number of energy phases (cables), as a higher number of cables is related to a higher risk of electrocution (Tintó et al., 2010). We then computed the density of energy phases per grid cell, using the same resolution (1 × 1 km). The density of energy phases was log-transformed to reduce the importance of the cells containing very high phase densities in peri-urban areas. Finally, we scaled the layer to range between 0 and 1 (Figure 2a).

2.4 | Data analyses

2.4.1 | Mapping the potential activity of Lear's macaw

We employed the MAXENT (Maximum Entropy) software (Phillips et al., 2006; Phillips & Dudík, 2007) to predict the potential activity of Lear's macaw within our study area, assuming that a higher likelihood of occurrence is correlated to higher movement activity, namely for foraging. The model was built using the environmental predictors distance to the main roost sites and the potential distribution of licuri palm (both at 1 × 1 km resolution), and non-duplicated occurrence records of Lear's macaw (277 unique grid cells). We removed the main urban centres from our study area as Lear's macaw avoids perching in these areas. We included a sampling bias layer to account for bias in species reporting (Phillips et al., 2009; Syfert et al., 2013), as some regions have very few or no records from this species, potentially due to issues relating to accessibility, for example, distance from roads or terrain conditions. The sampling bias was built using a Gaussian kernel density map of Lear's macaw sights with the 'kde2d' function of the R package MASS (Venables & Ripley, 2002).

We used bootstrapping to evaluate the MAXENT model outputs, with 10 replicates and 20% of the dataset left to test the models. The AUC of the receiver operating characteristics was taken as a measure of the overall fit of the models. The AUC ranges from 0 to 1, where the maximum score of 1 represents perfect discrimination and a medium score of 0.5 represents random predictive discrimination (Phillips et al., 2006). Variable importance was measured using the per cent contribution values from MAXENT outputs (Phillips et al., 2006).

2.4.2 | Assessing the risk of electrocution

Electrocution risk was calculated by multiplying the energy phase density layer with the potential activity surface, assuming that risk increases with higher species activity and greater exposure to electrocution hazards. Theoretically, risk values range from nearly 0, where the probability of occurrence and/or pylon density are very low, to 1, where both are at their maximum. We calculated the median and 25%–75% quantiles of electrocution risk for each county

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with confirmed and potential Lear's macaw occurrence (Biasotto et al., 2022).

2.4.3 | Model validation

We anticipated that, if the risk layer reliably represented electrocution risk, known electrocution records would be located in areas with higher estimated risk. Hence, for each known fatality location considered ($n=63$), we extracted the corresponding value from the risk layer. We then generated an equal number of random points across the risk surface (within the study area) and repeated this process 99 times, calculating the mean risk value for each iteration. We expected the mean risk from empirical records to be significantly higher than that of the iterations in at least 95% of cases.

2.4.4 | Cost–benefit assessment

We conducted a cost–benefit assessment to examine the relationship between the proportion of electrocutions that could be prevented by mitigating sections of the network with higher risk. This involved plotting the number of electrocutions per percentile of high-risk cells. For instance, we assessed what proportion of electrocutions could be avoided if one mitigated the top 1%, 5%, 10% and 20% of highest risk cells across the study region. Additionally, we quantified the number of pylons that would need retrofitting to achieve a given level of reduction in electrocution events.

3 | RESULTS

3.1 | Distribution of the Lear's macaw potential activity area

The MAXENT model presented good predictive performance for training and test data, with low omission error and a better prediction of test point distribution than by chance (minimum training presence probability; $p>0.01$). The AUC = 0.86 (SD = 0.01) indicated a high fit between the potential activity area and the points of presence used for the internal validation test (see Appendix S1). Both the distance to roosting areas and the potential presence of licuri made considerable contributions to the model, with the former contributing more substantially (85.5%) compared to the latter (14.5%) (see Appendix S1). Accordingly, the southern region of the study area showed a higher probability of Lear's macaw occurrence and, consequently, of increased activity (Figure S1.3).

3.2 | Risk of electrocution

The energy phase density varied significantly across the study area, from 0 to 279 phases per km^2 (see Appendix S2). The study area's central, northern and north-eastern sections had fewer medium-voltage lines than other municipalities. The risk layer ranged between 0 and 0.62, indicating that the areas with the highest pole density did not coincide with the areas of highest activity (Figure 3a). The validation procedure revealed that the risk layer provides a reliable representation of the electrocution occurrence (see Appendix S3). The locations of known electrocutions occurred in areas with higher risk values (Figure 3a). These areas with higher risk can be prioritized to implement mitigation areas (Figure 3b), and search on the ground for the most problematic pylons (e.g. Figure 3c). If thinking in jurisdictional management unities, the municipality of Euclides da Cunha had the highest median electrocution risk, followed by Canudos, Novo Triunfo and Jeremoabo (Figure 3d). However, the risk values showed considerable variation within each municipality's territory (Figure 3a,d).

3.3 | Cost–benefit analysis

Our assessment indicated that mitigating the top 1% of high-risk grid cells could prevent around 35% of known electrocutions, requiring intervention on at least 5668 energy pylons. Recognizing that this may not fully safeguard future population viability, we also evaluated mitigating the top 5% of risky cells, which could prevent about 60% of known electrocutions by addressing 22,037 pylons (Figure 4). Expanding mitigation efforts to the top 10% and 20% of high-risk cells could reduce known electrocutions by more than 80% and up to 90%, requiring the retrofit of 37,412 and 63,966 pylons, respectively (Figure 4).

4 | DISCUSSION

Detailed knowledge about the impact of electrocution on birds and other wildlife remains limited, particularly for rare species and in remote regions. These knowledge gaps can hinder the implementation of targeted mitigation measures, the strategic planning of power line routes, and the integration of electrocution risks into broader conservation programmes. In this study, we propose an approach that requires relatively limited data to produce an initial electrocution risk assessment. It represents the first example of a zoomed-in, species-specific approach, using the Lear's macaw as a case study within its primary range. This approach is particularly relevant for developing countries such as Brazil, where the grid is expanding at a fast pace. For example, power line infrastructure in our study area has expanded by 30% over 6 years (2018–2023) (*authors' data*). Such encroachment of power lines will likely increase the risks to local biodiversity.

This approach can be easily applied to other species for which similar or surrogate primary information of hazard density and species activity, or abundance is available. Importantly, different species can be integrated within the same analysis, allowing for the development of a multi-species model. Such assessments are urgently

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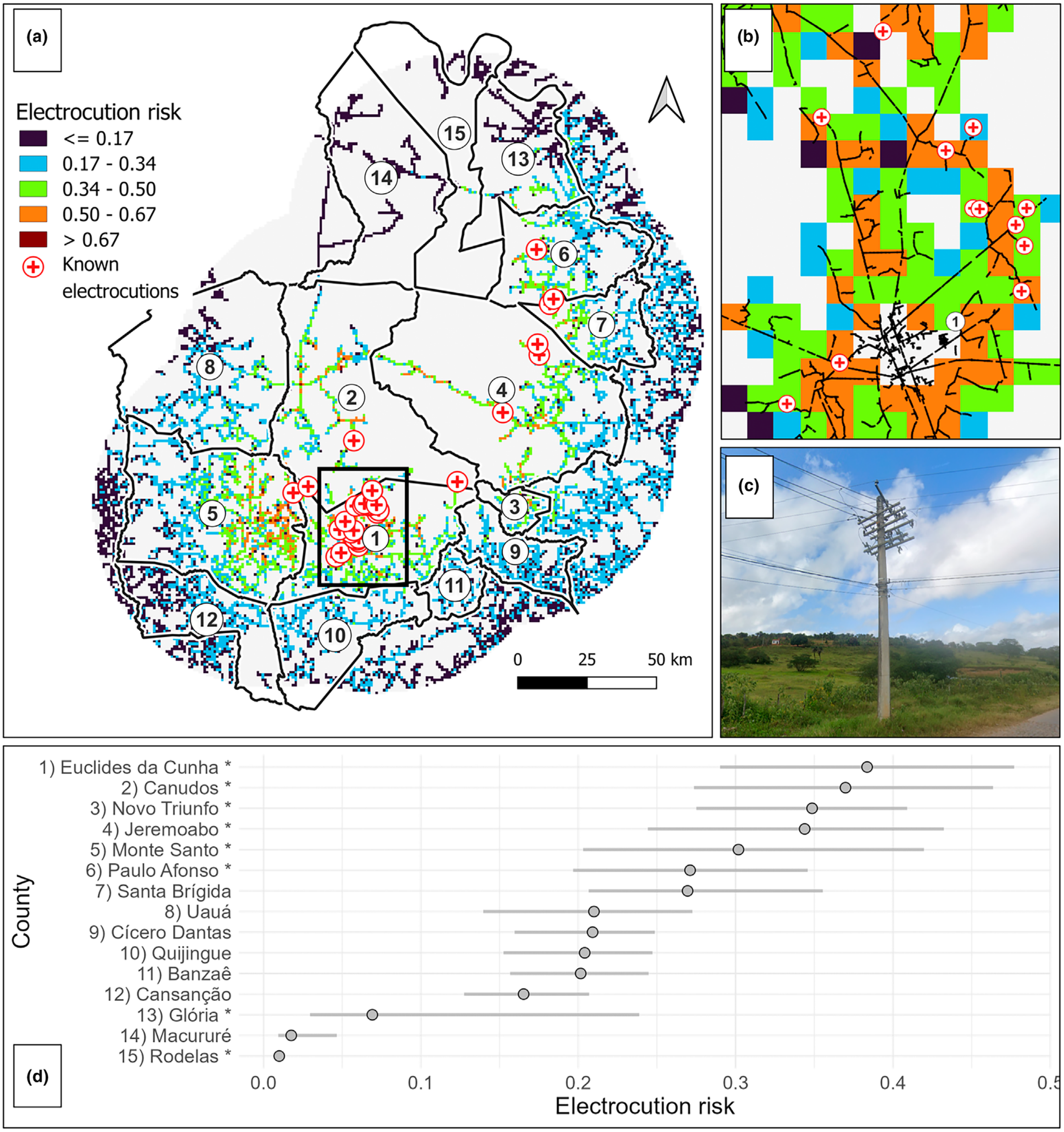

FIGURE 3 Panel (a) depicts the electrocution risk across the study area (colour gradient), with red dots indicating known fatality locations and numbers the counties' identification. The assessment highlights high-risk areas, as an example the region outlined by the black square, which is shown in detail in panel (b) (note that urban centres, identifiable by higher pylon density, were removed from analyses). These high-risk regions can guide the identification of priority pylons for retrofitting (e.g. panel c). Additionally, county-level risk information provides decision-makers with valuable insights to prioritize interventions: In panel (d), the median (dots) and 25%–75% quantile range (lines) are summarized for each county (numbers correspond to those in panel a). Asterisks (*) indicate counties where Lear's macaw has been recorded.

needed, given the potential regional co-occurrence of other species threatened by existing and expanding power grid infrastructure. For instance, within the same semi-arid region and overlapping mainly the northwest part of our study area, the Spix's macaw (*Cyanopsitta spixii*), a species classified as Extinct in the Wild (BirdLife International, 2025), and with an ongoing reintroduction programme (Purchase et al., 2024; Vercillo et al., 2023), probably has a similar behaviour as Lear's macaw on energy pylons. It is suggested that the

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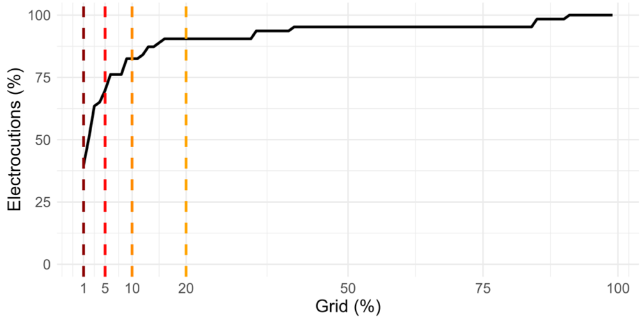

FIGURE 4 Cost–benefit assessment contrasting the percentage of the energy grid to be mitigated with the respective potential reduction in the percentage of known electrocutions. Hundred per cent of the assessed grid cells correspond to 243,285 pylons.

last wild Spix's macaw died because of a power line (Juniper, 2004), indicating that electrocutions may also be a future threat to this species (see ICMBio—Instituto Chico Mendes MMA, 2012). Furthermore, the carcass of a recently reintroduced individual was found underneath an energy pylon, which also strongly suggests death by electrocution according to veterinary assessment. In a multi-species application of our framework, an additional step could be added, where the resulting multiple single-species risk maps for a region of interest are integrated through the use, for example, of a spatial multi-criteria decision analysis (Esmail & Geneletti, 2018) for pole mitigation prioritization.

4.1 | Risk of electrocution for the Lear's macaw

Lear's macaw study area is situated in the tropical dry forest in northeast Brazil, one of the most populated semi-arid regions in the world, but where a significant proportion of the human population still lacks connection to the grid (Bezerra et al., 2022). Unquestionably, access to electricity should be universal, so an increase in the energy grid for these locations is welcomed. However, they must follow careful and sustainable planning based on the local context and biodiversity. According to the mitigation hierarchy, route selection in the planning phase is the most important step and the best opportunity to avoid impacts on biodiversity, followed by minimizing impacts and restoring conditions, and lastly, compensation for the residual impacts (Arlidge et al., 2018; Milner-Gulland et al., 2021). Our approach can identify areas with high Lear's macaw activity that should either be avoided for new distribution line installations or equipped with safe pole and cable configurations from the outset (proactive mitigation approach). Additionally, our electrocution risk map provides a prioritized output to guide decisions on where retrofitting should be implemented first to minimize electrocution risks effectively (Reactive mitigation approach).

Our findings confirm that areas with higher potential activity, particularly those closer to roosting sites and located in regions with a higher likelihood of licuri palm presence, tend to have higher electrocution cases. These results align with previous research, which has indicated that the presence of nesting sites and food availability are related to bird activity and exposure to energy infrastructure and should therefore be equally prioritized in mitigation planning (Biasotto et al., 2022). For instance, the proximity to foraging areas significantly predicts the electrocution risk for Bonelli's eagle (Mayrose et al., 2024). Similarly, for the griffon vulture (*Gyps fulvus*), research demonstrated that food and nest distance are related to vulnerability and exposure to wind farms (Morant et al., 2024).

The number of electrocutions can be significantly reduced by strategically prioritizing mitigation efforts (Chevallier et al., 2015; Hernández-Matías et al., 2020). Our cost–benefit analysis suggests that mitigating the top 1% of risky grid cells could prevent approximately 35% of known electrocutions by mitigating almost 5668 energy pylons. Mitigating the top 5% could imply avoiding about 60% of known electrocutions after mitigation of 22,037 pylons. However, based on the current Lear's macaw conservation status and its small population estimated at less than 2600 individuals (PAN Aves da Caatinga, 2024), even reducing 60% of fatalities, the remaining individual losses could still be relevant for the population, not featuring a long-term benefit for the Lear's macaw viability. Until we have a population viability analysis, a fatality reduction of closer to 90%, requiring between 10% and 20% of poles to be mitigated, is a more precautionary number, assuming that the known casualties represent the actual distribution of electrocutions. However, the number of pylons requiring mitigation reaches 37,412 (10% pylon retrofitting) and 63,966 (20% pylon retrofitting). It is reasonable to assume that addressing this entire scope through structural and permanent mitigation measures would not be logistically feasible in the short term (Martín et al., 2022). Our prioritization framework can, therefore, help inform where to begin implementing mitigation actions, ensuring that efforts are directed towards the most critical areas first. The electrocution risk map displays a varying focus across different counties, with higher risk values overall throughout the entire study area. This suggests that mitigation efforts should be simultaneously multifocal, covering not only the municipality of Euclides da Cunha, which accounts for the majority of fatalities observed (72%), but also other counties.

It should be noted that mitigation costs are balanced with the benefits of conserving biodiversity, and also by preventing power outages. For example, Rebolo-Ifrán et al. (2023) compiled data on power outages caused by bird collisions and electrocutions along distribution and transmission power lines in Peru, Chile and Argentina, using records provided by electric companies from 2009 to 2021. This dataset revealed a total of 19,335 power outage events attributed to bird interactions with power infrastructure. Although more specific data for our study area are unavailable, locals detect electrocuted macaws due to energy outages, which can potentially cause important economic losses and other social effects in the rural communities (Barbosa & Tella, 2019).

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Although as comprehensive as possible, we acknowledge some limitations in our approach. One caveat is that, although licuri is a highly important food source, it is not the only one for Lear's macaw. Additional food resources, such as approximately 30 different local fruits and corn crops, may be relevant to Lear's macaw diet and feeding activity distribution at certain times of the year (Lima et al., 2014). A direct measure of the macaw's feeding distribution would be preferable, but due to resource phenology, it is expected to be very dynamic. However, to the best of our knowledge, such spatial information is not currently available for our study area. We used the number of energy phases per grid cell as a measure of exposure, providing more refined information than pole density, which has already been used to infer exposure hazards (Biasotto et al., 2021; Dwyer et al., 2014). However, as mentioned before, not all pylons are the same, and some designs are more dangerous than others. Nevertheless, spatially detailed data on the energy grid are not available (Kettel et al., 2022). Other specific variables related to pylon configuration, such as the presence of transformers and bypasses (jumpers), were also not accessible in the database we used, but they are probably relevant for determining the risk of electrocution at finer scales or for individual pylons (Martín et al., 2022; Tintó et al., 2010). Based on the current species occurrence data available, we worked with a Maximum Entropy modelling approach to map the distribution of the activity area for Lear's macaw. Different tool or model combinations can be used to predict the potential distribution in various data availability contexts (e.g. when reliable absence points and/or abundance data are available), particularly for species that usually form large congregations (see de França et al., 2025). Finally, we utilized the best available information on potential Lear's macaw electrocution records, primarily based on local citizens' collections. Our dataset consisted of 63 fatality events with relatively low spatial uncertainty (<100 m). All carcasses were found near energy pylons, and some energy outages typically occurred just before villagers discovered the carcasses. However, many other casualties were likely never seen, perhaps leading to a spatial bias in the distribution of electrocutions towards more populated areas (La Sorte et al., 2024). Additionally, scavengers might have removed carcasses before they could be detected (Barrientos et al., 2018; Bernardino et al., 2020). Therefore, our dataset may underestimate the proper distribution and intensity of electrocutions. Nevertheless, our independent validation procedures indicated that the spatial patterns of modelled risk and actual electrocution overlap significantly, and until more refined information is available, mitigation must be carried out immediately, without hesitation.

4.2 | Translating the approach outcomes into mitigation best practices

The information derived from our framework can be used to define actions to reduce electrocution-related deaths. Various mitigation measures have been proposed to reduce electrocution risks (Chevallier et al., 2015; Demeter et al., 2018; Dwyer et al., 2019). The most common methods include increasing the distance between energized components to prevent contact (separation) or reversing the position of the insulators and jumpers, covering energized or grounded parts with resistant insulating materials (insulation) and using safe landing platforms or perch deterrents to steer birds away from hazardous equipment (redirection) (Eccleston & Harness, 2018). Just as important as installing a mitigation is its proper maintenance over time. Considering some knowledge gaps about how electrocutions occur, our map is handy for informing the priority areas for studying these events and the primary species behaviour linked to the risk. With few exceptions, studies on bird behaviour on poles are practically non-existent (García-Alfonso et al., 2021), but they are fundamental and should be systematized to guide the type of mitigation that should be installed and/or designed. Mitigation may vary depending on the specific group being focused on. Parrot bills are very strong (Bright et al., 2019), and their bite can easily destroy deterrent structures such as plastic spikes or insulator covers (Biasotto et al., 2022). Therefore, mitigation measures designed for raptors, which typically use poles for roosting or perching but do not interact with the multiple energized structures at a pole like psitacids, are likely to be ineffective (Biasotto et al., 2021).

We further emphasize the need for improved data to avoid unnecessary financial expenditure from energy companies. Sharing current data, such as species occurrence records, fatality reports and up-to-date information on the energy grid, is crucial for refining risk assessments (Kettel et al., 2022). Improving our understanding of mortality distribution is essential if we aim to enhance mitigation efficiency. Additionally, GPS-tracking data and long-term, systematically collected mortality data, as in Morant et al. (2024), could help better define activity distribution areas, enabling more accurate identification of electrocution risk zones. Furthermore, studies on bird behaviour at power poles are virtually non-existent (García-Alfonso et al., 2021); yet these are critical for guiding the design and installation of effective mitigation measures. It is important to recognize that only a Population Viability Analysis will provide a clearer understanding of how electrocution impacts population persistence, as in Hernández-Matías et al. (2015). However, until such analyses are available, we urge immediate action to implement mitigation measures in the highest-risk areas, namely for range-restricted and threatened species.

As Lear's macaw may serve as a flagship species for conserving tropical dry forests, other species that perch on pylons could also benefit from these electrocution mitigation efforts. For scenarios where species with different feeding and space-use behaviours are affected by electrocution and co-occur, an approach combining multiple species is recommended; so no individual models are applied that run the risk of generating contrasting recommendations. In these cases, it is ideal to identify areas of consensus with the highest risk of electrocution that can generate comprehensive conservation

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policy recommendations for the decision-making process regarding mitigation measures.

AUTHOR CONTRIBUTIONS

Larissa Donida Biasotto, Andreas Kindel and Fernando Ascensão conceived the ideas and designed the methodology; Larissa Donida Biasotto, Erica C. Pacífico, Thiago Filadelfo, Fernanda R. Paschotto, Gabriela R. Favoretto, Antônio Emanuel E. A. Sousa and Aldicir Scariot collected the data; Larissa Donida Biasotto, Andreas Kindel and Fernando Ascensão analysed the data; Larissa Donida Biasotto and Fernando Ascensão led the writing of the manuscript. Larissa Donida Biasotto, Andreas Kindel, Fernando Ascensão, Erica C. Pacífico, Thiago Filadelfo, Fernanda R. Paschotto, Gabriela R. Favoretto, Antônio Emanuel E. A. Sousa and Aldicir Scariot wrote, reviewed and edited the original draft. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data are available via the Zenodo https://zenodo.org/records/15657899; https://doi.org/10.5281/zenodo.15657899 (Donida Biasotto, 2025).

ORCID

Larissa D. Biasotto https://orcid.org/0000-0003-3128-5398
Andreas Kindel https://orcid.org/0000-0002-6358-1450
Erica C. Pacífico https://orcid.org/0000-0003-3518-1887
Thiago Filadelfo https://orcid.org/0000-0002-0523-9788
Fernanda R. Paschotto https://orcid.org/0000-0002-6651-8318
Gabriela R. Favoretto https://orcid.org/0000-0002-6382-140X
Antônio Emanuel E. A. Sousa https://orcid.org/0000-0002-8339-8274
Aldicir Scariot https://orcid.org/0000-0003-0771-3073
Fernando Ascensão https://orcid.org/0000-0003-1704-0212

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SUPPORTING INFORMATION

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

Figure S1. Receiver Operating Characteristic (ROC) showing a high fit between the potential activity area and the points of presence used for the internal validation test (AUC = 0.86, SD = <0.01).

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Figure S2. Curves show how both variables, distance from roosting sites (A) and presence of licuri palm (B), affect the model prediction.
Figure S3. The point-wise mean of the ten output grids created by the modelling approach.
Figure S4. The exposure surface was created using a number of phase densities by each grid cell, 1 × 1 km as resolution.
Figure S5. Null validation of the risk of electrocution surface with boxplot of the 99 random means compares it with the real electrocution mean (red boxplot).

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