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Bird electrocution on power lines: Spatial gaps and identification of driving factors at global scales

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ABSTRACT

Universal energy access is one of the targets of the Sustainable Development Goals (SDGs), and thus the deployment of electricity grids is expected to expand globally in the coming decades. However, the installation of power lines is not biodiversity-friendly. In particular, electrocution on power pylons is a major cause of bird mortality worldwide, including for some severely endangered species. Over the last decades, different studies have improved our understanding of the factors influencing the risk of electrocution in birds, but until now spatial gaps in our knowledge of these impacts and the factors driving global patterns of bird electrocution have not been assessed. In this study, we evaluated data from a total of 114 studies that provided information on bird mortality rates on power lines, and we analyzed the factors driving electrocution rates for all bird species, and then for all raptors and large eagles separately. Our results showed a high spatial distribution bias, as more than 80% of the studies were carried out in developed countries, mostly in Europe and North America. By contrast, no systematic studies have been found for Oceania and very few for South America and Africa. Europe showed the highest electrocution rates for birds, South America for raptor species and Africa for eagles. Socio-economic factors best-explained bird and raptor electrocution rates, while climate-related factors were the most influential for eagles. Contrary to our expectations, factors related to pylon design were the least influential on overall electrocution rates. Variables related to study design showed highly variable levels of influence. This could be due to the lack of standardized protocols. Although bird electrocution has been extensively studied, there are large areas where no studies have been carried out or for which data are inaccessible. This could be because in these areas the power distribution network is still sparse, or that most studies are not public or accessible to the international community. Researchers and managers should promote the publication of studies, as awareness is the first step to solving these problems. The factors identified could be applied globally to the design and planning of power grids and the identification of mortality hotspots. This would help mitigate the creation of new mortality hotspots, especially in developing countries where the installation of new power lines has been growing exponentially in recent years.

1. Introduction

Universal energy access is one of the targets of the Sustainable Development Goals, and thus the deployment of electricity grids is expected to expand globally in the coming decades (Griggs et al., 2013). The transport and distribution of electrical energy can cause high environmental impact given the great spatial extent of the power grid worldwide (Biasotto and Kindel, 2018). This includes visual alterations, atmospheric pollution, changes in habitat structure and interactions with wildlife (Negro, 1999). Indeed, the most thoroughly studied aspects of interactions between power lines and wildlife have shown negative impacts. These vary and include habitat fragmentation due to power line corridors (e.g. Kroodsma, 1982; Andrews, 1990), the effects of electromagnetic fields (Fernie and Reynolds, 2005; Balmori, 2015, but see Dell'Omo et al., 2009), changes in species interactions (Lammers and Collopy, 2007; Dinkins et al., 2010), increases in wildfires caused by electrocuted birds (Guil et al., 2018), a facilitation of invasive species (Kurek et al., 2015) and alterations in wildlife migration patterns

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(Reimers et al., 2007). The most widely recognized impact is the increase in non-natural mortality due to collisions with overhead wires (Loss et al., 2014; Bernardino et al., 2018), entanglement in pylon stabilizers (Gangoso and Palacios, 2002) and electrocution on power pylons (see review in Lehman et al., 2007). However, the electricity network can also have positive effects on wildlife, such as the use of pylons by birds as nesting and perching sites (Mañosa, 2001; Infante and Peris, 2003; Tryjanowski et al., 2014; Mainwaring, 2015) or the creation of new habitats for endangered species (Forrester et al., 2005; Hollmen et al., 2008; Berg et al., 2013).

The interaction with overhead power lines is one the key causes of bird mortality worldwide (Bevanger, 1994, 1998; APLIC, 2006; Prinsen et al., 2011; Loss et al., 2014, 2015). Electrocution is especially problematic for threatened species, particularly raptors (Bayle, 1999; Janss, 2000; González et al., 2007; Lehman et al., 2007; Hernández-Matías et al., 2015; McClure et al., 2018). Since 1970, work performed by researchers, managers, and conservationists around the world has led to an increased understanding of the factors that influence the risk of bird electrocution, such as bird size and behavior, design and types of materials used in pylons, and characteristics of the surrounding habitat (Mañosa, 2001; APLIC, 2006; Lehman et al., 2007; Tintó et al., 2010; Dwyer et al., 2014; Hernández-Lambraño et al., 2018; Kolnegari et al., 2020). This basic work has made possible new mitigation measures and optimized designs for reducing electrocution threat on pylons (Tintó et al., 2010). Wide areas restricting the installation of dangerous new designs have been established (Pérez-García et al., 2017), which have already achieved an increase in survival rates for certain threatened species (López-López et al., 2011).

Unfortunately, this is a problem without borders, and many of the threatened species are migrants (Prinsen et al., 2011). Thus, investing conservation efforts in only one region of the species' range may not be a useful tool for its conservation. There has been unequal attention paid toward interactions with overhead power lines across different regions and countries (Lehman et al., 2007), as well as a lack of knowledge regarding differences among species and approaches. Studying and identifying the common factors across all of the studies performed would allow the identification of spatial gaps in bird electrocution studies and an assessment of mortality patterns at a global scale (Tintó et al., 2010; López-López et al., 2011; Chevallier et al., 2015). Moreover, understanding these global factors could help predict high risk areas for bird electrocution in countries where no field studies have been carried out.

Thus, the objective of this paper was: 1) to assess the spatial bias in bird electrocution studies during the last decades; 2) to compare the electrocution mortality rates at three different taxonomic levels (birds, raptors and eagles) worldwide, and 3) to identify the main factors that drive bird electrocution at global scales.

2. Methods

2.1. Bibliographic search and data management

A systematic bibliographic search was carried out in key databases (WoS Web of Science Core Collection; Google Scholar; Global Raptor Information Network; On-Line Annotated Bibliography of Avian Interactions with Utility Structures of the PIER Program and Searchable Ornithological Research Archive). The references of relevant records were also searched. To search for publications on bird electrocution, we searched in three languages (English, Spanish and Portuguese) in an effort to minimize the biases in scientific publishing (Nuñez and Amano, 2021). The following search string was used and the results were recorded: "Bird" OR "Raptor" OR "Eagle" AND "Electrocution" OR "Power line" and "Electrocucion" OR "Tendido electrico" AND "Rapaz" OR "Aguila" and "Electrocuçao" OR "Linha eletrica" AND "Rapina" OR "Aguia". We also used eight unpublished datasets for low-density observation areas (authors' own data).

Electrocution of birds occurs in most cases on distribution lines (<66 kV), where the distance between the conductors or between the conductors and the power pole is small, so that the bird can be electrocuted (Bevanger, 1999). If during bibliographic search we found references that considered distribution and transmission lines together (i.e. Faanes, 1987; Infante et al., 2005), we only considered data for distribution. Studies not reporting effort on electrocution mortality rates were not considered nor were those that did not sample at least 20 different power pylons. In this way, we were able to correct the number of birds found for effort made. We assigned an average value of 10 pylons per kilometer when authors only included kilometers surveyed but not the number of pylons (Janss and Ferrer, 1999).

The data were standardized as mortality rates in three categories: total electrocuted birds, only raptors (Accipitriformes including Cathartidae, Falconiformes, and Strigiformes) (Gill et al., 2021), and large eagles (those included in the genera *Aquila* and *Clanga*, formerly part of the *Aquila* genus). This subsampling was justified because raptors and particularly large eagles (hereafter, eagles) showed the highest mortality rates on power lines (e.g. Lehman et al., 2010; Guil et al., 2015), and additionally, large eagles have been widely used as an indicator for the development of conservation actions linked to power lines (López-López et al., 2011). We did not include other potentially large eagles (i.e. *Pithecophaga jefferyi, Harpia harpya* or *Haliaateus* sp.) here as because mortality rates were not reported.

Because a single study may comprise information obtained from sampling in different areas, e.g. Infante et al. (2005), we decided to consider each of these spatially separate areas as "sampling sites". In the case of Infante et al. (2005), 29 distinct sampling sites were considered. If the same power line was surveyed more than once in a study, we considered the data from the first survey independently and the data together (e.g. Janss and Ferrer, 2001). We did not consider those single studies that were subsequently included in larger studies (i.e. Kovacs et al., 2008, as included in Demeter et al., 2018).

2.2. Spatial distribution and gaps in knowledge

To gain a global perspective, we estimated the area of each continent covered by studies. We considered an influential area of 5° for every sampling site (~550 km), using kernels in the Heat Map tool in QGIS 3.12. We considered only the resulting area with at least one sampling site. We then calculated the percentage of each continent covered by sampling sites and their densities in each continent (km^2 per sampling site).

To detect spatial biases in knowledge of the impact of electrocution between countries, we compared the number of papers conducted in each country with the richness of raptors and large eagles and with the mean, standard deviation and median global Human Footprint Index from 2009 for each country obtained from Venter et al. (2016).

2.3. Influential bird electrocution categories and variables

The relationship between bird, raptor, and eagle electrocution rates and the predictor variables were examined using boosted regression trees (BRTs). BRTs are a machine-learning method for data exploration and analysis that have advantages over more traditional modelling approaches such as generalized linear/additive models (GLMs/GAMs) as well as other machine-learning methods such as random forests (De'Ath, 2007; Elith et al., 2008). One of the advantages of these methods is that they allow dealing effectively with pseudoreplication due to they do not require independence for predictions (Humphries et al., 2018).

For each sampling site, we obtained 42 variables potentially involved in the electrocution of birds gathered in six groups: 1) Spatial location (e.g. continent, mean elevation and geographical coordinates); 2) Climatic (bioclimatic variables obtained from WorldClim Bioclimatic database v.2; Fick and Hijmans, 2017); 3) Socio-economic (variables such as Gross Domestic Product, population density, CO$_2$ emissions, PM2.5 and number of vehicles per 1000 inhabitants, that were gathered from the closest territorial unit available, first for a small region (EU NUTS level 3), then large regions (ISO 3166-2 level) and finally for countries); 4) Ecological (e.g. number of birds and raptor species, number of occurrences of raptor species, protected areas and habitats); 5) Survey design (e.g. year and decade when the sampling site started, number of surveyed pylons, total number of surveys made, and sampling site design); 6) Technical configuration (percentage of pylons with mitigation measures, percentage of pylons with phases over the crossarm and percentage of pylons with non-wooden pylons). The full list and description of the variables as well as the methodology used to obtain them is included in S1 (Supplementary material S1).

For BRT modelling, we followed the approach proposed by Elith and Leathwick (2013). Model performance is affected by the values selected for learning rate, bag fraction, and tree complexity. Exploratory analyses with the data suggested a reasonable learning rate to use for each analysis (using 0.001, 0.005, 0.01 and 0.05). We used variable learning rates (1, 2, 3, 5, 7, 10, 12 and 15). Although tuning the other variable, bag fraction, only had a modest effect on model performance, we decided to use fixed values for this input so as to avoid any bias generated by selection of the best-fitting run (out of a set of runs with different tuning variable values). We used a bag fraction of 0.75. The value for the bag fraction was based on what seemed to work well during the exploratory analyses. We used the brt. functions code provided by Elith et al. (2008) and Laplace and Gaussian families, to facilitate fitting BRT models in the statistical programming language R 3.6.2 (R Development Core Team, 2017). For all three models (bird, raptor and eagle electrocution rates) we checked for the five most influential variables and the overall explained deviance by each group of variables.

3. Results

We found 114 studies that provided detailed data allowing the calculation of electrocution rates, with a total of 222 sampling sites. Of these sampling sites, 211 reported data on birds (197 with at least 20 surveyed pylons), 203 for raptors (190 with at least 20 surveyed pylons) and 201 for eagles (188 with at least 20 surveyed pylons).

3.1. Spatial distribution and gaps in knowledge

Of the studies included, 62.28% were conducted in Europe, 19.30% in Asia and 9.64% in North America. Within Europe, the distribution of studies and sampling sites was uneven, with a very high number of references for the Iberian Peninsula (66.9% of the sampling sites). Europe had the largest surveyed area (44.0%), while Asia and North America were slightly above 10.5%, and South America and Africa were only minimally covered. We found no studies for Oceania.

For all continents the areas where bird electrocution rates were studied showed a higher Human Footprint Index (HFI) than the areas not studied (see Table 1). This difference was more pronounced in Europe (13.54 ± 8.63 vs. 8.68 ± 9.04) than on any other continent, and the lowest value was reached in South America (5.53 ± 5.29 vs. 5.00 ± 5.54). At the country level, no difference was found in the mean or median HFI between countries where studies were conducted and those where they were not (Wilcoxon Rank sum test, median HFI W = 2571.5, p = 0.751; mean HFI W = 2557, p = 0.789), although spatially there are notable differences in the coverage of studies (Fig. 3).

Considering only studies with at least 20 pylons surveyed, the highest average bird electrocution rates occurred in Europe (13.9 ± 29.4 electrocuted birds per 100 pylons surveyed), the highest raptor electrocution rates were found in South America (8.65 ± 6.07 electrocuted raptors per 100 pylons surveyed), and the highest eagle electrocution rates were found in Africa (2.98 ± 5.96 electrocuted eagles per 100 pylons surveyed) (Fig. 1). There were three sampling sites with a bird electrocution rate over 100 dead birds per 100 surveyed pylons, all in Europe. There are also three European sampling sites with a raptor electrocution rate of 50 or more, while the three sampling sites with an eagle electrocution rate over 10 dead birds per 100 surveyed pylons were recorded in Africa, Asia, and Europe.

3.2. Influential bird electrocution categories and variables

Of the total 208 sampling sites with 20 or more surveyed pylons, we could extract socio-economic values at a small regional level for 107 sampling sites, for large regions for 69 and national values for 32. We used Street View to determine the percentage of phases over the cross-arms for 22 sampling sites and in 21 cases to determine the percentage of non-wooden pylons.

The best model for bird electrocution rate explained 66.10% of the total deviance, while the best models for raptor and eagle electrocution rates explained 95.60% and 63.50%, respectively. Attending to the different groups of birds, there is a strong variation among the explained deviance by predictors (see Table 2). For birds, socio-economic variables explained 55.92% of the deviance, and survey variables gathered another 21.21%. For raptors, socio-economic variables were also the main group, accounting for 34.89% of the deviance, and climatic variables contributed with 26.00% of the deviance. Meanwhile, for eagles, climatic variables reached 52.85% of the deviance, and ecological variables reached 30.89%. Boosted regression tree models showed that five variables were repeated among at least two categories of electrocuted rates: Vehicles per 1000 inhabitants, population density, precipitation of wettest month and habitat (Table 3). Detailed results of all models

Table 1

Summary by continent of the results obtained in the systematic literature search for scientific studies reporting bird electrocution rates. We show the number of studies and sampling sites, the area covered by the studies, percentage of the continent with studies, the density of sampling sites (million km^2 per sampling site), and the global Human Footprint index (HFI) for the year 2009 (Venter et al., 2016) inside and outside the area of influence of the systematic sampling sites. Human Footprint Index was reported as mean and standard deviation, and median in brackets.

Continent	Studies	Sampling sites	Studied area (million km^2)	% studied area	Density (million km^2 per sampling site)	Human Footprint Index	
						Inside S.	Outside S.
Africa	4	4	0.97	3.3%	243.76	8.12 ± 6.73 (6.73)	5.18 ± 4.80 (4.26)
Asia	22	30	4.71	10.6%	156.95	7.32 ± 6.21 (5.27)	6.81 ± 7.41 (4.32)
North America	11	53	2.59	10.7%	48.83	5.24 ± 5.92 (3.28)	3.88 ± 7.20 (0.25)
South America	6	8	1.07	6.1%	134.25	5.53 ± 5.29 (4.00)	5.00 ± 5.54 (3.25)
Europe	71	127	4.37	44.0%	34.44	13.54 ± 8.63 (12.00)	8.68 ± 9.04 (5.67)
Oceania	0	0	**0**	0.0%	0	–	4.34 ± 5.17 (3.21)
Total	**114**	**222**	**13.72**	**10.2%**	**61.80**		

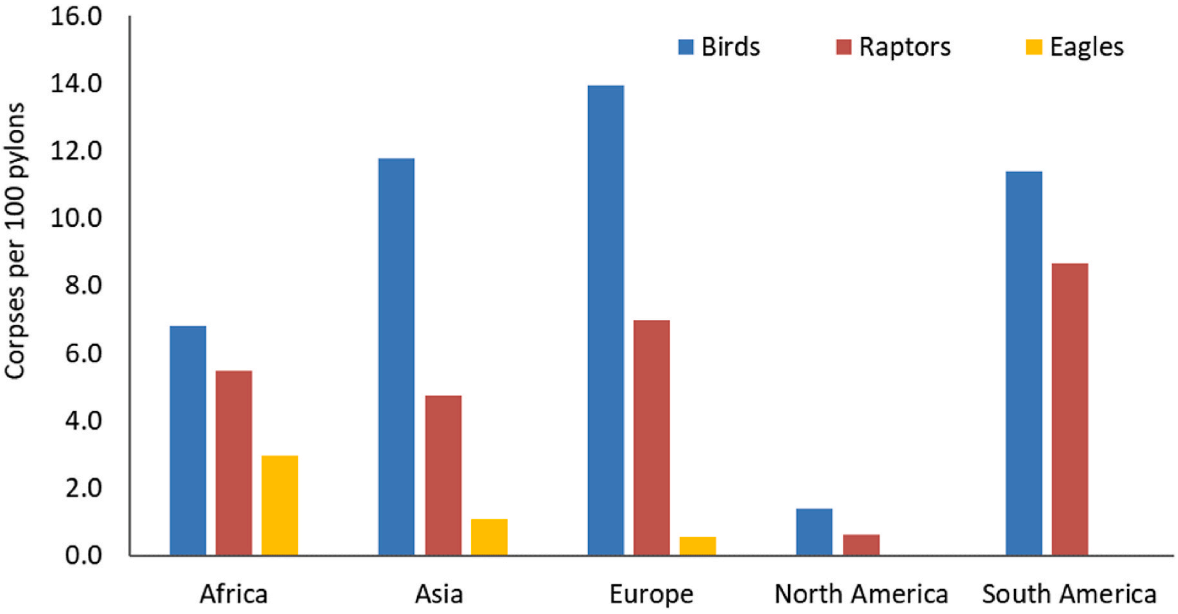

Fig. 1. Mean electrocution rates of birds, raptors and eagles on each continent. Only sampling sites with 20 or more poles surveyed were included. Electrocution rates were shown as birds killed per 100 poles. Oceania was excluded due to the absence of studies reporting bird electrocution rates.

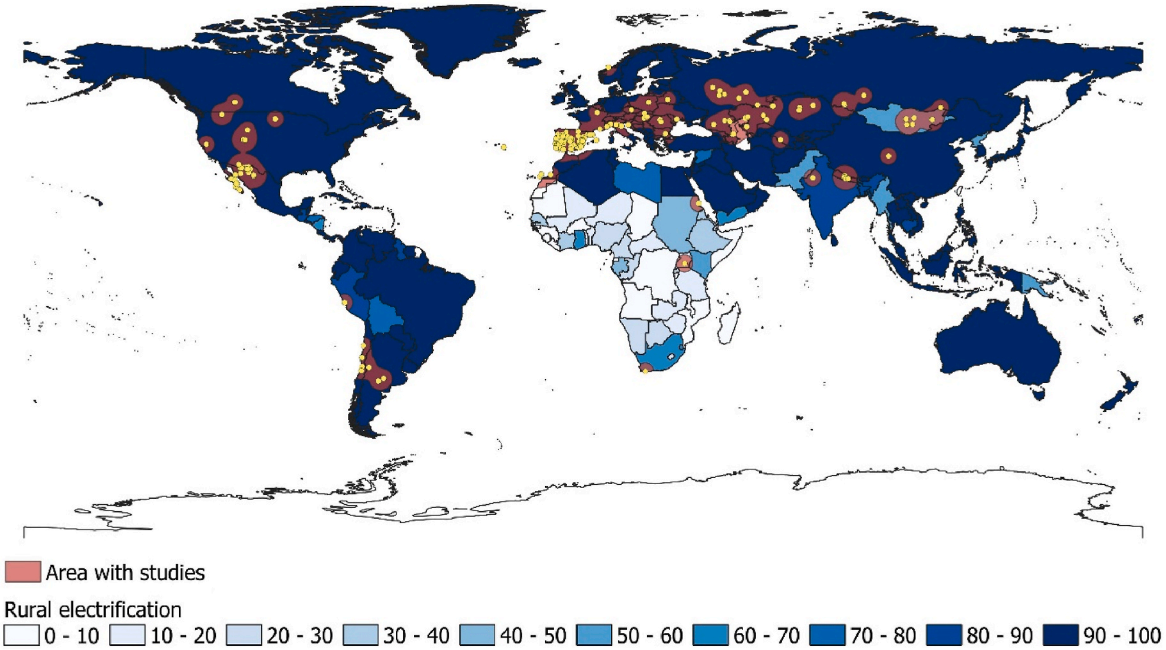

Fig. 2. Global spatial distribution of bird electrocution rate studies. Sampling sites (yellow dots) and their influential area (orange areas) were shown. The blue colour ramp represents the percentage of rural electrification in each country according to the World Bank Group (https://www.worldbank.org/). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

performed were included as supplementary material (see S2 in supplementary material).

4. Discussion

In this paper we reviewed the systematic monitoring of avian electrocutions around the world and used it to understand the main drivers underlying this impact globally. Our results allow us to assess how future monitoring efforts should be focused and to anticipate where major conflicts between power lines and birds are expected to occur.

4.1. Spatial distribution and gaps in knowledge

Our results indicate that public attention to this topic (using the spatial distribution of scientific publications as a surrogate) is spatially biased. Developed countries, mostly located in Europe and North America, account for more than 80% of the studies. Specifically, more than half of the evaluated sampling sites were carried out in Europe alone and, amongst these areas, there are differences indicating more studies in the most humanized areas.

The bias toward Europe-based research may be due to a variety of complementary effects. First, there are higher electrocution rates in

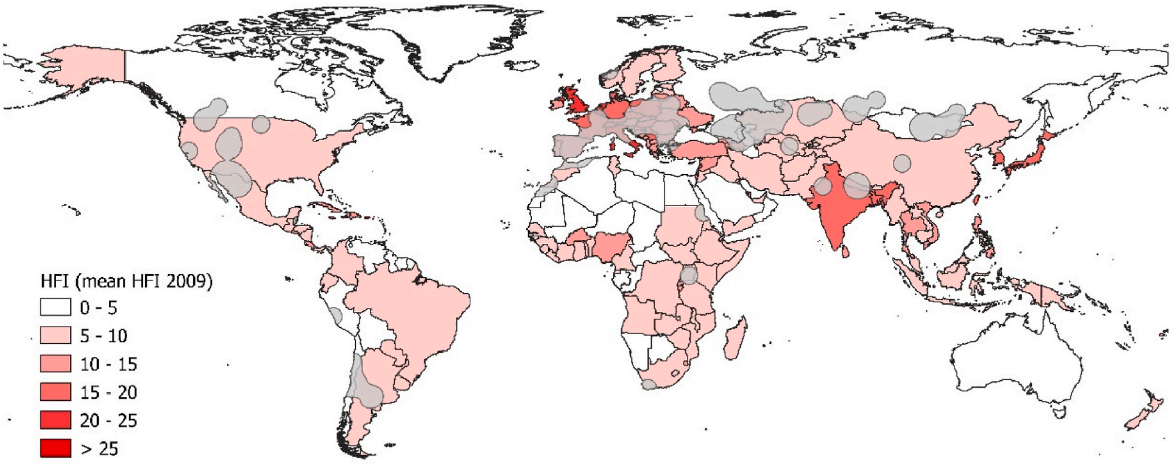

Fig. 3. Global spatial distribution of the influential area of bird electrocution sampling sites (grey areas) and mean global Human Footprint Index (HFI) for 2009 (Venter et al., 2016).

Table 2
Results of electrocution rate models using Boosted Regressions Tree (BRT) for each taxonomic group. We show the total explained deviance and the deviance explained by each group of variables analyzed, and the parameters of the models (Gaussian error distributions G, tree complexity TC and learning rate LR).

Model	Birds G, TC = 5; LR = 0.01	Raptors G, TC = 10; LR = 0.005	Eagles G, TC = 15, LR = 0.005
Total explained deviance	66.1%	95.6%	63.5%
Climatic variables	8.82%	26.00%	52.85%
Ecological variables	6.69%	20.88%	30.89%
Socio-economic variables	55.92%	34.89%	8.01%
Spatial location	6.91%	1.91%	1.21%
Survey variables	21.21%	15.89%	6.85%
Technical configuration	0.44%	0.42%	0.19%

Table 3
The five most influential variables retained in Boosted Regressions Tree (BRT) models for each taxonomic group (birds, raptors and eagles). We show the relative influence (RI) for each variable.

Order	Birds	Raptors	Eagles
1st	Vehicles per 1000 inhabitants RI: 42.14	Vehicles per 1000 inhabitants RI: 22.28	Precipitation of Wettest Month RI: 24.58
2nd	Nº of pylon surveys RI: 17.66	Occurrences of raptor species RI: 11.57	Nº of raptor species RI: 22.65
3rd	Population density RI: 8.88	Population density RI: 7.62	Precipitation of Coldest Quarter RI: 7.91
4th	Longitude RI: 5.32	Precipitation of Wettest Month RI: 6.85	Precipitation of Wettest Quarter RI: 6.44
5th	Habitat-LUC RI: 5.32	Habitat-LUC RI: 6.36	Habitat-LUC RI: 5.25

Europe because the majority of pylons are grounded (Bevanger, 1999). As a result, there is greater social awareness about this problem (as suggested in Guil et al., 2015). This may also explain the bias seen in the Human Footprint Index. Europe is a developed and densely populated area, which has led to a very extensive power grid (Janss and Ferrer, 1999). However, the distribution is not homogeneous, neither in terms of sampling sites nor in terms of mortality location (e.g. Pérez-García et al., 2011). Even within the European continent, spatial differences between countries were detected.

The North American literature on the interaction between birds and power lines is extensive. However, although this region has produced significant studies on this topic (APLIC, 2006), including attempts to estimate total mortality in the United States (Loss et al., 2014), there are relatively few systematic studies that provide comparable mortality rates (Mojica et al., 2009). This was previously noted by Olendorff et al. (1981) and Lehmann et al. (2007) who called for more detailed studies. One of the underlying causes for the lack of published studies with mortality rates may be the absence of mortality events in many power line surveys (R. Harness, pers. comm.).

In the case of Asia, although it was the second continent with the most published studies, most were concentrated in a few regions such as Altai (Russia) or Mongolia (e.g. Nikolenko and Karyakin, 2012; Dixon et al., 2013). We found that the language of publications was a major barrier to accessing field studies and collecting data, especially from reports that were not international scientific publications.

The continents with the most limited information were South America, Africa and Oceania. In South America, although some cases with high mortality rates have been reported (e.g. Alvarado and Cornejo, 2010; Ibarra and De Lucca, 2015), systematic studies were scarce (Galmes et al., 2018). In Africa, on the other hand, studies were biased towards intensive research in the south of the continent (e.g. Brown and Lawson, 1989). However, in the rest of the continent, studies were limited and highly localised. The absence of systematic studies in Oceania is surprising, especially when some studies highlight the importance of electrocution in the mortality of threatened species such as the New Zealand falcon (*Falco novaeseelandiae*) (Fox and Wynn, 2010).

Several aspects may contribute to this finding, such as the presence of large regions without electricity grids (particularly for Africa and South America), or the difference in environmental awareness between countries. Some of the information gaps we found were surprising, in particular for countries where monitoring is known to have been conducted. These data have often been collected by public administrations, electricity distribution and transmission companies, or NGOs, but the results of these reports are relatively difficult to find. In some cases, this is because this surveys detected a small number of mortality events. In other cases, this may be due to the fact that reports have been maintained as internal documents for management and decision making. In order to obtain a global view of the problem, we recommend that all of these studies be published in international journals (or national journal with a summary in English) or made available in public domains or repositories (such as arXiv.org). It should be noted that the publication of monitoring reports with a limited number of mortality cases can be very useful in identifying underlying factors. For reporting studies covering large geographical areas (e.g. Demeter et al., 2018), as variations within them can be considerable (Infante et al., 2005), we recommend that authors provide separate detailed data as supplementary material.

4.2. Influential bird electrocution categories and variables

Socio-economic variables were the most influential factors to explain bird and raptor electrocution rates, and climatic factors best explained eagle electrocution rates. Socio-economic variables may be related to the development and extent of the power grid. In particular, the number of vehicles per inhabitant and population density were the first and third most influential variables for bird and raptor electrocution rates. While the number of vehicles per inhabitant is clearly related to socio-economic development, population density could be related to the extent of the power grid, especially in countries with high levels of rural electrification. Advanced development of the power grid may lead to a higher conflict rate, thus provoking higher social impact and wider and more intense surveys (Guil et al., 2015). A complementary explanation could be related to the higher levels of environmental concern in developed countries (Bodur and Sarigöllü, 2005; Gifford and Nilsson, 2014) and therefore more research projects have been promoted.

Climatic variables play a relevant role in eagle and raptor electrocution rate models. In both cases, the precipitation in the wettest month is the most relevant factor, driving habitat patterns and favoring the prevalence of steppes (Yang et al., 2011), and thus the lack of safe alternative perches. It is a well-known fact that dispersing eagles select open spaces (Balbontín, 2005; Sergio et al., 2006).

The habitat factor showed a homogeneous effect for electrocution of all bird groups. Habitats with lower vegetation (grasslands and croplands) were positively related to electrocution rates. Some authors have previously suggested this relationship (e.g. Mañosa, 2001) and linked it to the absence of alternative and safe perches (Tryjanowski et al., 2014). Small- and medium-sized raptors are more tolerant to use human environments (Dwyer and Mannan, 2007) or transitional habitats (Bosakowski and Smith, 1997), while larger raptors generally avoid areas with frequent human presence (Chace and Walsh, 2006). In the case of wetlands, the number of dead raptors and eagles electrocuted tends to decrease, which may be due to their relatively lower abundance compared to other large birds (more prone to electrocution; Janss, 2000) and to other habitats (Maeda, 2001; Guadagnin and Maltchik, 2007).

We found that the influence of survey design variables differed considerably between the electrocution rates of the groups of birds studied. There is substantial variation between studies in the methods used, and apparent differences in mortality rates among regions might not actually reflect true mortality differences, but rather differences arising from methodology-related issues. There is also uncertainty about the degree to which major biases (e.g., number and ability of observers, periodicity, disappearance rates, scavenging community) (Ponce et al., 2010; Loss et al., 2014) are accounted for in the reviewed studies. Thus, a standardized protocol for monitoring power lines, accounting for the most relevant technical and environmental factors (Mañosa, 2001), should be developed and calibrated for different areas (Lehman et al., 2007). Despite this, the number of surveyed pylons was the second most influential variable in explaining bird electrocution rate. Broader studies may show lower mortality rates than more concentrated studies (as suggested in Guil et al., 2015). The role of the decade in which the field work began is more complicated to interpret. In general, as we have previously suggested, when the monitoring work is extended over time, the detected electrocution rates are progressively reduced (Guil et al., 2015). In this way, the works carried out since the year 2000 showed lower numbers of electrocutions in all cases. The works for the 1990s showed a more complicated pattern, with birds and eagles showing an increase in mortality rate. In part, this may be due to the small number of observations in the first decade (less than 5% of the data). Thus, it would seem logical that the detection of the problem in the first decades, and especially with the technical literature generated in the 1990s (i.e. Olendorff et al., 1981; Janss and Ferrer, 1999; APLIC, 2006; Haas and Schürenberg, 2008), contributed to the implementation of mitigation measure and the adoption of national legislation to prevent installation of new danger power lines (López-López et al., 2011; Guil et al., 2015).

The inclusion of geographic longitude as an influential factor for global rate of bird electrocution could be explained by two non-exclusive approaches. The first and foremost is the possible presence of electrocution mortality hotspots, due to the spatial concentration of sensitive birds to this impact or the large-scale landscape features (Pérez-García et al., 2017). Secondly, there may be a problem of bias in data collection that could be influencing our results. Studies are not homogeneously distributed and this could influence our results and even mask other results related to regional or national trends. For example, Infante et al. (2007) reported variations in relatively small country such as Portugal, and Pérez-García et al. (2017) even found high variability at the regional scale within Spain. The development of systematic studies in regions and habitats in unassessed longitudinal ranges would allow a better determination of the effect of this variable in the future.

Variables related to the technical configuration of power poles, e.g. the presence of phases on the crossarm or non-wooden poles, showed a strong influence on electrocution rates at the scale of power poles in previous studies (Ferrer and Janss, 1999; Mañosa, 2001). But, contrary to our expectations, technical configuration was the least relevant factor when studying electrocution rates for all bird taxa at the global scale. Our explanation for this result is that at the global scale technical factors could be obscured by the effect of other variables included in the model. This could be the case for socio-economic variables, which showed the highest influence on electrocution rates. On the other hand, no relationship is found between the percentage of dangerous pylons and mortality rates, but even when the percentages of dangerous pylons are low, high bird mortality rates can be recorded (Mañosa, 2001).

4.3. Methodological limitations of the study

We recognize that our study may encounter some limitations that may potentially hamper some of the results. The first, and most obvious, is the relatively small number of studies with reliable and comparable data. Electrocution of birds has been extensively studied, but many studies lack minimum standards that make them comparable (as highlighted by Lehman et al., 2007). Moreover, the comparative studies are spatially aggregated, more than 70% of the studies were conducted in Europe or North America, which is an additional limitation. One of the causes of this geographical bias is the difficulties in accessing non-English and Iberian language literature, especially in areas such as Asia, the Middle East, and parts of Africa. This includes countries where potentially high electrocution rates can be expected, and could therefore compromise the results of this study. The development and promotion of mortality monitoring programmes or citizen science initiative as well as the use of mobile applications, such as e-faunalert (IUCN, 2019) or Global Raptor Impact Network (GRIN) (www.globalraptors.org/), could help to reduce this gap, especially in countries where no research initiatives have been conducted.

Second, we should note that since some of the sampling sites were missing information on key features, such as the configuration of power lines, and these data were collected after the fact, this may have resulted in some mismatch potential problems. We used Street View to collect this missing data, but coverage (both temporal and spatial) is limited in some rural areas, so there could be differences between the dates of the mortality surveys and the Street View images, which could affect the accuracy of the data. However, this data collection was only carried out for a small number of surveys, and the renewal interval in the reconfiguration of electricity poles is generally very low. We, therefore, consider the effect on our results to be negligible.

5. Conclusions

The expansion of the electricity network is both a consequence and a driver of economic development (Kirubi et al., 2009; Calderón and Servén, 2010). But this socioeconomic growth also expands the risk of environmental impact to new regions. For example, the development of mobile phone networks has had a huge impact on communications and business opportunities in many remote locations (Aker and Mbiti, 2010). However, at the same time, this has led to the electrification of a large extent of remote areas, e.g. the steppes of Central Asia, causing significant impacts on birdlife (Nikolenko, 2011).

Despite significant progress in understanding the underlying factors that cause the impact of power lines on biodiversity (Biasotto and Kindel, 2018), and the serious threat that electrocution poses to endangered species, a significant number of countries still lack taking the necessary measures to reduce this impact. In this regard, to assess and reduce bird mortality on power lines, national governments should implement systematic monitoring and surveillance programmes and adopt specific regulations (Dwyer et al., 2017).

Prospective studies to obtain reliable mortality rates would allow comparison of results obtained in very different regional contexts (Bevanger, 1999; Lehman et al., 2007), facilitating the identification of the most critical areas for action. We suggest the establishment of a minimum monitoring protocol to assess wildlife mortality rates on power lines in each country. These monitoring protocols should record at least the following information: 1) Date and precise geographical location of the surveyed power line; 2) Pole type and configuration: including voltage, crossarm design, crossarm and pole material, anchoring, number of phases and location on the crossarm, auxiliary equipment (i.e. cutouts, transformers …) and retrofitting measures; 3) Mortality: dead animals found within 25 m radius (Mañosa, 2001), identification of species, estimate the time of death (or stages of carcass decomposition), and evidence of the cause of death (e.g. necropsy report or visual cues). When the survey belongs to periodic monitoring of power lines, the periodicity of the visits should be included. For reporting studies covering large geographical areas (e.g. Demeter et al., 2018), as variations within them can be considerable (Infante et al., 2005), we recommend published disaggregated detailed data as supplementary material.

Furthermore, local initiatives to standardise data collection through apps that can be used on mobile phones, which greatly facilitates this task (IUCN, 2019). It is also interesting to carry out training programmes for rangers and field technicians to improve data collection and standardisation. To this end, it is interesting to create or disseminate guides that facilitate the specific identification of carcasses and bones (e.g. García-Matarranz, 2019) or the estimation of the time of death (Valverde et al., 2020).

Regulation is the other major challenge at the global level. Specific regulations are needed both to establish effective measures to retrofit existing lines and safe designs for future new lines, this is essential for those countries where a strong expansion of the electricity grid is in progress (e.g. Orihuela-Torres et al., 2021). It is crucial to encourage the use of vaults or other crossarms for holder pylons (APLIC, 2006), which allow insulators to be suspended, and to avoid phasing on the crossarm to limit future impacts. Regulation should consider the renewal of outdated lines to avoid unintended impacts, as is happening in some Asian countries with the replacement of old wooden pylons with new steel pylons (Dixon et al., 2013).

Finally, the development of strategies that promote the generation of renewable energy near the places of consumption could be one of the great advances in the next century and is especially indicated for remote areas, as it would reduce the consumption of raw materials for the installation of power lines, and the impact of their installation and use (Sánchez-Zapata et al., 2016; Serrano et al., 2020).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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