Bird collisions with power lines: State of the art and priority areas for research

Bernardino, J.[1]; Bevanger, K.[2]; Barrientos, R.[3,4]; Dwyer, J.F.[5]; Marques, A.T. [1,4,6]; Martins, R.C.[1,4]; Shaw, J.M. [7,8]; Silva, J.P.[1,4,6] and Moreira, F.[1,4]

[1] REN Biodiversity Chair, CIBIO/InBIO – Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade do Porto, Campus Agrário de Vairão, 4485-661 Vairão, Portugal.

[2] Norwegian Institute for Nature Research (NINA), P.O. Box 5685 Torgarden, NO-7485 Trondheim, Norway.

[3] Infraestruturas de Portugal Biodiversity Chair, CIBIO/InBIO - Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade do Porto, Campus Agrário de Vairão, 4485-661 Vairão, Portugal.

[4] CEABN/InBIO – Centro de Ecologia Aplicada "Professor Baeta Neves", Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal.

[5] EDM International Inc., 4001 Automation Way, Fort Collins, CO 80525, USA.

[6] cE3c – Centro de Ecologia, Evolução e Alterações Ambientais, Faculdade de Ciências da Universidade de Lisboa, Edifício C2, Campo Grande, 1749-016 Lisboa, Portugal.

[7] FitzPatrick Institute of African Ornithology, DST-NRF Centre of Excellence, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa.

[8] Scottish Natural Heritage, Stilligarry, Isle of South Uist, HS8 5RS, United Kingdom.

Corresponding author

Joana Bernardino

Address: REN Biodiversity Chair, CIBIO/InBIO – Research Center in Biodiversity and Genetic Resources, Universidade do Porto, Campus Agrário de Vairão, 4485-661 Vairão, Portugal.

E-mail: jbernardino@cibio.up.pt

Phone: (00351) 918455345

Bernardino, J et al 2018 Bird collisions with power
lines: State of the art and priority areas for research.
Biological Conservation 2018 ;Volum 222. s. 1-13 10.1016/j.biocon.2018.02.029

Abstract

Transmission and distribution electricity grids are expanding rapidly worldwide, with significant negative impacts on biodiversity and, in particular, on birds. We performed a systematic review of the literature available on bird collisions with power lines to: (*i)* assess overall trends in scientific research in recent decades; (*ii)* review the existing knowledge of species-specific factors (e.g. vision, morphology), site-specific factors (e.g. topography, light and weather conditions, and anthropogenic disturbance), and power line-specific factors (e.g. number of wire levels, wire height and diameter) known to contribute to increased bird collision risk; and (*iii)* evaluate existing mitigation measures (e.g. power line routing, underground cabling, power line configuration, wire marking), as well as their effectiveness in reducing collision risk. Our literature review showed *(i)* there is comparatively little scientific evidence available for power line-specific factors, *(ii)* there is a scarcity of studies in Asia, Africa and South America, and *(iii)* several recommendations of good practice are still not supported by scientific evidence. Based on knowledge gaps identified through this review, we outline suggestions for future research and possible innovative approaches in three main areas: bird behaviour (e.g. further use of loggers and sensors), impact assessment (e.g. understanding the drivers of mortality hotspots, assess population-level impacts, develop methods for automatic detection of collisions) and mitigation measures (e.g. further need of BACI approaches to compare the effectiveness of different wire marking devices). The complex and region-specific interactions between collision drivers and bird ecology continue to limit our ability to predict impacts and the success of mitigation measures.

Highlights

- We review the scientific evidence on bird collisions with power lines.
- Research gaps are identified and lines of further research suggested.
- Several existing recommendations of best practice lack scientific evidence.
- Further studies in Asia, Africa and South America are needed.

Keywords

Bird mortality; Collision risk; Impact assessment and mitigation; Energy; Knowledge gaps; Transmission and distribution lines.

1 INTRODUCTION

Global energy demand is expected to grow 30% between 2016 and 2040, particularly in parts of Asia (where more than half the increase is expected), Africa, Latin America, and the Middle East (IEA, 2016). Bringing this energy to end users (people and industries) will require a 7.2-8.1 trillion USD investment in the global electricity grid (IEA, 2016), which is growing at a rate of about 5% annually (Jenkins et al., 2010). This expansion will require the construction of thousands of kilometres of new overhead power lines (Gellings, 2015), which can be divided in two main types: "*transmission lines*" carry electricity at high voltages from generating facilities to substations (where voltage is reduced) and "*distribution lines*" deliver electricity to individual consumers at lower voltages (IEA, 2016). The voltage threshold between these power line types usually varies between 60 kV and 132 kV, depending on the country or region (CIGRE, 2017).

Overhead power lines and associated infrastructure entail various impacts on biodiversity. One of the most well-known is bird mortality due to collision and electrocution, which represents a major source of anthropogenic mortality and kills hundreds of thousands to millions of birds every year (Erickson et al., 2005; Loss et al., 2015, 2014; Rioux et al., 2013). This paper is focused on collision as the most widespread interaction of these infrastructures with birds in the sense that virtually any aerial wire can pose an obstacle to flying birds, and it is thus associated with both distribution and transmission power lines (e.g. Bevanger, 1994).

Several studies suggest that power line collision mortality can have significant population-level impacts (Loss et al., 2012; Schaub et al., 2010; Schaub and Pradel, 2004), and red-listed and economically important species are commonly documented casualties (Bevanger, 1998, 1995a; Hobbs, 1987; Janss, 2000). In some cases, there is evidence that power line collision mortality can even lead to changes in migratory patterns and flyways (Palacín et al., 2017). Thus, it is important to continuously improve impact assessment methods and to design appropriate mitigation measures to be applied when new power lines are designed and constructed, as well as when existing lines are retrofitted. This would assist companies and authorities in ensuring that infrastructure is developed in the most environmentally friendly way.

Scientific understanding of the links between power lines and bird collisions, and effectiveness of mitigation measures, has steadily advanced over the past 20-30 years (e.g. Barrientos et al., 2012, 2011, Bevanger, 1994, 1990; Jenkins et al., 2010; Loss et al., 2015; Smith and Dwyer, 2016). The first peer-reviewed publications summarising available information on drivers of bird collision, as well as mitigation measures, were published by Bevanger (1998, 1994). Since then, there has been no peer-reviewed update of scientific evidence, with the exception of Jenkins et al. (2010) which focussed specifically on South Africa. Furthermore, there are still significant knowledge gaps that need to be identified (e.g. Richardson et al., 2017) as, for example, some widely accepted principles have never been tested, species-specific differences in collision risk are not well understood, and the evaluation of effectiveness of mitigation measures to date yields widely differing results (e.g. Barrientos et al., 2011; Jenkins et al., 2010).

In this review, we aim to evaluate the current science and practice of understanding and mitigating bird collisions with power lines, and seek to identify major knowledge gaps that should be the focus of subsequent research. For that purpose, we have structured this paper into four major components:

a) We first present results of a systematic literature review undertaken to assess the overall trends in scientific research on bird collisions with power lines in recent decades, as well as the more commonly studied topics;
b) We then review factors known to contribute to increased collision risk, including species-specific factors (vision, morphology and ecology), site-specific factors (topography, landscape context, light and weather conditions, and anthropogenic disturbance) and power line-specific factors (number and spacing of wire levels, wire height and diameter);
c) Thirdly, we summarise the existing strategies for reducing collision risk, namely power line routeing, underground cabling, power line configuration, wire marking, and habitat management, as well as understanding their effectiveness;
d) We conclude by identifying knowledge gaps and suggesting future research avenues to answer persisting questions.

2 METHODS

To review the literature, we compiled studies, both peer-reviewed and non-peer-reviewed (such as journal papers, books and book chapters, conference proceedings and technical reports) focusing on bird collision with power lines. We started with a systematic literature review, through the compilation of data from the search engines ISI Web of Knowledge and Google Scholar. The search was carried out in December 2016, using the term “power lines” combined with the following specific terms: “bird collision”; “bird collision mitigation”; “bird mortality”; “bird avoidance”; and “bird collision guidelines”. Based on the recommendations of Haddaway et al. (2015) the Google Scholar search focused on the first 300 results. All results from the ISI Web of Knowledge were checked and only documents assessing bird collision with power lines were included in the analysis (e.g. documents only reporting bird electrocutions or bird collisions with other man-made structures were excluded). Each document was assigned to one or more of the main topics of the manuscript (see Appendix, Table A1).

The systematic literature review had some limitations, as it was restricted to documents publicly available, accessible online, and written in English. Thus, whenever relevant to fulfil the objectives, we also reviewed key documents referenced by those identified through our systematic literature review, or included in our personal bibliographic collections (see Appendix, Table A2).

3 OVERALL TRENDS IN RESEARCH TOPICS

Overall, the systematic literature review resulted in 208 documents focusing on bird collision with power lines, of which 17 could not be accessed and were therefore excluded from the review. The first studies were carried out in the early 1970s and scientific evidence has been accumulating ever since, with the number of studies more than doubling over the last decade (Figure 1).

The majority of studies (60.2%), especially those published earlier, focused on quantifying bird fatalities from collisions (Figure 2). Collision risk factors were also frequently addressed, namely species-specific factors (51.3%), followed by site-specific (34.0%) and power line-specific factors (11.0%). Studies on strategies to mitigate bird collision events with power lines were also relatively frequent (46.6%).

Only a subset of 132 studies (69.1%) presented first-hand data on bird collisions with power lines (Figure 3). These studies were conducted mainly in Europe and North America (43.2% and 34.8%, respectively), which are currently the regions with the largest extent of power lines (Wildemann et al., 2013). Transmission power lines were by far the most studied type, with 91 studies (68.9%), compared to 49 (37.1%) on distribution lines, even though distribution networks are significantly larger (CIGRE, 2017). However, some studies focused on both types, and surprisingly, a quarter of the studies (25.8%) did not provide information about power-line type.

4 BIRD COLLISION RISK FACTORS

A wide range of factors can influence avian collision risk with power lines. For simplicity, we have divided these into three main groups: species-specific, site-specific and power-line specific factors, although they are frequently interconnected.

4.1 SPECIES-SPECIFIC FACTORS

Species-specific physiology, morphology and ecology are key to understanding collision risk. In this section, we summarise the current knowledge of how these factors may affect collision risk.

4.1.1 Sensory perception

The morphology and physiology of the avian eye, and therefore how information from the eye is processed, likely influences collision risk and the effectiveness of collision mitigation. Avian vision shares common principles with other terrestrial vertebrates (Martin, 1990, 1985; Martin and Osorio, 2008; Sillman, 1973). There are however, important differences that may limit our ability to understand how power lines and mitigation, such as wire markers, are perceived by birds.

Birds with eyes located laterally have broad visual coverage of the surrounding world (Martin, 2011, 1990, 1985), facilitating detection of conspecifics, predators and food (Fernández-Juricic et al., 2008; Rogers, 2008). However, a very wide visual field may also compromise a bird's ability to detect obstacles in the air. Martin (2011, 2009) argues that most birds do not have the ability to estimate the distance to a specific object (relative depth) due to the lateral position of the eyes, and that frontal binocular vision is important to birds only when it comes to control of the bill and close objects. Some bird species also have extensive blind regions above and behind the head, which can be fatal when flying birds pitch their head downwards to look for prey, roost sites or conspecifics, and the blind region projects forward in the direction of flight, therefore any obstacle lying ahead is not detected (Martin, 2012, 2011; Martin and Shaw, 2010). This may help to explain why even raptors with a visual acuity 2.5-3 times greater than humans (Reymond, 1987, 1985), can sometimes fail to see a power line (Bevanger, 1994; Martin and Shaw, 2010).

The majority of bird species have a single fovea area of the retina in which photoreceptors occur at high densities, providing a localised region of high spatial resolution (Sillman, 1973). Typical hunters like hawks, bitterns and swallows have two areas (Schmidt-Morand, 1992; Sillman, 1973). However, some birds, e.g. Galliformes, lack or have a very poorly developed area (Lisney et al., 2012). This is interesting as this taxon has one of the highest collision rates with power lines and fences (Baines and Summers, 1997; Bevanger, 1995a, 1995b; Bevanger and Brøseth, 2000).

The majority of bird species have also the ability to perceive ultraviolet (UV) light below 400 nm (for some species, to as low as 320 nm) (Cuthill et al., 2000; Ödeen et al., 2011; Zhang, 2003). Thus, some authors (e.g. Lee, 1978; Tyler et al., 2014) have suggested that the noise and UV emissions of the corona effect (small electromagnetic discharges from transmission lines) and the electromagnetic field around conductors may be perceived by birds and, consequently, reduce the collision risk. No experiments have been conducted to confirm this hypothesis, however the intensity of UV light in corona discharges is very low and unlikely to be visible to birds given their relative low sensitivity to UV (Lind et al., 2014).

4.1.2 Morphological features

Over the last 30 years, aerodynamic theory has become an important tool in understanding bird flight, and in examining how body morphology and physiology enable flight (e.g. Hedenström, 2002; Norberg, 1990; Rayner, 1988). Rayner (1988) categorised bird species according to how well they manoeuvre in the air to avoid oncoming obstacles, based on wing loading (ratio of weight to wing area) and wing aspect ratio (ratio of wingspan squared to wing area). He demonstrated that some bird groups (named “poor fliers”) were less manoeuvrable in flight than others, and data on species vulnerability to power line collisions have subsequently confirmed Rayner’s (1988) classification. Power line collision victims are frequently species with high wing loading and low or average wing aspect ratio, such as Anseriformes, Podicipediformes, Gruiformes and Charadiiformes (e.g. Bevanger, 1998; Crowder, 2000; Janss, 2000; Rioux et al., 2013; Rubolini et al., 2005). A good example of a “poor-flier” is the Great bustard (*Otis tarda*), which due to its heavy body and relatively small wings is less able to avoid unexpected obstacles, and has been consistently reported as a collision victim in Europe (e.g. Barrientos et al., 2012; Janss and Ferrer, 2000; Reiter, 2000).

Within some groups (e.g. Anatidae) there are, however, significant differences between wing loads and aspect ratios, highlighting the importance of species-specific assessment of manoeuvrability (Rayner, 1988). However, even when groups have similar wing morphology (e.g. cranes, storks, eagles and vultures), and presumably similar physical collision susceptibility, they may have different mortality rates because of different flight behaviour and local/regional abundance (Janss, 2000).

Rayner’s (1988) work was an important contribution to understanding the impact of body weight and wing form on birds’ ability to manoeuvre in flight. Nonetheless, there are still important questions remaining, for example regarding the relationship between wing loading and the minimum flight speed (required for sustained flight), or the role of the tail. For instance, it is known that tail provides lift, helps in flight control and steering, and is vital for maintaining balance and stability (Hedenström, 2002). Contradicting results on how the length of the tail influences the collision risk (e.g. Janss, 2000; Rubolini et al., 2005) highlight, however, the need of further research on the topic.

4.1.3 Flight behaviour

Collision susceptibility may be influenced by flight behaviour. Gregarious species are generally thought to be more vulnerable than species with solitary habits (APLIC, 2012; Drewitt and Langston, 2008). Birds such as ducks, cranes, pigeons and starlings tend to form large flocks and fly closely grouped together, which reduces the vision of trailing birds and gives them less space to manoeuvre around unexpected obstacles (e.g. Alonso and Alonso, 1999; Scott et al., 1972). On the other hand, Crowder (2000) observed that flocks with >10 individuals reacted at greater distances to power lines than single birds, suggesting that with more birds scanning for obstacles, flocks can adjust their flight path faster and better avoid power lines. However, trailing birds in large flocks (often immatures or juveniles; see section 4.1.5) may still have a higher collision risk.

During long distance migration flights, most birds fly at altitudes well above the height of power lines (Gauthreaux, 1978; Newton, 2010), unless unexpected changes in flight conditions occur (see section 4.2.3). Hence, collisions may occur mostly when birds cross power lines in their local, daily movements. Birds may spend a large part of their day flying between breeding/nesting or roosting sites, and foraging areas (or between foraging areas). These movements, often during crepuscular periods with low light levels (see section 4.2.3), can have a high collision risk, especially if the areas are relatively close together and birds tend to fly between them at lower altitudes (APLIC, 2012; Bevanger, 1994; Drewitt and Langston, 2008). Although raptors are infrequently reported as collision victims, power lines intersecting the home range of some eagle species can be problematic (Manosa and Real, 2001; Rollan et al., 2010; Watts et al., 2015). The exact location is important though; power line spans placed close to the nest may never be crossed by individuals, whereas spans more distant may pose a higher collision risk if located directly along flight paths between the nest and foraging areas (Rollan et al., 2010).

Henderson et al. (1996) suggested that the pressure to deliver food to hungry nestlings may change flight behaviour of parents and thereby increase their susceptibility to collision. The authors observed that, during the breeding season, adult terns flew more frequently under or between power lines, presumably to reduce their journey time between feeding areas and the nest when feeding chicks. Once their young had become free flying, however, these same birds resumed flying over power lines.

There are other flight behaviours that increase collision risk. During the breeding season, some species perform display flights and territorial disputes that can distract them from the surrounding environment (Bevanger, 1994; Sundar and Choudhury, 2005). Likewise, the hunting behaviour of some raptors (e.g. falcons and goshawks) can increase collision risk, as they entail high-speed flights in pursuit of prey (Bevanger, 1994) or because they may not be looking ahead when searching for prey and carrion on the ground below (Martin et al., 2012). Willard (1978) also described a situation in Klamath Basin (USA) where adult American white pelicans (*Pelecanus erythrorhynchos*) flying along canals, collided with power lines while searching for food.

4.1.4 Phenology and circadian habits

While local movements can be riskier than migration (if birds are travelling high), there are several studies which have documented high collision rates of migratory species (Shaw, 2013; van Rooyen and Diamond, 2008). This is because during migration, birds undertake long distance movements into unfamiliar terrain, tend to form large aggregations, fly at lower altitudes near stopover areas and therefore can increase their probability of collision with power lines (e.g. Faanes, 1987; Janss and Ferrer, 2000; Stehn and Wassenich, 2008). Resident species, on the other hand, have a profound knowledge of all the obstacles within their home range, and seem to adapt their flight to avoid the exposure to power lines (e.g. Shimada, 2001).

Circadian habits (often in association with gregarious behaviour and light conditions) can also influence exposure risk to power line collision (i.e., power-line crossings per unit time; Janss and Ferrer, 2000), both for migrant and resident birds. For example, cranes and a wide variety of water birds such as gulls, flamingos, and herons tend to make regular dusk and dawn flights between their roosts and feeding areas, and/or even forage during the night (e.g. Janss and Ferrer, 2000; McNeil et al., 1985; Murphy et al., 2009; Scott et al., 1972; Tere and Parasharya, 2011). Nocturnal migrants, such as rails, thrushes, starlings, and other passerines, appear to be more susceptible to collision than diurnal migrants (Drewitt and Langston, 2008; Scott et al., 1972). Diurnal migrants include swifts, skylarks, cranes and raptors, which can take advantage of thermals developed during the day and, with daylight, may have improved ability to see and avoid power lines (Luzenski et al., 2016). Despite their nocturnal habits, owls and nighthawks seem to collide with power lines in relatively small numbers, especially compared to other anthropogenic sources of mortality (e.g. Alonso et al., 1994; Schaub et al., 2010).

4.1.5 Age, sex and health

Several authors found that immature birds, in particular waterfowl and other water birds such as egrets and cranes, are more susceptible to collision than adults (e.g. Anderson, 1978; Brown and Drewien, 1995; Krapu, 1974; Sundar and Choudhury, 2005; Ward and Anderson, 1992). On some occasions, the proportion of juveniles recorded killed by power lines was over 90% (e.g. Crivelli et al., 1988). It has been hypothesized that young, inexperienced birds are not only less manoeuvrable, but also unfamiliar with the area and consequently unaware of the presence of overhead power lines. Furthermore, immatures usually fly behind their parents which may reduce their ability to avoid sudden obstacles. Henderson et al. (1996) observed that juvenile terns flew consistently closer to wires than adults, with most juvenile crossings <1 m above the top wire. Most juveniles also reacted late to the power line and many needed a second attempt to cross it.

Some studies have identified gender as a possible collision risk factor. It has been suggested that male ducks are more prone to collision during breeding season, as they may be less alert to overhead wires when in aerial pursuit of a female (Anderson, 1978; Faanes, 1987). Male-biased collision mortality has also been observed in studies of tetraonids and bustards, in this case probably because males are larger, heavier and less manoeuvrable (Bevanger, 1995b; Jenkins et al., 2011). Such differences may be affected by the higher detectability of male carcasses (see Bevanger, 1995b; Ponce et al., 2010), so this should be taken this into account.

Studies addressing health condition as a possible collision risk factor are scarce. One exception is a study by Kelly & Kelly (2005), who observed that Mute swans (*Cygnus olor*) with moderately elevated blood lead levels suffered an increased risk of collision, while individuals with even higher blood lead levels did not, possibly because they were too weak to fly.

4.2 SITE-SPECIFIC FACTORS

Power lines can be found in a large range of landscape contexts (including habitat types), variations in weather and light conditions, and topography, which may affect collision risk. Disturbance caused by human activities is also highlighted as a site-specific risk factor.

4.2.1 Topography

Geyr von Schweppenburg (1929) introduced a classic term – “*leading line*” - to describe landforms, like coastlines, which are of great importance to migrating birds, as these contribute to defining migratory flyways. The placement of a power line perpendicular to these major flyways can pose high risk for shorebirds and other species on migration, when birds fly at lower altitudes (e.g. Shobrak, 2012).

River valleys, topographical depressions, mountain passes and ridges can also act as leading lines as they tend to channel and concentrate flight paths (Bevanger, 1994; Thompson, 1978). For instance, mountain chains provide excellent flyways for soaring-gliding birds due to the development of thermals and other updrafts (Newton, 2010). It is expected that power lines bisecting such migration corridors would result in frequent collision events (e.g. Stehn and Wassenich, 2008). However, there is little scientific evidence to date to support this. Rollan et al. (2010) found that topographic position is not a determining factor in predicting collision risk for Bonelli's eagles (*Aquila fasciata*), although there is a slight tendency for eagles to fly lower relative to ground level over ridges. Similar results were found by Luzenski et al. (2016), who did not observe any collisions with a new power line crossing the Kittatinny Ridge (USA), an important navigational feature traversed annually by tens of thousands of migrating raptors.

General knowledge of how leading lines and other topographic elements affect flight path choices among birds, locally or on long distance movements, may be important in explaining why collisions are more frequent at some spots compared to others. Nevertheless, the effects of power lines that bisect such landforms are still hard to predict and require further investigation (Luzenski et al., 2016).

4.2.2 Habitat features

Vegetation plays an important role in bird exposure to power lines (APLIC, 2012). In general, open areas like bogs or pastures allow birds to fly closer to the ground than forested habitats, and consequently can pose higher collision risk when crossed by power lines. Some species, such as geese, may use indirect paths to reach their foraging areas and, to some extent, prefer to fly over woodlands rather than open areas that are crossed by power lines (Shimada, 2001). In forested habitats, collision data from Galliformes in central Norway (Bevanger, 1990; Bevanger and Brøseth, 2004) as well as other species and regions (e.g. Mojica et al., 2009), indicate that collisions occur particularly when power lines are higher than (adjacent) treetops.

Power lines that bisect wetlands, coastal areas, extensive steppes and other major bird congregation habitats are assumed to be the most hazardous (Andriushchenko and Popenko, 2012; Faanes, 1987; Malcolm, 1982), as birds establish breeding and wintering colonies in these habitats, use them as stopover areas during migration, and consequently concentrate at high densities, which dramatically affects the likelihood of collisions. At a smaller scale, power lines crossing riparian habitats or nearby landfills may have similar effects as these areas are heavily used by some groups of birds such as passerines (e.g. Faanes, 1987) and storks (e.g. Garrido and Fernandez-Cruz, 2003), respectively.

4.2.3 Weather and light conditions

It is widely accepted that adverse weather conditions can affect the behaviour of birds in flight, and render overhead wires particularly inconspicuous (APLIC, 2012; Drewitt and Langston, 2008). Heavy fog, rainfall, snow and cloudy conditions (particularly low cloud ceilings), force birds to fly at low altitudes, even close to the ground (Bevanger, 1994; Elkins, 1988). Most reported incidents of mass bird mortality with anthropogenic structures have occurred during such weather conditions (e.g. Avery et al., 1977; Hüppop et al., 2016).

Wind direction and speed also play important roles in flight altitude and stability. Strong tail and crosswinds can increase collision risk as birds approach power lines faster and lack sufficient flight control to avoid the wires (e.g. Savereno et al., 1996; Ward and Anderson, 1992). Susceptibility to collision also may be increased by headwinds, which force birds to fly at lower altitudes where wind speed is lowest, to save energy (Bergman, 1978; Bevanger, 1994; Perdeck and Speek, 1984). Nonetheless, the effect of wind and other adverse weather conditions on bird collision risk is not always consistent. Several authors (e.g. Brown and Drewien, 1995; Murphy et al., 2009; Taylor and Walker, 2015) have not observed an obvious relationship between collision risk and strong wind or otherwise inclement weather.

Understanding the effects of light conditions on collision risk is an important, though quite neglected, issue. At high latitudes, there is significant variation in the number of daylight hours throughout the year. Norway, for example, covers 13 degrees of latitude, and resident species have to cope with low light conditions for much of the year. Data for ten years (1984-1995) from across Norway indicated that the majority of collisions occurred during winter and early spring, periods with poor light and frequent bad weather (Bevanger, 1995b, 1993, Bevanger and Brøseth, 2004, 2000). Likewise, waterbirds that fly at night can be less likely to react to a power line (Deng and Frederick, 2001), or react with less time to manoeuvre (Murphy et al., 2016a), suggesting that collision risk is higher during darkness (Murphy et al., 2016b).

4.2.4 Anthropogenic disturbance

Some studies reported power line collisions resulting from birds being flushed by human activities. Hunting is the most common source of disturbance (e.g. Brown and Drewien, 1995; Willard, 1978), yet recreational or agricultural activities, and power line maintenance works are also recognised as potential disturbance sources (Murphy et al., 2009; Sastre et al., 2009; Thompson, 1978; van Rooyen and Diamond, 2008).

Transportation disturbance from roads and railways (e.g. Krapu, 1974; Schroeder, 1977), or even aircraft noise (Blokpoel and Hatch, 1977) may also increase collision risk with nearby power lines. Rollan et al. (2010) suggested that the presence of nearby motorways may be associated with a 50% increase in the probability of a Bonelli's eagle (*A. fasciata*) flying at the critical height for colliding with power lines, although the presence of railways did not have a clear effect. Conversely, other authors (Shaw et al., 2017; Silva et al., 2010) have suggested that birds may avoid the vicinity of roads, and other areas with intense human activities, with a potential reduction in collision risk.

Further research is needed to clarify the relationships between such linear infrastructure and associated impacts on bird collision risk with nearby power lines.

4.3 POWER LINE-SPECIFIC FACTORS

In this section, we summarise the main power line features that can influence the risk of bird collision, including wire diameter and height, and line configuration (number of vertical wire levels). Most of these features are strongly dependent on power line voltage, due to relatively rigid technical constraints on engineering performance, service reliability and public safety (Miller, 1978). Specification of power line features also involves cost-driven decisions by electricity companies, national governments and regulatory entities, which can result in notable geographical (national or regional) variation within voltage levels (e.g. Haas et al., 2005).

4.3.1 Number of vertical wire levels

The risk of bird collision is assumed to depend on the number of vertical levels of wires and the spacing between them (e.g. Bevanger, 1994; Drewitt and Langston, 2008; Jenkins et al., 2010). Though this makes intuitive sense, there is little scientific evidence in support of it, due to the practical difficulties of testing such effects (APLIC, 2012). Still, Bevanger and Brøseth (2001) recorded a 51% reduction in Ptarmigan (*Lagopus* spp.) collision rates after removing the earth wire from a three phase distribution (22 kV) power line. This modification represented a reduction from two vertical levels to one, as (unusually) the earth wire had exactly the same diameter as the conductors. Prinsen et al. (2011) reported another line modification example near a wetland. In this case, a transmission line was modified to replace three vertical levels with two, which resulted in a 72% reduction in the bird collision rate (from 0.51 to 0.14 fatalities/km/day). These results are confounded however, because modifications also reduced power line height and the distance between pylons. Pylon spacing is thought to play an important role (Jenkins et al., 2010), as collision rates near pylons tend to be lower than at mid-span (Neves et al., 2005; Pandey et al., 2008; Ward and Anderson, 1992).

Infante et al. (2005) and Neves et al.(2005), leading two large-scale bird mortality surveys on Portuguese distribution (15-30 kV) and transmission (150-400 kV) lines respectively, did not find correlation between collision rates and the number of vertical levels. Thus, at least at local scales and considering all bird species, other factors may be more important or confound effects.

4.3.2 Wire height

The effect of power line height above ground on collisions is strongly dependent on flight altitude and consequently on factors such as species' flight behaviours, stage of the yearly cycle and habitats surrounding power lines (Bevanger, 1994; Brown et al., 1987); see also sections 4.1.3 and 4.2.2, respectively). There is a general agreement though that taller structures pose higher collision risks (APLIC, 1994; Haas et al., 2005; Prinsen et al., 2012), as birds approaching at wire height tend to gain altitude to fly over the obstacle rather than passing below (Beaulaurier, 1981; Luzenski et al., 2016; Murphy et al., 2009). However, very few studies have tried to evaluate the influence of wire height alone on the incidence of collision. An exception is provided by Neves et al. (2005), who found a positive correlation between collision rate (all bird species) and pylon height (range 23-33 m) of transmission lines (150-400 kV), but only when a single wire configuration (flat) and habitat (extensive farmland) were considered.

Several authors provided comparisons of collision rates between distribution and transmission lines under similar circumstances (e.g. Meyer, 1978; Ward and Anderson, 1992). These results are often used as a proxy for the effects of wire height of various power line configurations (van Rooyen and Diamond, 2008), supporting the general observation that transmission lines are associated with higher collision rates than distribution lines (Manville II, 2005; Shaw et al., 2017). This idea is supported, for instance, by Meyer (1978), focusing mostly on wildfowl and shorebirds, by Ward & Anderson (1992) with cranes, and through a comparison of the results obtained by Infante et al. (2005) and Neves et al. (2005). It should, however, be noted that in most cases wire height cannot be dissociated from others features associated with voltage, such as number and spacing of wires levels, span length, and cable diameter of conductors (compared to earth wires).

4.3.3 Wire diameter and earth wire

The probability of power line collisions is expected to depend on a bird's species-specific capacity to detect wires, and consequently on the visual perception of the various wires used (APLIC, 2012; Martin and Shaw, 2010); see also section 4.1.1). Wire diameter is widely accepted as a determinant of collision risk (e.g. Jenkins et al., 2010). However, support for this hypothesis comes almost entirely from the evaluation of the relative contribution of earth wires and phase conductors to the occurrence of bird collisions with transmission power lines (Beaulaurier, 1981; Brown et al., 1987; Faanes, 1987; Murphy et al., 2009). Earth wires almost always run along the top of the wire array and are notably thinner (~50 %) than conductors, so there is no possibility of disentangling the effects of wire height and diameter, although an experimental design to clarify this could be easily implemented.

Earth wires have been shown to account for the majority of collisions involving transmission lines. Of a total of 208 bird collisions observed in five studies, mostly through systematic observations of flight behaviour (Faanes, 1987; Meyer, 1978; Murphy et al., 2009; Scott et al., 1972), 84% involved earth wires and only 16% involved conductors. It may be that earth wires at the top of structures, interfere more with bird flight paths than the conductors below (even when the latter are on several vertical levels). There is, however, also evidence that a substantial fraction of the observed earth wire collisions or near collisions involve birds originally flying lower than the earth wires, and reacting (late) to the presence of the conductors (Faanes, 1987; Meyer, 1978; Scott et al., 1972). Reductions in collision mortality by 78% and 48% obtained through experimental removal of earth wires (Beaulaurier, 1981; Brown et al., 1987, respectively) also illustrate the relative importance of these wires.

5 STRATEGIES TO MITIGATE COLLISIONS

In this section, we describe the mitigation measures that are usually adopted to reduce collision risk associated with power lines, highlighting those that require further scientific evidence to demonstrate their effectiveness.

5.1 UNDERGROUND CABLING

Burying the power line is the only solution that completely prevents bird collisions. Low and medium-voltage power lines have been successfully laid underground, and the practice is now common in several countries, including Belgium, Germany, Norway, Netherlands and USA (Haas et al., 2005; Prinsen et al., 2012). The adoption of this solution is sometimes imposed by legal regulations or based on aesthetics, electrical system safety or reliability (Brockbank, 2014); yet on some occasions it has been exclusively justified by bird conservation concerns. For example, in Eastern Austria and Western Hungary, extensive underground cabling of distribution lines was implemented in an important area for West-Pannonian Great bustards (*O. tarda*) (Raab et al., 2012). This measure, complemented with wire marking (see section 5.4) of other lines in the area, successfully decreased the mortality rate of bustards within a short time period. In Italy, approximately one-third of the high- and medium-voltage power lines constructed at the Po Delta Regional Park were also completely or partially buried wherever they crossed critical areas for birds (Parco Regionale Delta del Po, 2005).

The effectiveness of this measure to reduce bird collisions is unquestionable. However, burying power lines is not economically feasible in all countries and terrains, especially where the electric network is growing rapidly or is already extensive, and funding for ground cabling will not be available in the near future (Antal, 2010). When technically feasible, the costs of installing underground cables can be 4-10 times higher than the construction of traditional overhead lines (Hall, 2013; Parsons Brinckerhoff, 2012). Transmission lines are particularly problematic because their burying entails greater technical and legal challenges (particularly to ensure low levels of electromagnetic fields at the surface) and consequently much higher costs (e.g. Raab et al., 2012). Higher costs are a major concern for electric utilities since not all consumers, despite the increasing public awareness of the problem, are willing to pay more for undergrounding (APLIC, 2012; Hall, 2013). Thus, worldwide it is likely that overhead power lines will remain in use for power transmission at least, unless significant impacts justify the additional costs (APLIC, 2012; Haas et al., 2005; SNH, 2016).

5.2 ROUTE PLANNING

Careful route planning is considered one of the most effective ways to mitigate bird collisions with overhead power lines (D'Amico et al., in press). European Union environmental legislation endorses this by making Strategic Environmental Assessments (SEA; SEA Directive 2001/42/EC) mandatory for all public energy plans or programmes (e.g. EirGrid, 2013). SEA aims to engage all stakeholders in the primary stages of the planning process and promote higher-level discussions so national electricity grids can expand sustainably. Strategic planning often can be helped by national and regional sensitivity maps based on modelled bird collision risk (Quinn et al., 2011; Shaw et al., 2010; Silva et al., 2014), or simply on species distribution models or locations (e.g. Allinson, 2017; Australian Government, 2015). Unfortunately, these are not always publicly available, developed or possible to achieve.

Once strategic planning is completed, it is important to consider alternative corridors for each individual project under the Environmental Impact Assessment procedure (e.g. APLIC, 2012; Haas et al., 2005; SNH, 2016; Williams, 2003). At a broader scale, power line routing should avoid large wetlands and other sensitive bird habitats, important migratory routes or protected areas designated for species of conservation concern. For example, a proposed transmission line in Nebraska (USA) that partially overlapped a federally designated migration corridor of the endangered Whooping crane (*Grus americana*), was rerouted to avoid important roosting and foraging areas by at least one mile (Tracy et al., 2012). At a finer scale, routes should avoid, to the greatest extent possible, crossing nesting and foraging sites, main flight paths of resident and migratory species, and prominent landscape features such as important rivers and mountain ridge lines (e.g. Bevanger, 1994; Faanes, 1987; Harness and Carlton, 2001; SNH, 2016; Thompson, 1978). Birds commonly take off into the wind and thus, it is recommended that power lines are orientated parallel to the prevailing wind direction (Bevanger, 1994; Heck, 2007), despite the lack of scientific evidence on the effectiveness of this practice.

According to best practice guidelines (e.g. Prinsen et al., 2012; SNH, 2016; Williams, 2003), new power lines should preferably run along existing linear elements (e.g. other power lines, rows of trees, roads, railways) to reduce habitat fragmentation and mitigate bird collisions. Some authors suggest that clustering linear obstacles can reduce collision risk as they become more visible and birds need to complete only one ascent and descent flight to cross several obstacles at once (APLIC, 1994; Bevanger, 1994; Thompson, 1978). However, few studies (e.g. Shaw, 2013) have attempted to evaluate the effectiveness of this measure in terms of the bird collision hazard. A potential unintended consequence, that multiple adjacent lines of different heights could create a fence which may increase collisions, especially in poor light conditions, has not been evaluated either.

5.3 POWER LINE CONFIGURATION

Removal of the earth wire can lead to significant reductions in bird collision rates (see section 4.3.3). However, on many occasions this measure is not a realistic option, as the earth wire is crucial to protect the power line from lightning strikes and to guarantee service reliability (APLIC, 2012).

Alternative options to adjust power line features include the arrangement of the conductors, cable diameter, span lengths (i.e. the distance between two adjacent pylons) and topographic position of the pylons. Studies carried out for the specific purpose of testing the influence of power line design on collision rates are lacking, probably because these technical details are defined a priori at the planning stage. However, it may be beneficial to reduce the number of vertical wire levels and, consequently, the collision risk zone, by changing the relative position of the conductors from a multi-level to a single level arrangement (APLIC, 2012; Bevanger, 1994; Haas et al., 2005). There is also general agreement that *i)* wires should be kept as low as possible, *ii)* span lengths should be kept as short as possible (e.g. by adding a pole mid-span) and *iii)* cabling used should be as thick as possible (APLIC, 2012; Jenkins et al., 2010; Shaw et al., 2010), but we found little scientific evidence that these recommendations are effective (see sections 4.3.2 and 4.3.3). Adoption of these measures is unlikely though, apart from when constructing new power lines or retrofitting existing lines, due to the resulting costs and technical constraints involved (e.g. right-of-way requirements, system reliability, country-specific regulations).

5.4 WIRE MARKING

The attachment of markers in the form of e.g. spirals, plates, flappers, swivels or spheres to overhead wires to increase their visibility has been by far the most common mitigation measure employed to reduce bird collisions with power lines (APLIC, 2012; Barrientos et al., 2011). Barrientos et al. (2011) conducted a meta-analysis of 21 wire-marking studies, and concluded that it decreases bird collision by 55-94% (on average, 78%). The study confirmed the overall efficacy of wire marking, although potential explanatory variables (e.g. habitat, type of marker) explaining the large variability found were not well studied, nor were potential biases like carcass persistence and detectability rates (Costantini et al., 2017; Ponce et al., 2010), or crippling (collision fatalities that "land" outside survey area or injured animals that die only after moving away from it; see Murphy et al., 2016b). In fact, wire-marking efficacy varies greatly depending on surrounding environment, target bird species and device characteristics (Jenkins et al., 2010). Thus, there is still considerable uncertainty in choosing the most effective design and arrangement for each particular circumstance.

The devices most commonly used in the 32 wire-marking studies compiled in this review were spirals or vibration dampers (51%), followed by flappers or other clamps with moving parts (32%) and clamps without moving parts (8%) (see Appendix, Figure A1 for specific examples). Some of the most recent devices on the market have not yet been included in published studies. Devices with reflective or glow-in-the-dark parts are becoming more prevalent (e.g. Murphy et al., 2016a; Sporer et al., 2013), whereas aviation balls used in the early marking experiments are generally being phased out (see references in Barrientos et al., 2011). Current trends reflect the expectation that, based on what we know of bird vision, bigger markers or closer together, markers of brighter colours and more contrast, and those with moving components should be the most effective (Martin, 2011).

There is little evidence for the comparative effectiveness of different marker types. This is due in part to limited study designs (Barrientos et al., 2011), lack of publication of studies with negative conclusions and potential variations in effectiveness of each marker type depending on the species. Most studies comparing different markers found inconclusive results (e.g. De La Zerda, 2012; Scott et al., 1972; Shaw, 2013; Sporer et al., 2013). There are, however, exceptions. For instance, Murphy et al. (2016a) found that Sandhill cranes (*Antigone canadensis*) reacted at greater distances and with more gradual avoidance behaviours to power lines marked with FireFly flappers and large double spirals than to those marked with aviation balls. Nonetheless, and depending on the circumstances, these same large spirals appear to be less effective than small spirals, although both reduce mortality rates compared to unmarked spans (Crowder, 2000; Ventana Wildlife Society, 2009). Brown & Drewien (1995) found that spiral vibration dampers were slightly more effective than plates. Both Anderson (2002) and Calabuig & Ferrer (2009) found that spirals were less effective than, respectively, flappers and clamps without moving parts. Calabuig & Ferrer (2009) found also that the colour of spirals, namely white, yellow or orange, did not affect their effectiveness in reducing mortality.

Information on optimal marker spacing is even more scarce than information on the efficacy of different marker types (Barrientos et al., 2011 and references therein). There may be an inflection point below which adding more markers improves mitigation, and above which little additional benefit is gained (Sporer et al., 2013). However, published experiments have not explored these potential thresholds (Anderson, 2002; Sporer et al., 2013). Other studies that explored marker spacing indirectly did not control confounding variables, as in Murphy et al. (2016a), who reported that closely spaced glow-in-the-dark markers were more effective in mitigating collision mortality than widely spaced non-glowing markers.

There are technical constraints that affect the possibilities and effectiveness of wire marking. For example, most transmission lines can only be marked on earth wires (which are not energized), because the attachment of devices to the conductors can result in additional corona discharges and unacceptable levels of audio noise, radio interference and power loss (e.g. Hurst, 2004; Murphy et al., 2016a). Aviation balls on a line can accumulate ice and snow in cold weather, and can be misleading to human pilots when installed for bird safety rather than around airports. For those reasons, aviation balls have mostly been replaced by spirals, which are less problematic in these regards (Bevanger et al., 2014). The recent shift toward flappers reduces ice loading but can be problematic because flappers are less durable, falling more easily from the wire (Dashnyam et al., 2016; Sporer et al., 2013). High wind also can twist flappers locking them into fixed positions, reducing their effectiveness (Dashnyam et al., 2016). However, recent modifications by line marker manufacturers are intended to address these concerns.

5.5 HABITAT MANAGEMENT

Habitats present along or near power line rights-of-way can be attractive to some bird species (e.g. Tryjanowski et al., 2013), increasing their exposure to collision (see section 3.2). Thus, a suggested strategy to change local flight paths and prevent bird collisions is the modification of adjacent habitats, land uses or management practices (APLIC, 2012; Thompson, 1978). For instance, when a power line is located between a feeding area and a roosting site and birds cross it regularly during low altitude flights (e.g.

Harness and Carlton, 2001), it could be helpful to reduce the crossing frequency by creating new feeding and roosting areas on one side of the power line.

Habitat management approaches may face significant implementation constraints as *i)* landowners are usually reluctant to implement land use changes; *ii)* changes of flight paths and land usage by birds are hard to achieve; and *iii)* actions targeting a specific species may cause negative effects on other species that need to be properly addressed.

Another possibility is to distract or deter birds from the vicinity of power lines. Taking advantage of their high-resolution lateral vision (e.g. to look for conspecifics and foraging opportunities), Martin (2011) and others (e.g. APLIC, 2012; Thompson, 1978) suggest the creation of foraging patches to encourage birds to land before encountering a power line obstacle, or to install visual stimuli and alerting sounds (placed at a suitable distance from the power line) to help birds change their intended flight path. Collisions caused by frightened birds may be reduced by restricting high-disturbance activities on power line rights-of-way (e.g. limiting hunting activities, reducing speed limits on nearby roads) (APLIC, 2012; Thompson, 1978). However, very few studies have tested the efficacy of such measures, and those that have yielded contradictory results. For instance, Heijnis (1980) found that the use of raptor silhouettes (falcon/hawk) resulted in a significant decrease in collision frequency; while, Janss et al. (1999) found that decoys (*Aquila* sp. and *Accipiter* sp.) had no effect on collisions or the potential for collisions, and actually underwent a high number of attacks from other raptors.

6 KNOWLEDGE GAPS AND FUTURE PERSPECTIVES

Overall, our literature review shows (i) there is comparatively little scientific evidence for power line-specific factors, namely what is the impact of the number of vertical levels, or wire height and diameter; (ii) more studies from Asia, Africa and South America are needed, as addressing bird species or power line features specific of these regions of the planet will increase overall scientific knowledge, eventually enabling the identification of conservation-valued species that might be impacted at population-level in these specific geographical contexts. Eventually some studies from these regions might exist in local reports/ languages, and this information should be published on international journals to make a better use of this research; and (iii) several recommendations of good practice are still not supported by scientific evidence, e.g. clustering new power lines with other existing linear elements, or habitat management to change local flight paths and prevent bird collisions.

Identified knowledge gaps and suggestions for research and innovative approaches are summarised in Table 1, divided into three major topics (behaviour aspects, impact assessment and mitigation measures). Here we highlight those we considered of highest priority.

6.1 BIRD BEHAVIOUR AND PERCEPTION

The main research challenges in terms of bird behaviour relate to understanding the conditions under which flight patterns increase collision risk, as well as understanding the level of perception of power line cables by birds. Information from birds with state-of-the-art tracking devices allowing a high frequency sampling effort can be particularly useful to characterise flight behaviour (height and pattern) in three-dimensional space. This can be translated to collision risk (Luzenski et al., 2016), and related to topography and local weather conditions. Data from birds tracked with precision loggers could allow for unbiased assessment of different anthropogenic causes of mortality. Sensors to identify collisions of tracked birds could expand our knowledge of habitat drivers and power line configuration on mortality, as well as enabling more accurate mortality estimates, including a better assessment of crippling bias (see section 6.3).

In parallel, understanding the level of visual perception of power line cables and wire markers by birds is another important research area. More information on interspecific differences in visual acuity and colour- and UV-perception, could contribute to understanding differences in collision risk and help in the design of more efficient markers. Experimental approaches have an important role here (e.g. Martin and Shaw, 2010), although detailed behavioural studies of tracked birds crossing power lines could also yield valuable data (e.g. changes in behaviour and reaction distances).

6.2 IMPACT ASSESSMENT

Increased knowledge of factors underlying mortality hotspots (e.g. Prinsen et al., 2012; Quinn et al., 2011) is key to identifying sensitive areas that should be prioritised for mitigation. This is particularly important in regions where the electricity grid is expected to increase most, such as Asia (IEA, 2016).

One of the most challenging research questions is to what extent collision mortality causes population-level impacts (Loss et al., 2015). This requires research on both key demographic parameters for population viability analysis (Jenkins et al., 2011) and on the development of suitable modelling approaches that enable clarification of the degree to which anthropogenic mortality is compensatory (at least some individuals killed would have died in the absence of collisions) or additive (killed birds would not have died otherwise) (Loss et al., 2015). Addressing cumulative impacts from multiple sources of mortality is a particularly important (although difficult) challenge. Examples of studies addressing these issues are mostly focussed on electrocution (e.g. Chevallier et al., 2015; Hernández-Matías et al., 2015), although a few studies dealing with collisions exist

(Bevanger et al., 2014; Schaub and Pradel, 2004). The conduction of impact assessment studies that integrate multiple projects, such as wind and solar energy facilities and the associated power lines, should become a common practice to optimize the decision-making process and managing of cumulative impacts. Ideally, long term monitoring would be implemented to assess local-level and population-level impacts, in particular for high priority species.

Current methods to evaluate and quantify bird collision mortality usually use field surveys where human observers (sometimes with the help of dogs) search for dead birds or their remains under power lines. Such surveys are constrained by several limitations and biases. Research effort should be focused on technological advances towards the automated detection of collisions that in the future may replace traditional field surveys. This would also be helpful for evaluating the effectiveness of wire marking. Bird strike indicators - a vibration-sensing and recording tool designed to detect bird collisions (e.g. Harness et al., 2003; Pandey et al., 2008) - are a promising tool, and existing data strongly suggests these devices can significantly outperform traditional corrected-count mortality estimators (Murphy et al., 2016b).

While automated detection of collisions is not fully developed and widespread, standardisation of field methods for mortality assessments is badly needed. This is a priority shared with wind turbine impact research (Piorkowski et al., 2012) as it will improve the reliability and accuracy of both data collection and research conclusions (Hunting, 2002). The wide diversity of approaches and techniques currently used during field surveys (Loss et al., 2015) hinders comparison across studies and reduces the value of data for meta-analysis in drawing reliable conclusions (Barrientos et al., 2011). A further drawback of currently used approaches is that studies are biased towards lines with known collision problems, which hinders extrapolation to population-level impacts.

Biases involved in bird mortality estimates through classic surveys – carcass removal by scavengers, searcher efficiency and crippling bias - represent three particular areas for further research (Murphy et al., 2016b; Ponce et al., 2010; Rioux et al., 2013). Further research is also needed to refine the estimators used to correct for those biases (Bernardino et al., 2013; Huso et al., 2016; Stevens and Dennis, 2013).

6.3 MITIGATION MEASURES

Improving our knowledge on the effectiveness of mitigation measures relies mostly on implementation of experimental before-after-control-impact (BACI) monitoring designs including test and control segments and sampling before implementation of the measure (Barrientos et al., 2011; Thiault et al., 2017). Further studies on comparing different types of devices (including glow-in-the-dark) and colours, together with the effects of habitat and weather on device effectiveness are badly needed (e.g. Sporer et al., 2013; Yee, 2008), as well on device durability and technical limitations (e.g. Dashnyam et al., 2016; Hurst, 2004). Optimal spacing is another priority area for research, with Sporer et al. (2013) hypothesising that there is a threshold density above which adding more line markers should provide little additional benefit. The use of other mitigation measures should be further investigated, such as thickening, coating or colouring of least visible wires, and acoustic or silhouette scaring methods (Bevanger, 1994; Swaddle and Ingrassia, 2017).

A final topic to clarify is power line configuration and optimal-routing. There is scarce scientific evidence on the effect of conductor arrangement (horizontal or vertical) (Bevanger, 1994), and the recommendation for grouping power lines in a common corridor (APLIC, 2012) has never, to our knowledge, been robustly assessed.

7 ACKNOWLEDGEMENTS

FM, JB and RCM work was carried out in the framework of REN Biodiversity Chair, funded by REN - Redes Energéticas Nacionais and Fundação para a Ciência e a Tecnologia (FCT). JB also benefited from a doctoral grant (SFRH/BD/117845/2016) from FCT. ATM work was funded by FCT, under the doctoral grant (SFRH/BD/100147/2014). JPS work was funded by FCT, under the postdoctoral grant (SFRH/BPD/111084/2015). RB would like to thank to Infraestruturas de Portugal Biodiversity Chair.

We are thankful to Rowena Langston for her suggestions and comments to the manuscript. Finally, we would like to thank the many colleagues with whom we have worked on studies of avian collision. Though too numerous to name, this work would not have been possible without their numerous insights over many decades of research.

8 ONLINE SUPPLEMENTARY MATERIAL

Table A1 – List of studies compiled through systematic literature search.

Table A2 – List of additional studies included in the review, besides the studies compiled through systematic literature search.

Figure A1 – Examples of some common line markers currently available on the market.

9 REFERENCES

Allinson, T., 2017. Introducing a New Avian Sensitivity Mapping Tool to Support the Siting of Wind Farms and Power Lines in the Middle East and Northeast Africa, in: Köppel, J. (Ed.), Wind Energy and Wildlife Interactions: Presentations from the

CWW2015 Conference. Springer International Publishing, Cham, pp. 207–218. doi:10.1007/978-3-319-51272-3_12

Alonso, J.A., Alonso, J.C., 1999. Collision of birds with overhead transmission lines in Spain, in: Ferrer, M., Janss, G.F.E. (Eds.), Birds and Power Lines: Collision, Electrocution, and Breeding. Quercus, Madrid, pp. 57–82.

Alonso, J.C., Alonso, J.A., Muñoz-Pulido, R., 1994. Mitigation of bird collisions with transmission lines through groundwire marking. Biol. Conserv. 67, 129–134. doi:https://doi.org/10.1016/0006-3207(94)90358-1

Anderson, M.D., 2002. The effectiveness of two different marking devices to reduce large terrestrial bird collisions with overhead electricity cables in the eastern Karoo, South Africa. Johannesburg, South Africa.

Anderson, W.L., 1978. Waterfowl Collisions with Power Lines at a Coal-Fired Power Plant. Wildl. Soc. Bull. 6, 77–83.

Andriushchenko, Y.A., Popenko, V.M., 2012. Birds and Power Lines in Steppe Crimea: Positive and Negative Impacts, Ukraine. Raptors Conserv. 24, 34–41.

Antal, M., 2010. Policy measures to address bird interactions with power lines – a comparative case study of four countries. Ostrich 81, 217–223. doi:10.2989/00306525.2010.517921

APLIC, 2012. Reducing avian collisions with power lines: The state of the art in 2012. Washington, DC.

APLIC, 1994. Mitigating bird collisions with power lines: the state of the art in 1994. Washington, D.C.

Australian Government, D. of the E., 2015. Draft referral guideline for 14 birds listed as migratory species under the EPBC Act, Commonwealth of Australia 2015. Canberra.

Avery, M., Springer, P.F., Cassel, J.F., 1977. Weather Influences on Nocturnal Bird Mortality at a North Dakota Tower. Wilson Bull. 89, 291–299.

Baines, D., Summers, R.W., 1997. Assessment of Bird Collisions with Deer Fences in Scottish Forests. J. Appl. Ecol. 34, 941–948. doi:10.2307/2405284

Barrientos, R., Alonso, J.C., Ponce, C., Palacín, C., 2011. Meta-analysis of the effectiveness of marked wire in reducing avian collisions with power lines. Conserv. Biol. 25, 893–903. doi:10.1111/j.1523-1739.2011.01699.x

Barrientos, R., Ponce, C., Palacín, C., Martín, C.A., Martín, B., Alonso, J.C., 2012. Wire Marking Results in a Small but Significant Reduction in Avian Mortality at Power Lines: A BACI Designed Study. PLoS One 7, e32569. doi:10.1371/journal.pone.0032569

Beaulaurier, D.L., 1981. Mitigation of bird collisions with transmission lines. Portland, Oregon, USA.

Bergman, G., 1978. Effects of Wind Conditions on the Autumn Migration of Waterfowl between the White Sea Area and the Baltic Region. Oikos 30, 393–397. doi:10.2307/3543488

Bernardino, J., Bispo, R., Costa, H., Mascarenhas, M., 2013. Estimating bird and bat fatality at wind farms: a practical overview of estimators, their assumptions and limitations. New Zeal. J. Zool. 40, 63–74. doi:10.1080/03014223.2012.758155

Bevanger, K., 1998. Biological and conservation aspects of bird mortality caused by electricity power lines: a review. Biol. Conserv. 86, 67–76. doi:10.1016/S0006-3207(97)00176-6

Bevanger, K., 1995a. Estimates and Population Consequences of Tetraonid Mortality Caused by Collisions with High Tension Power Lines in Norway. J. Appl. Ecol. 32, 745–753. doi:10.2307/2404814

Bevanger, K., 1995b. Tetraonid mortality caused by collisions with power lines in boreal forest habitats in central Norway. Fauna Nor. Ser. C Cinclus 18, 41–51.

Bevanger, K., 1994. Bird interactions with utility structures: collision and electrocution, causes and mitigating measures. Ibis. 136, 412–425.

Bevanger, K., 1993. Bird collisions with a 220 kV transmission line in Polmak, Finnmark.

Bevanger, K., 1990. Topographic aspects of transmission wire collision hazard to game birds in Central Norwegian forest. Fauna Nor. Ser. C Cinclus 13, 11–18.

Bevanger, K., Brøseth, H., 2004. Impact of power lines on bird mortality in a subalpine area. Anim. Biodivers. Conserv. 27, 67–77.

Bevanger, K., Brøseth, H., 2001. Bird collisions with power lines — an experiment with ptarmigan (Lagopus spp.). Biol. Conserv. 99, 341–346. doi:10.1016/S0006-3207(00)00217-2

Bevanger, K., Brøseth, H., 2000. Reindeer Rangifer tarandus fences as a mortality factor for ptarmigan Lagopus spp. Wildlife Biol. 6, 121–127.

Bevanger, K.M., Bartzke, G., Brøseth, H., Dahl, E.L., Gjershaug, J.O., Hanssen, F.O., Jacobsen, K.-O., Kleven, O., Kvaløy, P., May, R.F., Meås, R., Nygård, T., Refsnæs, S., Stokke, S., Thomassen, J., 2014. Optimal design and routing of power lines; ecological technical and economic perspectives (OPTIPOL). Final Report, findings 2009 – 2014. Trondheim.

Blokpoel, H., Hatch, D.R.M., 1977. Snow geese, disturbed by aircraft, crash into power lines. Can. F. Nat. 90, 195.

Brockbank, R.A., 2014. Environmental Effects of Underground and Overhead Transmission Line Construction and Maintenance, in: Doucet, J. (Ed.), Proceedings of the 10th International Symposium on Environmental Concerns in Rights-of-Way Management. pp. 37–69.

Brown, W.M., Drewien, R.C., 1995. Evaluation of Two Power Line Markers to Reduce Crane and Waterfowl Collision Mortality. Wildl. Soc. Bull. 23, 217–227.

Brown, W.M., Drewien, R.C., Bizeau, E.G., 1987. Mortality of cranes and waterfowl from power line collisions in the San Luis Valley, in: Lewis, J.C. (Ed.), Proceedings 1985 Crane Workshop. Platte River Whooping Crane Maintenance Trust, Grand Island, Nebraska, pp. 128–136.

Calabuig, C.P., Ferrer, M., 2009. Análisis de la eficacia y la vida útil de la señalización anticolisión “salvapájaros” en líneas de transporte de energía eléctrica. Seville, España.

Chevallier, C., Hernández-Matías, A., Real, J., Vincent-Martin, N., Ravayrol, A., Besnard, A., 2015. Retrofitting of power lines effectively reduces mortality by electrocution in large birds: an example with the endangered Bonelli’s eagle. J. Appl. Ecol. 52, 1465–1473. doi:10.1111/1365-2664.12476

CIGRE, 2017. International Council on Large Electric Systems [WWW Document]. Off. website. URL http://www.cigre.org/ (accessed 8.1.17).

Costantini, D., Gustin, M., Ferrarini, A., Dell’Omo, G., 2017. Estimates of avian collision with power lines and carcass disappearance across differing environments. Anim. Conserv. 20, 173–181. doi:10.1111/acv.12303

Crivelli, A.J., Jerrentrup, H., Mitchev, T., 1988. Electric Power Lines: A Cause of Mortality in Pelecanus crispus Bruch, a World Endangered Bird Species, in Porto-Lago, Greece. Colon. Waterbirds 11, 301–305. doi:10.2307/1521012

Crowder, M.R., 2000. Assessment of devices designed to lower the incidence of avian power lines strikes. Purdue University.

Cuthill, I.C., Partridge, J.C., Bennett, A.T.D., Church, S.C., Hart, N.S., Hunt, S., 2000. Ultraviolet Vision in Birds. Adv. Study Behav. 29, 159–214. doi:10.1016/S0065-3454(08)60105-9

D'Amico, M., Catry, I., Martins, R.C., Ascensão, F., Barrientos, R., Moreira, F., (in press). Bird on the wire: landscape planning considering costs and benefits for bird populations coexisting with power lines. Ambio. A J. Hum. Environ.

Dashnyam, B., Purevsuren, T., Amarsaikhan, S., Bataa, D., Buuveibaatar, B., Dutson, G., 2016. Malfunction rates of bird flight diverters on powerlines in the Mongolian Gobi. Mong. J. Biol. Sci. 14, 13–20. doi:10.22353/mjbs.2016.14.02

De La Zerda, S., 2012. Testing the Effectiveness of a Colombian-Designed Bird Flight Diverter to Mitigate Collisions with Transmission Lines, in: Evans, J.M., Goodrich-Mahoney, J.W., Mutrie, D., Reinemann, J. (Eds.), Proceedings of the 9th International Symposium on Environmental Concerns in Rights-of-Way Management. pp. 209–220.

Deng, J., Frederick, P., 2001. Nocturnal Flight Behavior of Waterbirds in Close Proximity to a Transmission Powerline in the Florida Everglades. Waterbirds Int. J. Waterbird Biol. 24, 419–424. doi:10.2307/1522074

Drewitt, A.L., Langston, R.H.W., 2008. Collision effects of wind-power generators and other obstacles on birds. Ann. N. Y. Acad. Sci. 1134, 233–66. doi:10.1196/annals.1439.015

EirGrid, 2013. SEA statement of the GRID25: Implementation Programme 2011-2016. Dublin, Ireland.

Elkins, N., 1988. Weather and bird behaviour. T. & A.D. Poyser, Calton, England.

Erickson, W.P., Johnson, G.D., Jr, D.P.Y., 2005. A summary and comparison of bird mortality from anthropogenic causes with an emphasis on collisions, General Technical Reports.

Faanes, C.A., 1987. Bird behavior and mortality in relation to power lines in prairie habitats, Technical Report. Washington, DC.

Fernández-Juricic, E., Gall, M.D., Dolan, T., Tisdale, V., Martin, G.R., 2008. The visual fields of two ground-foraging birds, House Finches and House Sparrows, allow for simultaneous foraging and anti-predator vigilance. Ibis (Lond. 1859). 150, 779–787. doi:10.1111/j.1474-919X.2008.00860.x

Garrido, J.R., Fernandez-Cruz, M., 2003. Effects of power lines on a White Stork Ciconia

ciconia population in central Spain. Ardeola 50, 191–200.

Gauthreaux, S.A., 1978. Migratory behavior and flight patterns, in: Avery, M.L. (Ed.), Proceedings of the workshop “Impacts of Transmission Lines on Birds in Flight.” U.S. Fish and Wildlife Service, Washington, D.C., pp. 12–26.

Gellings, C.W., 2015. Let’s Build a Global Power Grid: With a little DC wizardry and a lot of cash, we could swap power across continents [WWW Document]. IEEE Spectr. URL http://spectrum.ieee.org/energy/the-smarter-grid/lets-build-a-global-power-grid

Geyr von Schweppenburg, H.F., 1929. „Zugstraßen“ - Leitlinien. J. Orn. Erg. Bd. (Festschrift Hartert) 17–32.

Haas, D., Nipkow, M., Fiedler, G., Scheneider, R., Haas, W., Schürenberg, B., 2005. Protecting birds from powerlines. Nature and environment 140.

Haddaway, N.R., Collins, A.M., Coughlin, D., Kirk, S., 2015. The Role of Google Scholar in Evidence Reviews and Its Applicability to Grey Literature Searching. PLoS One 10, e0138237. doi:10.1371/journal.pone.0138237

Hall, K.L., 2013. Out of Sight, Out of Mind 2012: An Updated Study on the Undergrounding Of Overhead Power Lines. Washington, D.C.

Harness, R., Pandey, A., Phillips, G., 2003. Bird Strike Indicator/Bird Activity Monitor and Field Assessment of Avian Fatalities.

Harness, R.E., Carlton, R., 2001. New Solutions for Bird Collision and Electrocution Outage Problems, in: Proceedings of the 2001 IEEE Power Engineering Society Winter Meeting. pp. 341–354. doi:10.1109/PESW.2001.917060

Heck, N., 2007. A landscape-scale model to predict the risk of bird collisions with electric power transmission lines in Alberta. University of Calgary, Faculty of Environmental Design.

Hedenström, A., 2002. Aerodynamics, evolution and ecology of avian flight. Trends Ecol. Evol. 17, 415–422. doi:10.1016/S0169-5347(02)02568-5

Heijnis, R., 1980. Vogeltod durch Drathanflüge bei Hochspannungsleitungen. Okol Vogel. 2, 111–129.

Henderson, I.G., Langston, R.H.W., Clark, N.A., 1996. The response of common terns Sterna hirundo to power lines: An assessment of risk in relation to breeding commitment, age and wind speed. Biol. Conserv. 77, 185–192. doi:10.1016/0006-3207(95)00144-1

Bernardino, J et al 2018 Bird collisions with power lines: State of the art and priority areas for research. Biological Conservation 2018 ;Volum 222. s. 1-13 10.1016/j.biocon.2018.02.029 CC-BY-NC-ND

Hernández-Matías, A., Real, J., Parés, F., Pradel, R., 2015. Electrocution threatens the viability of populations of the endangered Bonelli's eagle (Aquila fasciata) in Southern Europe. Biol. Conserv. 191, 110–116. doi:10.1016/j.biocon.2015.06.028

Hobbs, J.C.A., 1987. Powerlines and gamebirds: North American experiences for southern Africa. South African Wildl. Res. Suppl. 1, 24–31.

Hunting, K., 2002. A roadmap for PIER research on avian collisions with power lines in California.

Hüppop, O., Hüppop, K., Dierschke, J., Hill, R., 2016. Bird collisions at an offshore platform in the North Sea. Bird Study 63, 73–82. doi:10.1080/00063657.2015.1134440

Hurst, N., 2004. Corona Testing of Devices Used to Mitigate Bird Collisions.

Huso, M., Dalthorp, D., Miller, T.J., Bruns, D., 2016. Wind energy development: methods to assess bird and bat fatality rates post-construction. Human-Wildlife Interact. 10, 62–70.

IEA, 2016. World Energy Outlook 2016. International Energy Agency, Paris, France.

Infante, S., Neves, J., Ministro, J., Brandão, R., 2005. Impact of distribution and transmission power lines on birds in Portugal (in Portuguese). Castelo Branco, Portugal.

Janss, G.F.E., 2000. Avian mortality from power lines: a morphologic approach of a species-specific mortality. Biol. Conserv. 95, 353–359. doi:10.1016/S0006-3207(00)00021-5

Janss, G.F.E., Ferrer, M., 2000. Common Crane and Great Bustard Collision with Power Lines: Collision Rate and Risk Exposure. Wildl. Soc. Bull. 28, 675–680.

Janss, G.F.E., Lazo, A., Ferrer, M., 1999. Use of raptor models to reduce avian collisions with powerlines. J. Raptor Res. 33, 154–159.

Jenkins, A.R., Shaw, J.M., Smallie, J.J., Gibbons, B., Visagie, R., Ryan, P.G., 2011. Estimating the impacts of power line collisions on Ludwig's Bustards Neotis ludwigii. Bird Conserv. Int. 21, 303–310. doi:DOI: 10.1017/S0959270911000128

Jenkins, A.R., Smallie, J.J., Diamond, M., 2010. Avian collisions with power lines: a global review of causes and mitigation with a South African perspective. Bird Conserv. Int. 20, 263–278. doi:10.1017/S0959270910000122

Kelly, A., Kelly, S., 2005. Are Mute Swans with Elevated Blood Lead Levels More Likely to Collide with Overhead Power Lines? Waterbirds Int. J. Waterbird Biol. 28, 331–334.

Krapu, G.L., 1974. Avian mortality from collisions with overhead wires in North Dakota. Prairie Nat. 6, 1–6.

Lee, J.M., 1978. Effects of transmission lines on bird flights: studies of Bonneville Power Administration Lines, in: Avery, M. (Ed.), Proceedings of the workshop “Impacts of Transmission Lines on Birds in Flight.” pp. 53–68.

Lind, O., Mitkus, M., Olsson, P., Kelber, A., 2014. Ultraviolet vision in birds: the importance of transparent eye media. Proceedings. Biol. Sci. 281, 20132209. doi:10.1098/rspb.2013.2209

Lisney, T.J., Iwaniuk, A.N., Kolominsky, J., Bandet, M. V, Corfield, J.R., Wylie, D.R., 2012. Interspecific variation in eye shape and retinal topography in seven species of galliform birds (Aves: Galliformes: Phasianidae). J. Comp. Physiol. A 198, 717–731.

Loss, S.R., Will, T., Marra, P.P., 2015. Direct Mortality of Birds from Anthropogenic Causes. Annu. Rev. Ecol. Evol. Syst. 46, 99–120. doi:10.1146/annurev-ecolsys-112414-054133

Loss, S.R., Will, T., Marra, P.P., 2014. Refining Estimates of Bird Collision and Electrocution Mortality at Power Lines in the United States. PLoS One 9, e101565. doi:10.1371/journal.pone.0101565

Loss, S.R., Will, T., Marra, P.P., 2012. Direct human-caused mortality of birds: improving quantification of magnitude and assessment of population impact. Front. Ecol. Environ. 10, 357–364. doi:10.1890/110251

Luzenski, J., Rocca, C.E., Harness, R.E., Cummings, J.L., Austin, D.D., Landon, M.A., Dwyer, J.F., 2016. Collision avoidance by migrating raptors encountering a new electric power transmission line. Condor 118, 402–410. doi:10.1650/CONDOR-15-55.1

Malcolm, J.M., 1982. Bird Collisions with a Power Transmission Line and Their Relation to Botulism at a Montana Wetland. Wildl. Soc. Bull. 10, 297–304.

Manosa, S., Real, J., 2001. Potential negative effects of collisions with transmission lines on a Bonelli’s Eagle population. J. Raptor Res. 35, 247–252.

Manville II, A.M., 2005. Bird Strikes and Electrocutions at Power Lines, Communication Towers, and Wind Turbines: State of the Art and State of the Science – Next Steps

Toward Mitigation.

Martin, G.R., 2012. Through birds' eyes: insights into avian sensory ecology. J. Ornithol. 153, 23–48. doi:10.1007/s10336-011-0771-5

Martin, G.R., 2011. Understanding bird collisions with man-made objects: a sensory ecology approach. Ibis. 153, 239–254. doi:10.1111/j.1474-919X.2011.01117.x

Martin, G.R., 2009. What is binocular vision for? A birds' eye view. J. Vis. 9, 14.1–19. doi:10.1167/9.11.14

Martin, G.R., 1990. Birds by Night. Poyser Monographs.

Martin, G.R., 1985. Eye, in: King, A.S., McLelland, J. (Eds.), Form and Function in Birds, Volume 3. Academic Press, London, pp. 311–373.

Martin, G.R., Osorio, D., 2008. Vision in birds, in: Masland, R.H., Albright, T. (Eds.), The Senses: A Comprehensive Reference. Elsevier, pp. 25–52.

Martin, G.R., Portugal, S.J., Murn, C.P., 2012. Visual fields, foraging and collision vulnerability in Gyps vultures. Ibis. 154, 626–631.

Martin, G.R., Shaw, J.M., 2010. Bird collisions with power lines: Failing to see the way ahead? Biol. Conserv. 143, 2695–2702. doi:10.1016/j.biocon.2010.07.014

McNeil, R., Rodriguez, J.R.S., Ouellet, H., 1985. Bird mortality at a power transmission line in Northeastern Venezuela. Biol. Conserv. 31, 153–165. doi:10.1016/0006-3207(85)90046-1

Meyer, J.R., 1978. Effects of Transmission Lines on Bird Flight Behavior and Collision Mortality. Portland, Oregon, USA.

Miller, W.A., 1978. Transmission line engineering and its relationship to migratory birds, in: Avery, M. (Ed.), Proceedings of the workshop "Impacts of Transmission Lines on Birds in Flight." U.S. Fish and Wildlife Service, pp. 77–86.

Mojica, E.K., Watts, B.D., Paul, J.T., Voss, S.T., Pottie, J., 2009. Factors Contributing to Bald Eagle Electrocutions and Line Collisions on Aberdeen Proving Ground, Maryland. J. Raptor Res. 43, 57–61. doi:10.3356/JRR-07-60.1

Murphy, R.K., Dwyer, J.F., Mojica, E.K., McPherron, M.M., Harness, R.E., 2016a. Reactions of Sandhill Cranes Approaching a Marked Transmission Power Line. J. Fish Wildl. Manag. 7, 480–489. doi:10.3996/052016-JFWM-037

Murphy, R.K., McPherron, S.M., Wright, G.D., Serbousek, K.L., 2009. Effectiveness of avian collision averters in preventing migratory bird mortality from powerline strikes in the central Platte River, Nebraska. Grand Island, Nebraska, USA.

Murphy, R.K., Mojica, E.K., Dwyer, J.F., McPherron, M.M., Wright, G.D., Harness, R.E., Pandey, A.K., Serbousek, K.L., 2016b. Crippling and Nocturnal Biases in a Study of Sandhill Crane (Grus canadensis) Collisions with a Transmission Line. Waterbirds 39, 312–317. doi:10.1675/063.039.0312

Neves, J., Infante, S., Ministro, J., Brandão, R., 2005. Impact of transmission lines on birds in Portugal (in Portuguese). Castelo Branco, Portugal.

Newton, I., 2010. The Migration Ecology of Birds. Elsevier Science.

Norberg, U.M., 1990. Vertebrate Flight. Mechanics, Physiology, Morphology, Ecology and Evolution. Springer. doi:10.1007/978-3-642-83848-4

Ödeen, A., Håstad, O., Alström, P., 2011. Evolution of ultraviolet vision in the largest avian radiation - the passerines. BMC Evol. Biol. 11, 313. doi:10.1186/1471-2148-11-313

Palacín, C., Alonso, J.C., Martín, C.A., Alonso, J.A., 2017. Changes in bird-migration patterns associated with human-induced mortality. Conserv. Biol. 31, 106–115. doi:10.1111/cobi.12758

Pandey, A., Harness, R., Schriner, M.K., 2008. Bird Strike Indicator Field Deployment at the Audubon National Wildlife Refuge in North Dakota: Phase Two.

Parco Regionale Delta del Po, 2005. Free skies over the Delta:a sustainable electricity network in the Regional Parl Area.

Parsons Brinckerhoff, 2012. Electricity Transmission Costing Study.

Perdeck, A.C., Speek, B.J., 1984. A radar study of the influence of expected ground speed, cloudiness, and temperature on diurnal migrating intensity. Ardea 72, 189–198.

Piorkowski, M.D., Farnsworth, A.J., Fry, M., Rohrbaugh, R.W., Fitzpatrick, J.W., Rosenberg, K. V, 2012. Research priorities for wind energy and migratory wildlife. J. Wildl. Manage. 76, 451–456. doi:10.1002/jwmg.327

Ponce, C., Alonso, J.C., Argandoña, G., García Fernández, A., Carrasco, M., 2010. Carcass removal by scavengers and search accuracy affect bird mortality estimates at power lines. Anim. Conserv. 13, 603–612. doi:10.1111/j.1469-1795.2010.00387.x

Prinsen, H.A.M., Boere, G.C., Píres, N., Smallie, J.J., 2011. Review of conflict between migratory birds and electricity power grids in the African-Eurasian region.

Prinsen, H.A.M., Smallie, J.J., Boere, G.C., Píres, N., 2012. Guidelines on How to Avoid or Mitigate Impact of Electricity Power Grids on Migratory Birds in the African-Eurasian Region. Bonn, Germany.

Quinn, M., Alexander, S., Heck, N., Chernoff, G., 2011. Identification of Bird Collision Hotspots along Transmission Power Lines Alberta: An Expert-Based Geographic Information System (GIS) Approach. J. Environ. Informatics 18, 12–21. doi:10.3808/jei.201100194

Raab, R., Schütz, C., Spakovszky, P., Julius, E., Schulze, C.H., 2012. Underground cabling and marking of power lines: conservation measures rapidly reduced mortality of West-Pannonian Great Bustards Otis tarda. Bird Conserv. Int. 22, 299–306. doi:DOI: 10.1017/S0959270911000463

Rayner, J.M. V, 1988. Form and Function in Avian Flight, in: Johnston, R.F. (Ed.), Current Ornithology, Vol. 5. Springer US, Boston, MA, pp. 1–66. doi:10.1007/978-1-4615-6787-5_1

Reiter, A.S., 2000. Casualties of Great Bustards (Otis tarda L.) on overhead power lines in the western Weinviertel (Lower Austria). Egretta 43, 37–54.

Reymond, L., 1987. Spatial visual acuity of the falcon, Falco berigora: A behavioural, optical and anatomical investigation. Vision Res. 27, 1859–1874. doi:10.1016/0042-6989(87)90114-3

Reymond, L., 1985. Spatial visual acuity of the eagle Aquila audax: a behavioural, optical and anatomical investigation. Vision Res. 25, 1477–1491. doi:10.1016/0042-6989(85)90226-3

Richardson, M.L., Wilson, B.A., Aiuto, D.A.S., Crosby, J.E., Alonso, A., Dallmeier, F., Golinski, G.K., 2017. A review of the impact of pipelines and power lines on biodiversity and strategies for mitigation. Biodivers. Conserv. 26, 1801–1815. doi:10.1007/s10531-017-1341-9

Rioux, S., Savard, J.-P.L., Gerick, A.A., 2013. Avian mortalities due to transmission line collisions: a review of current estimates and field methods with an emphasis on applications to the Canadian electric network. Avian Conserv. Ecol. 8. doi:10.5751/ACE-00614-080207

Rogers, L.J., 2008. Development and function of lateralization in the avian brain. Brain Res. Bull. 76, 235–244. doi:10.1016/j.brainresbull.2008.02.001

Rollan, À., Real, J., Bosch, R., Tintó, A., Hernández-Matías, A., 2010. Modelling the risk of collision with power lines in Bonelli's Eagle Hieraaetus fasciatus and its conservation implications. Bird Conserv. Int. 20, 279–294. doi:DOI: 10.1017/S0959270910000250

Rubolini, D., Gustin, M., Bogliani, G., Garavaglia, R., 2005. Birds and powerlines in Italy: an assessment. Bird Conserv. Int. 15, 131–145. doi: 10.1017/S0959270905000109

Sastre, P., Ponce, C., Palacín, C., Martín, C.A., Alonso, J.C., 2009. Disturbances to great bustards (Otis tarda) in central Spain: human activities, bird responses and management implications. Eur. J. Wildl. Res. 55, 425–432. doi:10.1007/s10344-009-0254-7

Savereno, A.J., Savereno, L.A., Boettcher, R., Haig, S.M., 1996. Avian behavior and mortality at power lines in coastal South Carolina. Wildl. Soc. Bull. 24, 636–648.

Schaub, M., Aebischer, A., Gimenez, O., Berger, S., Arlettaz, R., 2010. Massive immigration balances high anthropogenic mortality in a stable eagle owl population: Lessons for conservation. Biol. Conserv. 143, 1911–1918. doi:10.1016/j.biocon.2010.04.047

Schaub, M., Pradel, R., 2004. Assessing the relative importance of different sources of mortality from recoveries of marked animals. Ecology 85, 930–938. doi:10.1890/03-0012

Schmidt-Morand, D., 1992. Vision in the animal kingdom. Vet. Int. 4, 3–32.

Schroeder, C.H., 1977. Geese Hit Power Transmission line. Outdoors, 40(2) inside cover.

Scott, R.E., Roberts, L.J., Cadbury, C.J., 1972. Bird deaths from power lines at Dungeness. Br. birds 65, 273–286.

Shaw, J.M., 2013. Power line collisions in the Karoo conserving Ludwig's bustard. University of Cape Town.

Shaw, J.M., Jenkins, A.R., Smallie, J.J., Ryan, P.G., 2010. Modelling power-line collision risk for the Blue Crane Anthropoides paradiseus in South Africa. Ibis (Lond. 1859). 152, 590–599. doi:10.1111/j.1474-919X.2010.01039.x

Shaw, J.M., Reid, T.A., Schutgens, M., Jenkins, A.R., Ryan, P.G., 2017. High power line collision mortality of threatened bustards at a regional scale in the Karoo, South Africa. Ibis (Lond. 1859). doi:10.1111/ibi.12553

Shimada, T., 2001. Choice of Daily Flight Routes of Greater White-Fronted Geese:

Effects of Power Lines. Waterbirds Int. J. Waterbird Biol. 24, 425–429. doi:10.2307/1522075

Shobrak, M., 2012. Electrocution and collision of birds with power lines in Saudi Arabia. Zool. Middle East 57, 45–52. doi:10.1080/09397140.2012.10648962

Sillman, A.J., 1973. Avian vision, in: Farner, D.S., Roger, J. (Eds.), Avian Biology, Vol. 3. Academic Press, London, pp. 349–387. doi:10.1016/B978-0-12-249403-1.50013-X

Silva, J.P., Palmeirim, J.M., Alcazar, R., Correia, R., Delgado, A., Moreira, F., 2014. A spatially explicit approach to assess the collision risk between birds and overhead power lines: A case study with the little bustard. Biol. Conserv. 170, 256–263. doi:10.1016/j.biocon.2013.12.026

Silva, J.P., Santos, M., Queirós, L., Leitão, D., Moreira, F., Pinto, M., Leqoc, M., Cabral, J.A., 2010. Estimating the influence of overhead transmission power lines and landscape context on the density of little bustard Tetrax tetrax breeding populations. Ecol. Modell. 221, 1954–1963. doi:10.1016/j.ecolmodel.2010.03.027

Smith, J.A., Dwyer, J.F., 2016. Avian interactions with renewable energy infrastructure: An update. Condor 118, 411–423. doi:10.1650/CONDOR-15-61.1

SNH, 2016. Assessment and mitigation of impacts of power lines and guyed meteorological masts on birds. Guidance.

Sporer, M.K., Dwyer, J.F., Gerber, B.D., Harness, R.E., Pandey, A.K., 2013. Marking power lines to reduce avian collisions near the Audubon National Wildlife Refuge, North Dakota. Wildl. Soc. Bull. 37, 796–804. doi:10.1002/wsb.329

Stehn, T. V, Wassenich, T., 2008. Whooping Crane Collisions with Power Lines: an Issue Paper, in: Folk, M.J., Nesbitt, S.A. (Eds.), Proceedings of the 10th North American Crane Workshop. pp. 25–36.

Stevens, B.S., Dennis, B., 2013. Wildlife mortality from infrastructure collisions: statistical modeling of count data from carcass surveys. Ecology 94, 2087–2096. doi:10.1890/12-1052.1

Sundar, K.S.G., Choudhury, B.C., 2005. Mortality of sarus cranes (Grus antigone) due to electricity wires in Uttar Pradesh, India. Environ. Conserv. 32, 260–269. doi:DOI: 10.1017/S0376892905002341

Swaddle, J.P., Ingrassia, N.M., 2017. Using a Sound Field to Reduce the Risks of Bird-Strike: An Experimental Approach. Integr. Comp. Biol. 57, 81–89.

doi:10.1093/icb/icx026

Taylor, P.D., Walker, J., 2015. Auld's Cove Radar Study- Summer 2015.

Tere, A., Parasharya, B.M., 2011. Flamingo mortality due to collision with high tension electric wires in Gujarat, India. J. Threat. Taxa 3, 2192–2201.

Thiault, L., Kernaléguen, L., Osenberg, C.W., Claudet, J., 2017. Progressive-Change BACIPS: a flexible approach for environmental impact assessment. Methods Ecol. Evol. 8, 288–296. doi:10.1111/2041-210X.12655

Thompson, L.S., 1978. Transmission line wire strikes: mitigation through engineering design and habitat modification, in: Avery, M.L. (Ed.), Proceedings of the workshop "Impacts of Transmission Lines on Birds in Flight." U.S. Fish and Wildlife Service, Washington, D.C., pp. 27–52.

Tracy, D., Askew, L., Bainbridge, B., Dean, D., 2012. Avian Impact on Overhead Transmission Line Construction, in: Pugh, A.D. (Ed.), Proceedings of the 2012 Electrical Transmission and Substation Structures Conference. American Society of Civil Engineers (ASCE), pp. 336–347.

Tryjanowski, P., Sparks, T.H., Jerzak, L., Rosin, Z.M., Skórka, P., 2013. Paradox for Conservation: Electricity Pylons May Benefit Avian Diversity in Intensive Farmland. Conserv. Lett. 7, 34–40. doi:10.1111/conl.12022

Tyler, N., Stokkan, K.-A., Hogg, C., Nellemann, C., Vistnes, A.-I., Jeffery, G., 2014. Ultraviolet Vision and Avoidance of Power Lines in Birds and Mammals. Conserv. Biol. 28, 630–631. doi:10.1111/cobi.12262

van Rooyen, C., Diamond, M., 2008. Wildlife - Power line interaction management. Indwa 6, 7–16.

Ventana Wildlife Society, 2009. Evaluating Diverter Effectiveness in Reducing Avian Collisions With Distribution Lines at San Luis National Wildlife Refuge Complex, Merced County, California.

Ward, J.P., Anderson, S.H., 1992. Sandhill crane collisions with power lines in southcentral Nebraska, in: Wood, D.A. (Ed.), Proceedings 1988 North American Crane Workshop. pp. 189–196.

Watts, B.D., Mojica, E.K., Paxton, B.J., 2015. Using Brownian bridges to assess potential interactions between bald eagles and electrical hazards within the upper Chesapeake Bay. J. Wildl. Manage. 79, 435–445. doi:10.1002/jwmg.853

Wildemann, H., Blomberg, C., Engelmeier, T., Hellmann, C., Offizier, M.A., 2013.

Connecting Possibilities - Scenarios for Optimizing Energy Systems.

Willard, D.E., 1978. The impact of transmission lines on birds (and vice versa), in: Avery, M.L. (Ed.), Proceedings of the workshop “Impacts of Transmission Lines on Birds in Flight.” U.S. Fish and Wildlife Service, Washington, D.C., pp. 3–7.

Williams, J.H., 2003. International Best Practices for Assessing and Reducing the Environmental Impacts of High-Voltage Transmission Lines, in: Third Workshop on Power Grid Interconnection in Northeast Asia. September 30 -October 3, 2003. Vladivostok, Russia. p. 35.

Yee, M.L., 2008. Testing the effectiveness of an avian flight diverter for reducing avian collisions with distribution power lines in the Sacramento Valley, California : PIER final project report.

Zhang, J., 2003. Paleomolecular biology unravels the evolutionary mystery of vertebrate UV vision. Proc. Natl. Acad. Sci. U. S. A. 100, 8045–7. doi:10.1073/pnas.1533183100

TABLES

Table 1. Identification of knowledge gaps and suggestions of research and innovative approaches to fill those gaps.

Topic	Knowledge gaps / Research questions	Potential research and innovative approaches
Behavioural aspects	Understand individual-level behavioural changes and drivers of collisions	• Bio-logging approaches including use of accelerometers, magnetometers and girometers, to characterise flight behaviour changes of tracked birds, coupled with environmental sensors to measure weather conditions associated with flight patterns. • Assess drivers of flight height and patterns, including species, age, body condition, seasonal, day/night differences, flocking/solitary differences and anthropogenic disturbance. • Development of movement sensors to detect collisions of tracked birds. • Field surveys to assess crossing rates and behavioural reactions to power lines, using the support of technologies including thermal, video and radar.
Behavioural aspects	Assess visual and perceptual aspects	• Experimental approaches to assessing colour differentiation (including UV) and visual field parameters. • Assess behavioural responses to power lines and wire markers (from tracked birds) • Field surveys to assess behavioural responses to power lines and wire markers, using the support of technologies including thermal, video and radar.
Impact assessment methods	Improve knowledge of species affected and hotspots of mortality	• Investigate and model factors driving the occurrence of hotspots of mortality (namely topography, migration routes, land cover features) at species-level and overall. • Characterise species traits (e.g. morphology, habitat, brain size) and region-specific behaviour that increase susceptibility to collision. • Explore the potential of metagenomics to identify species colliding with power lines (through samples in cables).
Impact assessment methods	Characterise population-level impacts	• Development of population models taking into account the cumulative impact of existing or foreseen energy infrastructure, and enabling the assessment of compensatory versus additive mortality. • Long-term studies to assess local/regional population trends.
Impact assessment methods	Improve detection of collisions and methods for fatality estimation	• Technological development and testing of remote bird activity and collision monitoring devices, including thermal, video, small unmanned aircraft, bird strike indicators, and radar.

Topic	Knowledge gaps / Research questions	Potential research and innovative approaches
		• Development of methods to accurately estimate bird fatality (based on carcass searches) and related correction factors, with particular focus on crippling bias.
Mitigation measures	Evaluate effectiveness of wire markers	• Development of standardised protocols to improve reliability and potential utility in meta-analyses. Use BACI approach, complemented with assessment of crossing rates and behavioural reactions to wire markers. • Focus research on comparative effectiveness of different types of markers, colour, size, movement (or static) and spacing (for specific types). • Assess technical limitations of wire markers (durability, effects of adverse weather e.g. ice and strong winds, corona effects).
Mitigation measures	Evaluate effectiveness of non-marker mitigation measures (e.g. thicker earth wires, scaring methods including audio)	• Use BACI approach, complemented with assessment of crossing rates and/or behavioural response to visual/sound deterrents.
Mitigation measures	Assess the importance of optimal line routing and configuration	• Difficult to test optimal routing using experimental approaches. Alternative strategies include the production of collision risk maps for sensitive species, which can be used to set routes minimising impacts. • Develop experimental procedures to compare mortality between line sections set close versus apart (from other power lines, roads or other linear infrastructures), and with differing number of conductor horizontal levels. As BACI approach is not possible, characterization of crossing rates is important to evaluate differences.

Bernardino, J et al 2018 Bird collisions with power
lines: State of the art and priority areas for research.
Biological Conservation 2018 ;Volum 222. s. 1-13 10.1016/j.biocon.2018.02.029 CC-BY-NC-ND

FIGURES

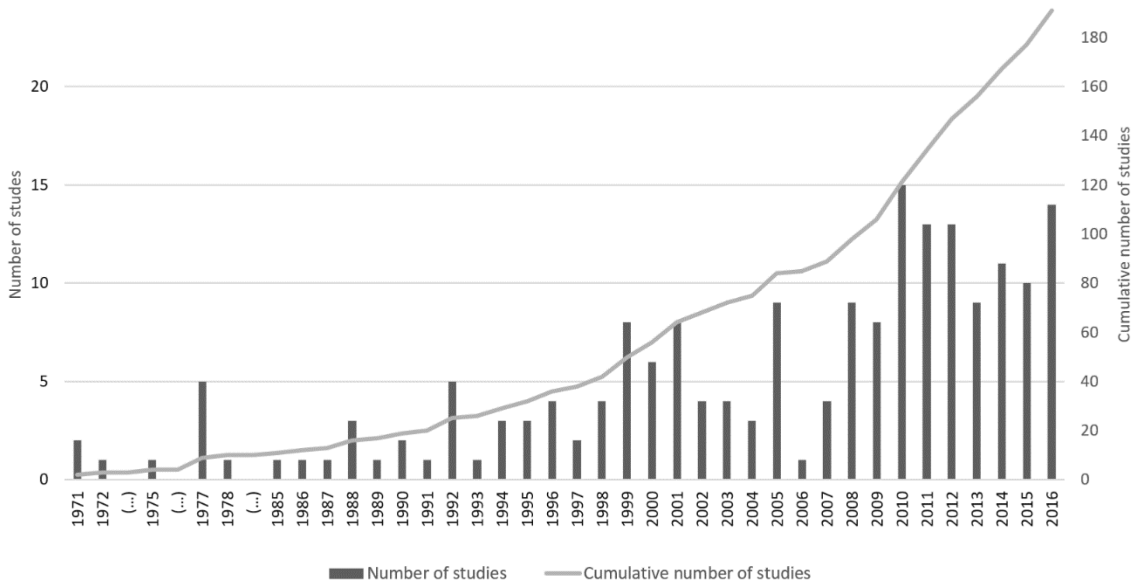

Figure 1 – Number of studies per publication year focusing on bird collision with power lines, compiled through a systematic literature search (*N* = 191). No studies found for the years 1973-74, 1976 and 1979-84.

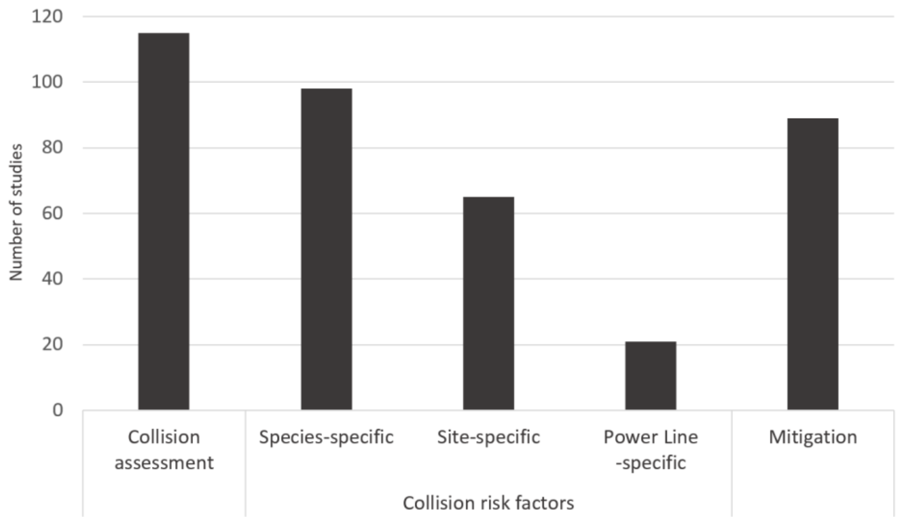

Figure 2 – Number of studies addressing each of the main research topics, compiled through a systematic literature search (*N* = 191). Many studies addressed more than one topic.

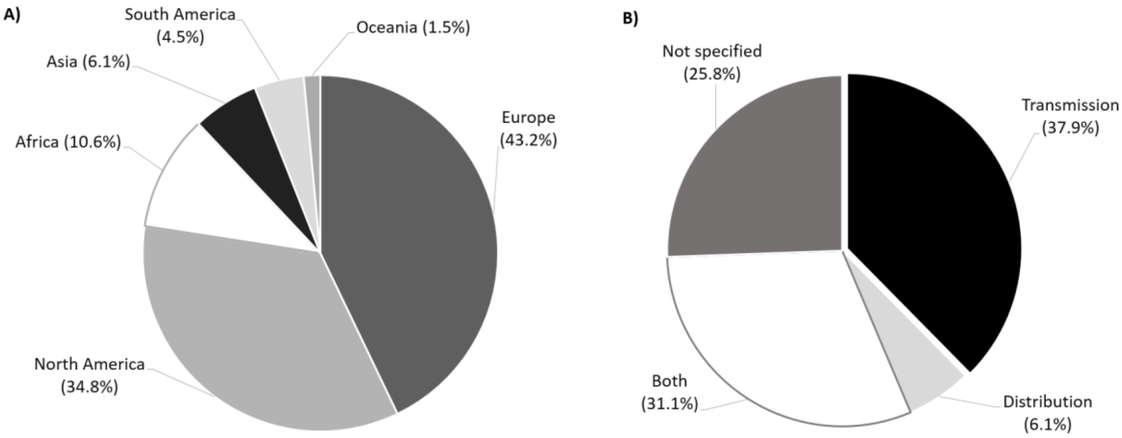

Figure 3 – Percentage of studies conducted (A) in each region of the world and (B) on each power-line type, compiled through a systematic literature search and reporting first-hand data on bird collisions with power lines (N = 132).