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Improving impact monitoring and mitigation of bird collisions with power lines

Joana Lopes Vieira Bernardino

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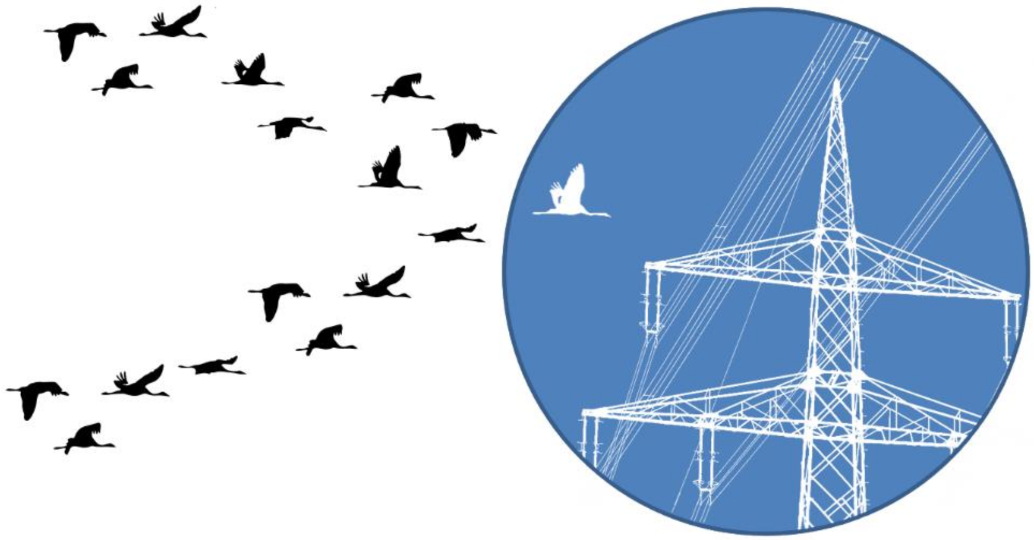

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Abstract

Tackling climate change and the threat it poses to biodiversity will require a profound transformation of the global energy system, transitioning from a fossil-based system to one with high shares of renewables. Transmission and distribution (T&D) power lines are key elements in the clean energy transition, as many renewable resources, such as wind and solar power, are located in remote areas. The predicted expansion of T&D networks worldwide raises, however, important conservation issues for birds because, among other impacts, overhead power lines are a major source of direct mortality due to electrocutions and collisions with wires. While electrocutions are already a reasonably well-understood phenomenon, bird collisions have been considerably harder to understand and mitigate. Over the last decades, extensive work has been carried out on the topic under ‘Research and Development’ (R&D) projects, but also under post-construction bird monitoring programmes required by the current Environmental Impact Assessment (EIA) legislation. However, this body of evidence has hardly ever been integrated and/or systematically reviewed.

The overall goal of this thesis is to increase the understanding of bird collisions with power lines and advance the methods used to quantify and mitigate this impact, in order to better inform decision-making and monitoring of future T&D developments. Specifically, the thesis aims to: (1) review the biotic and abiotic drivers of bird collisions with power lines and identify remaining knowledge gaps; (2) describe the existing mitigation measures and evaluate their effectiveness in reducing bird collisions; (3) better understand and assess sources of bias in bird fatality assessments, namely carcass persistence and searcher efficiency; and (4) identify the limitations and improve the design of field experiments to quantify bird collisions and assess mitigation effectiveness. To achieve these goals, this thesis includes exhaustive literature searches and a meta-analysis of both R&D and post-EIA monitoring studies, available in peer-reviewed articles but also very often scattered in grey literature. In addition, field experiments were performed to investigate a topic on which scientific literature is lacking, namely infrastructure effect on vertebrate scavenger behaviour and its consequences for bird fatality assessments.

The extensive literature review revealed that bird collisions with power lines are explained by species-specific, site-specific and infrastructure-specific factors, that sometimes act together in unexpected ways, which still limits our ability to predict and effectively mitigate bird collision events. Wire-marking – i.e., attaching flappers, spirals, or other devices to the overhead wires to increase their visibility for birds - is currently the mitigation measure most widely used in the world. The meta-analysis showed that wire-marking reduces, on average, bird collision rates with power lines by half (50.4%; 95% confidence interval: 40.4 - 58.8%) and flappers (devices with moving parts) tend to perform better than static devices. Nonetheless, the results of this thesis also uncovered the presence of high heterogeneity in wire-marking effectiveness across studies and the limited number, or even absence, of studies testing the effectiveness of other mitigation measures widely recommended (e.g., enhanced power line routing and configuration, habitat management). Based on the identified knowledge gaps, opportunities for future research are outlined in the following broad areas: (1) bird perception and behavioural response to power line infrastructure; (2) assessment of individual- and population-level impacts; and (3) development and testing of mitigation measures. Regarding the sources of bias in bird fatality assessments, the results of this thesis demonstrated that, despite some broad patterns, carcass removal and searcher efficiency rates varied greatly across studies, even between transmission projects located in a same region and/or bisecting similar habitats. Additionally, the results confirmed that bird fatality monitoring programmes that are poorly designed produce inaccurate estimates of bird fatality and mitigation effectiveness, or achieve inconclusive results. Thus, several recommendations are presented to improve future wire-marking experiments and design of carcass removal and searcher efficiency trials.

Overall, this thesis underlines the value of systematic literature reviews and meta-analysis to, first, summarise existing evidence (including in grey literature) and, then, inform the decision-making, impact mitigation and monitoring of T&D power lines or any other infrastructures. The establishment of collaborative working relationships between applied researchers, T&D developers and other stakeholders (environmental authorities, NGOs, consultants, etc.) is of utmost importance for the development of future R&D projects, and also for faster and better use of scientific knowledge in EIA practice and post-construction monitoring.

Keywords

transmission lines, distribution lines, linear infrastructures, post-construction monitoring, wildlife mortality, carcass removal, searcher efficiency, experimental design, wire-marking, environmental impact assessment, survey bias, meta-analysis, bird collision risk.

Resumo

O combate às alterações climáticas e à ameaça que estas representam para a biodiversidade exigirá uma profunda transformação do sistema energético mundial, tendo este de passar de um sistema baseado em combustíveis fósseis para um sistema com elevadas quotas de energias renováveis. As linhas de transmissão e distribuição (T&D) de eletricidade são infraestruturas fundamentais nesta transição energética, dado que a maioria das fontes de energia renováveis, como a energia eólica e solar, se encontra em áreas remotas. A expansão prevista da rede de T&D a nível mundial levanta, no entanto, importantes questões para a conservação da avifauna uma vez que, entre outros impactes, as linhas elétricas aéreas são uma importante fonte de mortalidade direta de aves, devido a eletrocussões e colisões com os cabos. Ao contrário da mortalidade por eletrocussão, que é já um fenómeno razoavelmente bem compreendido, a mortalidade de aves por colisão tem se revelado consideravelmente mais difícil de compreender e de mitigar. Nas últimas décadas, foi realizado extenso trabalho sobre o tema no âmbito de projetos de investigação, mas também no âmbito de programas de monitorização da mortalidade de aves, exigidos pela atual legislação de Avaliação de Impacte Ambiental (AIA). No entanto, a evidência científica resultante destes estudos raramente foi integrada e/ou revista de forma sistemática.

O objetivo geral desta tese é aumentar a conhecimento sobre a colisão de aves com linhas elétricas e desenvolver os métodos utilizados para quantificar e mitigar este impacte, por forma a informar a tomada de decisões e o acompanhamento de futuros projetos de T&D. Os objetivos específicos são: (1) caracterizar os fatores bióticos e abióticos que explicam as colisões de aves com linhas elétricas e identificar eventuais lacunas de conhecimento; (2) identificar as medidas de mitigação existentes e avaliar a sua eficácia na redução de colisões de aves; (3) compreender e quantificar as fontes de enviesamento nos trabalhos de prospeção de mortalidade de aves, nomeadamente a taxa de remoção e detetabilidade de cadáveres; e (4) identificar as limitações e melhorar o delineamento das experiências de campo para quantificar a mortalidade de aves e avaliar a eficácia das medidas de mitigação. Para atingir estes objetivos, foram realizadas revisões exaustivas e uma meta-análise de estudos de investigação e de programas de monitorização de impactes (decorrentes de processos de AIA), que se encontram publicados em revistas científicas mas também, muito frequentemente, dispersos por literatura cinzenta. Adicionalmente, foram realizadas experiências de campo para investigar um tema sobre o

número de estudos científicos é ainda reduzido, nomeadamente o efeito que a presença da infra-estrutura tem no comportamento dos necrófagos vertebrados, nas taxas de remoção dos cadáveres e, consequentemente, nas estimativas de mortalidade das aves.

A extensa revisão bibliográfica realizada revelou que as colisões de aves com linhas elétricas são explicadas por diferentes fatores relacionados com a biologia e ecologia das espécies, com as características da área de estudo e com as características da própria linha elétrica. Estes fatores atuam frequentemente em conjunto e, por vezes, de formas inesperadas, o que limita a capacidade de prever e minimizar eficazmente os eventos de colisão com a infra-estrutura. A sinalização da linha elétrica, através da colocação de dispositivos nos cabos por forma a aumentar a sua visibilidade para as aves, é atualmente a medida de mitigação mais amplamente utilizada no mundo. A meta-análise demonstrou que a instalação de dispositivos anti-colisão reduz, em média, as taxas de colisão de aves para metade (50,4%; intervalo de confiança de 95%: 40,4 - 58,8%) e que os dispositivos dinâmicos (e.g., com partes rotativas ou do tipo fitas) tendem a ser mais eficazes, do que os dispositivos estáticos (e.g., espirais duplas). No entanto, os resultados da meta-análise também revelaram uma elevada heterogeneidade nos estudos analisados, ao nível da eficácia da sinalização na redução da colisão de aves. Através da revisão bibliográfica, constatou-se também que existe um número limitado, ou mesmo uma ausência, de estudos que testem a eficácia de outras medidas de mitigação amplamente recomendadas, como, por exemplo, a otimização do traçado e configuração das linhas elétricas. Dadas estas lacunas de conhecimento, na presente tese são identificadas oportunidades de investigação futura nas seguintes áreas gerais: (1) percepção e resposta comportamental das aves à presença da linha elétrica; (2) avaliação dos impactes da infra-estrutura, a nível individual e populacional; e (3) desenvolvimento e teste de medidas de mitigação. Relativamente às fontes de enviesamento na campanhas de prospeção da mortalidade de aves, os resultados desta tese demonstram que, apesar de alguns padrões gerais, as taxas de remoção e deteção dos cadáveres variam muito entre estudos, mesmo entre linhas de transmissão localizadas numa mesma região e/ou que atravessam habitats semelhantes. Além disso, os resultados confirmaram que experiências de campo incorretamente delineados produzem estimativas imprecisas de mortalidade de aves e da eficácia de mitigação, ou alcançam resultados inconclusivos. Como tal, são apresentadas várias recomendações para melhorar o delineamento de futuras experiências de avaliação da eficácia da sinalização das linhas e também dos testes de remoção e deteção dos cadáveres de aves.

A presente tese vem, globalmente, reforçar a importância da revisão sistemática da literatura e das técnicas de meta-análise para resumir a evidência científica existente (incluindo em literatura cinzenta), por forma a informar a mitigação e monitorização de impactes das linhas elétricas nas aves. O estabelecimento de protocolos de colaboração entre a academia, promotores dos projetos de T&D e outros interessados (autoridades ambientais, organizações não governamentais, consultores, etc.) é da maior importância para o desenvolvimento de futuros projectos de investigação no tema, mas também para uma mais rápida e melhor aplicação do conhecimento científico nos processos de AIA e nos decorrentes programas de monitorização de impactes.

Palavras-chave

Linhas elétricas, infra-estruturas lineares, monitorização pós-construção, mortalidade de aves, remoção e detetabilidade de cadáveres, fatores de enviesamento, desenho experimental, sinalização anti-colisão, avaliação de impacte ambiental, risco de colisão de aves.

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Chapter 1

General introduction

1. General introduction

1.1. Background

1.1.1 The development of a sustainable electricity grid

Climate change and the threat it poses to biodiversity is the biggest environmental challenge facing humanity today. The historic Paris Agreement adopted on 12 December 2015 at the 21st United Nations Framework Convention on Climate Change (COP21) represents a major turning point on global cooperation to tackle climate change, as it sets the goal of *"holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels*". Achieving this goal will require the global energy system to undertake a profound transformation, shifting from a system based on fossil fuels to one based on renewable energy resources (IRENA 2019). At the same time, world's electricity demand is expected to continue growing in the coming decades and to almost double by 2050 (IEA 2019). Fortunately, renewable energy technologies, such as solar photovoltaics and wind power, have achieved massive technological advances and cost reductions in recent years, which will facilitate the green energy transition at the scale and magnitude needed (Elia *et al.* 2021).

The path towards a global decarbonization of the electricity sector entails, however, an additional challenge: to ensure that electricity is delivered to consumers in an environmentally sustainable way. The electricity generated at power plants travels long distances over high-voltage transmission lines to substations, where voltage is transformed from high to low, so it can then be distributed to end-consumers (Figure 1.1). Transmission and distribution (T&D) power lines are therefore key elements in any national electricity system and have become ubiquitous features in modern landscapes. For instance, the European network of T&D power lines is already more than 11.2 million kilometres long (Wildemann *et al.* 2013). Still, a reinforcement and expansion of the existing domestic and cross-border electricity networks will be needed to ensure their reliable operation with a high share of variable renewable sources (Egerer *et al.* 2016). These energy developments will have, however, negative impacts on the environment, particularly on biodiversity, that will need to be properly addressed (Richardson *et al*. 2017; Biasotto and Kindel

2018). Ultimately, the much-needed energy transition can only be called "green" if the associated power lines are developed in harmony with nature and ensure biodiversity conservation.

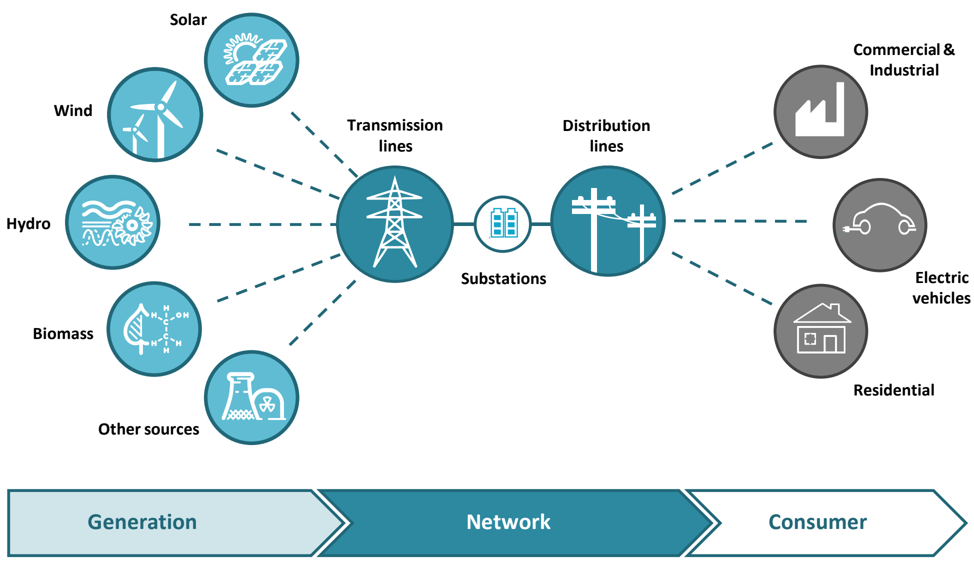


Figure 1.1 - Diagram of the electricity system.

Within the European Union (EU), the development of energy infrastructures must be fully compliant with the EU's environmental policy, including the Habitats and Birds Directives[1], and the Environmental Impact Assessment (EIA) Directives[2]. In Portugal, for instance, EIA procedure is mandatory for transmission projects of ≥110 kV and ≥10km long, and for transmission projects of ≥ 110 kV within "Sensitive areas"[3] (regardless of its length), as required under the Decree-law no. 151-B/2013[4]. In addition, T&D projects with potential adverse effects on Natura 2000 sites are subject to an "Appropriate Assessment" (AA) procedure, as required under the Decree-law no. 140/99[5] (that transposes into national legislation the EU Habitats and Birds Directives). Besides complying with EU and national legal requirements, several T&D system operators have also

[1] Directive 92/43/EC on the Conservation of natural habitats and of wild fauna and flora; Directive 2009/147/EC on the Conservation of wild birds.
[2] Directive 2001/42/EC2 (on 'Strategic Environmental Assessment' - 'the SEA Directive'); Directive 2014/52/EU (on 'Environmental Impact Assessment' – 'the EIA Directive').
[3] "Sensitive areas" include Natura 2000 sites and the National Network of Protected Areas.
[4] Amended by the Decree-laws no. 47/2014 and 179/2015, Law no. 37/2017 and Decree-law no. 152-B/2017.
[5] Amended by the Decree-laws no. 49/2005 and 156-A/2013.

voluntarily promoted or joined initiatives aimed to create evidence-based knowledge and/or facilitate collaborations among stakeholders to enable a timely and environmentally sensitive development of electricity networks. Good examples of that are, for instance, the initiative '*act4nature*' (http://www.act4nature.com/en/), the '*Renewable Grid Initiative*' (https://renewables-grid.eu/) and, in Portugal, the 'REN Chair in Biodiversity' (https://catedraren.wixsite.com/renchair). Hence, T&D system operators seem to be committed to finding the best solutions to ensure that their company activities contribute to the achievement of climate change and biodiversity conservation targets.

Over the years, regulators, non-governmental organizations (NGOs) and leading energy companies have produced practical guidelines and tools to help integrate biodiversity considerations into the development of T&D power lines and other energy infrastructures (e.g., IFC 2007; APLIC 2012; Birdlife International 2015; EC 2018; Bennun *et al*. 2021). There is a broad consensus that the construction, operation and decommissioning of such infrastructures should be based on four main pillars:

1) **Strategic planning –** Development of sensitivity maps and strategic impact assessments, usually by government agencies and on a national scale, that identify suitable areas for power generation and transmission corridors, as well as 'no-go' areas due to their biodiversity values (e.g., World Heritage Sites and protected areas) (EirGrid 2013; Allinson *et al*. 2020);
2) **Environmental Impact Assessment –** Implementation of a rigorous EIA (or AA) procedure to identify the species and habitats that are likely to be affected by the T&D infrastructure project, and careful evaluation of all available alternatives to the baseline scenario (Birdlife International 2015; EC 2017).
3) **'Mitigation hierarchy' framework –** Implementation of a sequence of management actions to achieve a 'No Net Loss' of biodiversity (or, ideally, a 'Net Gain'). It involves four critical steps beginning with the (1) avoidance of impacts, then developers must seek to (2) minimise impacts and (3) restore the areas affected by the project, and lastly (4) the residual impacts must be offset/compensated (Ekstrom *et al.* 2015; Richardson *et al*. 2017).

4) **Post-construction monitoring –** Careful design and implementation of monitoring programmes to determine whether the predicted impacts occurred and evaluate the effectiveness of mitigation measures (Marshall *et al*. 2005).

Nonetheless, T&D operators, environmental practitioners and other stakeholders must acknowledge that, despite their best efforts, there will always be uncertainty in the prediction of the impacts of the infrastructure, as well as in mitigation effectiveness (Tenney *et al*. 2006). This uncertainty should be tackled through the adoption of an “Adaptive Management” strategy, which essentially entails ‘learning by doing’ and where monitoring is a key element (Kato and Ahern 2008; Williams and Brown 2014). First, the results of post-EIA monitoring should be evaluated so that, if unforeseen impacts occur, the necessary corrective or additional mitigation actions can be readily implemented (“single-loop learning”; Figure 1.2). The accumulated data and lessons learned from this iterative process should then be used to inform the EIA and decision-making of future T&D infrastructure projects (“double-loop learning”; Figure 1.2).

The evidence-based knowledge gathered over time from multiple projects should be complemented with EIA applied research and development (“R&D”; Figure 1.2), to address major knowledge gaps and respond to immediate challenges posed by the development of “green” infrastructures (Fisher and Noble 2015). A collaborative relationship between academics, EIA practitioners and T&D operators will help to steadily reduce uncertainty in impact predictions, develop mitigation strategies and technologies, improve the design of the monitoring programmes and, ultimately, achieve the goal of a sustainable T&D grid development.

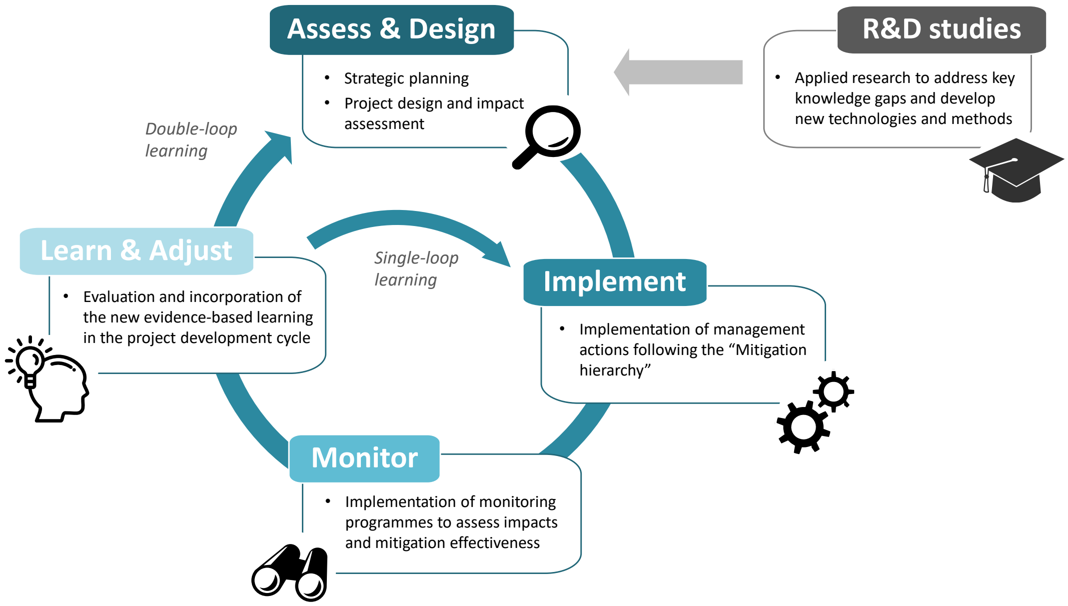


Figure 1.2 - 'Adaptive Management' cycle and 'Research & Development' (R&D) for sustainable infrastructure development (adapted from Williams and Brown 2014).

1.1.2 Conflicts between power lines and birds

Power lines have a myriad of impacts on biodiversity and, particularly, on bird communities. Some bird species can benefit from the installation of power lines, for example by using the infrastructure as nesting and perching sites (Tryjanowski *et al*. 2013; Morelli *et al*. 2014; D'Amico *et al*. 2018). However, power lines have mostly negative impacts on birds, namely through:

- **Habitat loss and fragmentation** - Disruptive changes in the vegetation due to clearing and maintenance of rights-of-way along power lines, particularly the ones bisecting forests, that contribute to habitat fragmentation with accompanying effects on bird populations (e.g., Rich *et al*. 1994; Askins *et al.* 2012);
- **Disturbance, and displacement** – Changes in bird abundance and diversity, selection of displaying and nesting sites, and/or breeding success due to power line proximity (e.g., Kroodsma 1982; Silva *et al*. 2010; Lóránt and Vadász 2014; Kohl *et al.* 2019);
- **Barrier effect** – Alterations in bird flight paths and power line crossings, with a potential reduction in connectivity between populations on both sides of the right-of-way (Pruett *et al.* 2009; Raab *et al.* 2011);

- **Direct mortality** - Bird casualties due to collisions with the overhead wires and electrocutions at both wires and poles (Lehman *et al.* 2007; Jenkins *et al*. 2010).

Direct mortality is undoubtedly the most visible and severe impact (Richardson *et al*. 2017; Biasotto and Kindel 2018). Power lines, along with roads and windows, are the infrastructures that kill more birds worldwide (Loss *et al.* 2015). For instance, two systematic reviews have estimated that ca. 28.6 million and 25.6 million birds are killed annually at power lines in the United States and Canada, respectively (Rioux *et al.* 2013; Loss *et al.* 2014a). In Norway, Bevanger (1995a) estimated that the national annual mortality caused by power lines among only three species – Western Capercaillie (*Tetrao urogallus*), Black Grouse (*Lyrurus tetrix*) and Willow Grouse (*Lagopus lagopus*) – was of ca. 96,000 individuals. In South Africa, Shaw *et al*. (2010b) estimated that approximately 12% (5 - 23%) of the total Blue Crane (*Anthropoides paradiseus*) population in the Overberg region is killed annually in power-line collisions. Although there is some uncertainty in these national- or regional-scale estimates, the integration and/or extrapolation of mortality data from multiple projects is important to assess population-level effects and raise awareness of the problem (Loss *et al*. 2012; Machtans and Thogmartin 2014; May *et al.* 2019). Few studies have, however, assessed long-term demographic consequences for bird communities and the ones that did focused mostly on endangered species, such as the Great Bustard (*Otis tarda*) in Morocco (Palacín *et al.* 2016), the Bonelli's Eagle (*Aquila fasciata*) in Spain (Hernández-Matías *et al.* 2015) and the Eagle Owl (*Bubo bubo*) in Switzerland (Schaub *et al.* 2010). The cumulative effect that bird electrocutions and collisions at individual power lines have on overall population dynamics and viability remains, therefore, relatively unknown.

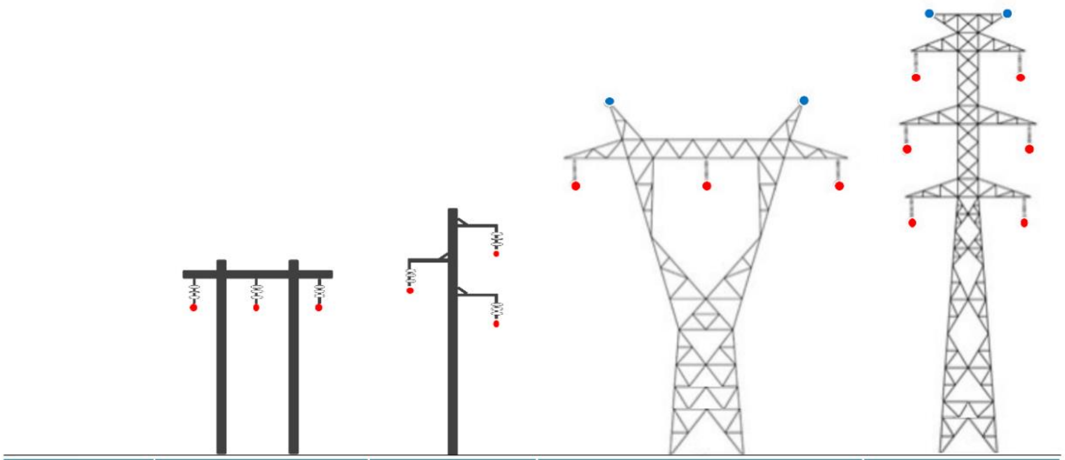
Bird collisions may occur at all types of power lines, while electrocutions are most prevalent on distribution lines and rarely occur on transmission lines (Bevanger 1994; APLIC 2012). According to the review made by Loss (2014a), power lines in the United States kill per year 8 - 57 million birds by collision and 0.9 - 11.6 million birds by electrocution (ca. 84% and 16%, respectively). Similarly, a study performed in Italy (Rubolini *et al.* 2005) estimated that power lines killed 0 - 86.9 birds/km/year by collisions and 2.1 - 20.5 birds/km/year by electrocution (ca. 79% and 21%, respectively). A wide variety of bird species are among the power line victims, though the bird groups affected by collisions and by electrocutions are typically different (e.g., Janss 2000; Rubolini *et al*. 2005; Demerdzhiev 2014; Fransson *et al*. 2019).

Bird electrocution occurs when a bird makes contact with two electrical wires, or when it perches on a power line pylon and comes into simultaneous contact with a wire (Kagan 2016). These events are explained mainly by three factors: (1) power line configuration; (2) bird biology and morphology, but particularly their wingspan; and (3) environmental factors, namely habitat features and weather conditions (Bevanger 1994; Lehman *et al*. 2007; Mojica *et al.* 2018). Avian electrocutions occur most often at distribution lines (≤69 kV) because the spacing between energised and grounded parts is typically smaller. Although small birds can be electrocuted, large birds are considerably more vulnerable because their outstretched wings or other body parts can easily become in direct contact with energised elements. Lastly, the electrocution risk is higher under inclement weather (e.g., rain and snow, because wet feathers have much higher conductivity) and in open habitats with high prey density, where power lines are the (or one of the) most prominent features in the landscape and birds are more likely to use them as hunting perches and nesting sites.

In the 1970s and 80s, the alarming numbers of eagles, falcons, vultures, corvids, owls and water birds electrocuted at power lines raised negative media attention and shed light on the magnitude of the problem (e.g., Boeker and Nickerson 1975; Ledger and Annegarn 1981; Ferrer *et al*. 1991). Since then, extensive research has been conducted on the topic and relatively simple but effective measures, like changes in pylon design and insulation of dangerous components, were developed to prevent bird electrocutions (Janss and Ferrer 1999; Haas *et al.* 2005; APLIC 2006). The adoption of such measures in new power lines, along with retrofitting of dangerous, poorly-designed power lines, has been responsible for drastic reductions in electrocution rates (Tintó *et al.* 2010; López-López *et al.* 2011; Chevallier *et al.* 2015; Dixon *et al.* 2019). In sum, although it is still a major conservation issue worldwide (e.g., Dixon *et al.* 2013), bird electrocutions are nowadays a well-understood phenomenon and cost-effective mitigation measures are available.

Unlike for electrocution events, an effective mitigation of bird collisions with power lines has been considerably harder to achieve, probably because collision events are explained by a wider number of ecological and technical factors, and also more difficult to address. Depending on power line voltage and other technical aspects, the energised wires (also called conductors) can be arranged in a single vertical level (“horizontal” configuration), or in two or more levels (“vertical” configuration) (Figure 1.3). Higher voltage power lines usually also have earth wires (also called static or ground wires), which protect the power line from lightning strikes and typically run above the conductors (Figure 1.3). In theory, birds can collide with any one of the wires, and the risk of bird collisions will increase with the number of vertical wire levels. However, the collision risk may also depend on wire diameter, their relative position (e.g., top, middle, or bottom wire), spacing between vertical wire levels and their overall height.

In addition to factors related to power line design, bird collisions may be explained by species morphology, behaviour and ecology (e.g., Henderson *et al.* 1996; Janss 2000; Shimada 2001; Martin 2011), and by a multitude of environmental factors (e.g., landscape features, weather conditions, anthropogenic disturbance) (e.g., Savereno *et al.* 1996; Mojica *et al.* 2009; Rollan *et al.* 2010; Shaw *et al.* 2018). However, and despite the large number of studies conducted on the topic, there is still no broad agreement in which way and/or to what extent each factor influences the bird collision risk. For instance, GPS telemetry data collected over a period of 12 years revealed that collisions with power lines are a main threat to the adult populations of Little Bustard (*Tetrax tetrax*) in Iberian Peninsula (Marcelino *et al*. 2018). The estimated annual mortality rate resulting from power line collisions was of 3.4 – 3.8%, followed by illegal killing (2.4 – 3.0%) and collisions with vehicles (0.8 – 1.0%). This was a rather unexpected finding, as predation was thought to be the main cause of mortality (Schulz 1984) and relatively low attention had been given to power lines in the EU action plan for Little Bustard conservation (Iñigo and Barov 2010). It became clear how poorly understood Little Bustard's mortality at power lines was and that further studies were needed to better assess the magnitude of the problem and the underlying causes. For Little Bustard, as for birds in general, a broad understanding of the drivers of collisions with power lines will help to reduce the uncertainty in mortality predictions at future T&D infrastructures and to effectively address the problem by improving the mitigation strategies.



No. of vertical wire levels	1	3	2	4
Power line type	Distribution lines		Transmission lines	

Figure 1.3 - Examples of typical distribution and transmission line configurations and corresponding number of vertical wire levels (adapted from Marques *et al.* 2020). Red dots represent the position of conductors and blue dots the earth wires.

1.1.3 Strategies to mitigate bird collisions

The *Mitigation hierarchy* - a sequence of actions to avoid, minimise and, finally, compensate negative impacts – is nowadays regarded as the best-practice approach to manage the impacts of any type of infrastructure development (e.g., Ekstrom *et al.* 2015). In 2014, the EU fully endorsed this methodological approach through the Article 8a of Directive 2014/52/EU (amending the original EIA Directive 2011/92/EU), by establishing that any project subject to EIA should include:

> *"(…) a description of any features of the project and/or measures envisaged in order to* ***avoid, prevent or reduce and, if possible, offset*** *likely significant adverse effects on the environment as well as, where appropriate, monitoring measures."*

Power lines are no exception and their impacts on bird communities, namely direct mortality due to collisions, should be addressed step by step (EC 2018). Bird collisions with a new power line should primarily be prevented through bird-friendly routing (e.g., by avoiding the bisection of 'Bird Important Areas') and, if technically possible, by burying the infrastructure (e.g., Hanssen *et al.* 2014; Šmídt *et al.* 2019). Then, they should be minimised as much as possible, for instance, by adopting power line configurations considered less harmful to birds and by increasing the visibility of the wires, or infrastructure in general (e.g., Bevanger and Brøseth 2001; Frost 2008). Compensation measures (or offsets) should be undertaken as a last resort, only to address bird collisions that could not be completely avoided and/or minimised. This last step of the mitigation hierarchy may encompass measures, for instance, to enhance habitats or protect nesting sites of bird species impacted by the project (e.g., Paula *et al*. 2011a; Bretagnolle *et al*. 2011).

Despite the broad consensus on the mitigation hierarchy, the 'true' effectiveness and contribution of each individual mitigation measure is still not entirely known. This can happen because their evaluation is methodologically demanding (which limits the design and replication of experiments), and/or because their effectiveness may be influenced by a wide range of ecological and technical factors (Sinclair and DeGeorge 2016; Rytwinski *et al.* 2016). A good example of that is 'wire-marking' effectiveness. Increasing wire visibility through the installation of devices – 'Bird Flight Diverters' (BFDs) – has been seen as one of the best solutions to reduce collisions. The installation of BFDs is widely recommended in best-practice guidelines from Europe (Haas *et al.* 2005; SNH 2016; EC 2018) and several other regions of the world (APLIC 2012; Prinsen *et al.* 2012; Birdlife International 2015). Nevertheless, there is still considerable uncertainty about the best-performing BFDs and wire-marking scheme.

To the best of my knowledge, Scott *et al.* (1972) was the first scientific study reporting the implementation of wire-marking and evaluating its effectiveness in reducing bird collisions. The study was conducted in the coastal area of Dungeness (Southern England) and luminous orange tapes or strips were fitted to the earth wires of two 400 kV transmission lines. The marked power line spans and the ones left unmarked (as controls) were monitored for three years, but the experiment provided no conclusive evidence on the effectiveness of clipped strips and tapes in reducing bird casualties. Ever since, a wide range of BFDs has been developed and installed in power lines worldwide. The devices had initially quite simple designs (e.g., small spirals) and then gradually evolved into larger devices that may incorporate dynamic features and/or reflective parts (Figure 1.4). The wire-marking schemes, i.e., which wires are marked and with what spacing between devices, have also been subject to changes. Only a fraction of these BFDs and wire-marking schemes has, however, been properly tested in the field (Jenkins *et al.* 2010).

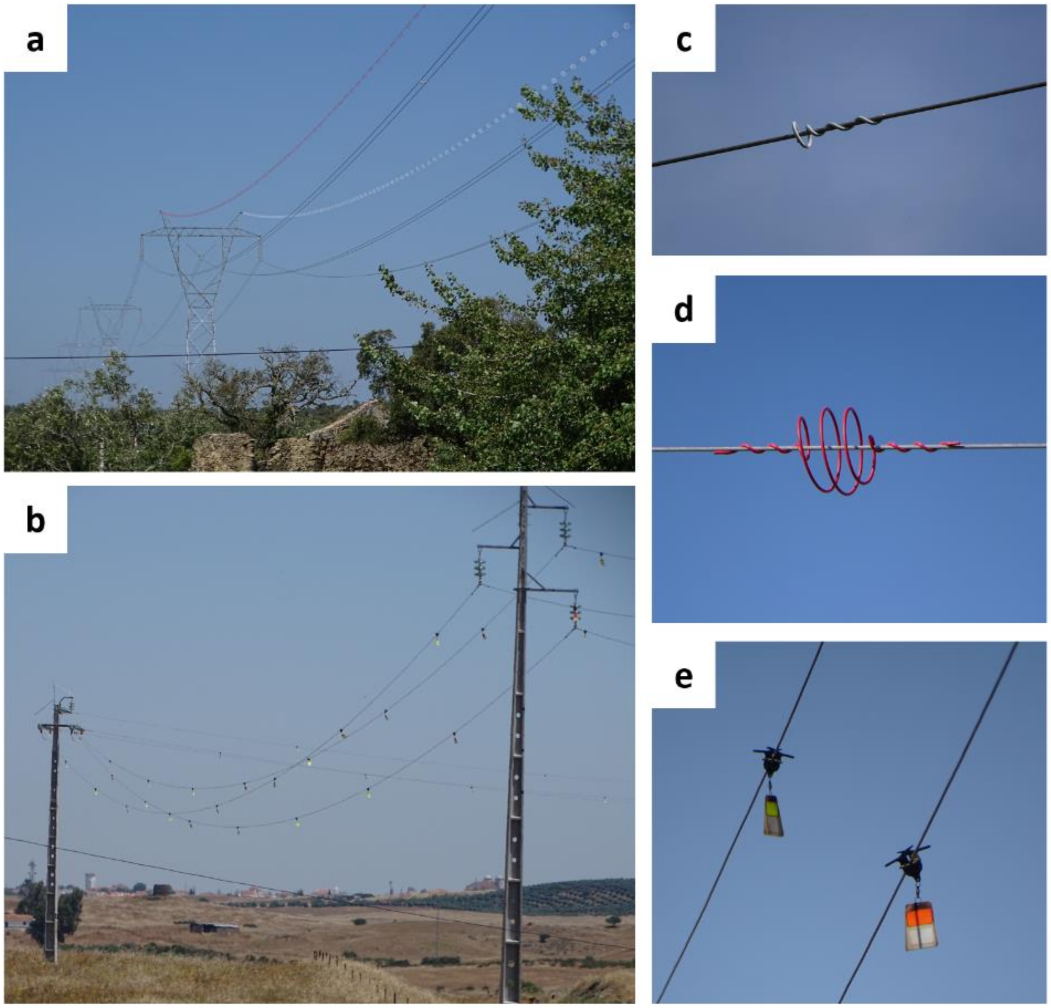


Figure 1.4 - Examples of wire-marked transmission (a) and distribution (b) power lines, and different types of 'Bird Flight Diverters': small spirals (c), large spirals (d) and flappers (e) (Photo credits: Ricardo C. Martins).

Wire-marking effectiveness may be assessed through: (1) surveys of bird activity and behaviour, and their reactions towards a marked wire (Luzenski *et al*. 2016; Murphy *et al*. 2016a; Pavón-Jordán *et al.* 2020); and/or (2) searches of bird carcasses beneath the power line (e.g., Alonso *et al.* 1994; Sporer *et al. 2013)*. The latter method is the one most often used. Nevertheless, naïve direct comparisons of studies testing the effect of different BFDs on fatality rates may be misleading due to the variety of bird species, ecological conditions, power line features and wire-marking schemes involved in each study, as well as differences in the bird fatality survey methods (see next section 1.1.4). Heterogeneity in ecological studies is inevitable, yet it can be taken into account and explored through meta-analytical approaches (Senior *et al*. 2016). The first and only meta-analysis that assembled a series of independent studies on wire-marking effectiveness was performed by Barrientos *et al.* (2011). The authors estimated that bird collision rates were reduced, on average, by 78% (95% Confidence Interval: 55 – 94%) at wire-marked power lines. However, the study did not explore the potential moderating effect of BFD type, power line features and/or other site-specific factors on wire-marking effectiveness. Moreover, since then, more field experiments have been conducted, and/or the results made available (e.g., Estanque *et al.* 2012; Sporer *et al.* 2013; Horenk *et al.* 2018). The gathering and meta-analysis of these recently published studies, together with the 'old' ones, may help explain the heterogeneity in wire-marking effectiveness and inform evidence-based decisions on the best measures to minimise bird collisions with power lines.

1.1.4 Challenges in quantifying bird collisions

T&D line developers, environmental authorities and EIA practitioners often pose the following question: What monitoring methods are best to determine the number of bird collisions? The answer to this question is essential so that the best experimental designs and methods may be implemented, and we can be sure that (1) the impacts of a power line are being properly assessed, as well as the effectiveness of the mitigation measures; and (2) we fully understand the spatial and temporal patterns of bird collisions to inform siting decisions and mitigation strategies for new power lines.

Most post-EIA monitoring and R&D studies aiming to quantify bird collisions with power lines rely on bird fatality searches beneath the infrastructure. Considerably different fatality search protocols have been implemented worldwide, in terms of search frequency and period of the year covered (e.g., Faanes 1987; Janss and Ferrer 2000; Rubolini *et al.* 2005; Shaw *et al.* 2018). For instance, if the monitoring target species is a large bird resident in the study area (e.g., White Stork, *Ciconia ciconia*), carcass searches may be performed once a month and cover the entire year; whereas, if the target species are small-sized migratory birds, searches may be performed every week but only cover the months of interest (e.g., migration season). During each carcass search, one or more searchers look for bird carcasses or their remains (e.g., bones, feather spots) usually by means of walked, linear transects along the power line corridor. Searches are mostly carried out by human observers but scent detection dogs may also be trained and used to find bird carcasses at power lines, as they can considerably improve the efficiency of carcass searches due to their olfactory capabilities (Homan *et al.* 2001; Paula *et al.* 2011b; Reyes *et al.* 2016).

Alternative methods to quantify bird fatalities have been proposed, such as the use of "Bird Strike Indicators". These devices are installed on power line wires and automatically register bird collisions based on the vibration of the wires (Pandey *et al.* 2008; Murphy *et al*. 2016b). Although a promising tool for estimating bird collision rates, this technology has not yet been widely tested and still needs to be further developed to overcome several limitations (e.g., identification of bird species or group, sensitivity in detecting collisions of small-sized birds). Thus, both post-EIA monitoring and R&D studies continue to depend on traditional approaches, i.e., carcass searches either using human observers or dog-handler teams, to assess bird collisions with power lines.

The number of bird carcasses found during the regular searches does not represent the 'true' number of birds killed by a power line. In fact, the observed fatalities are just the "tip of the iceberg" (Figure 1.5), as several bird carcasses are never found by the searchers due to three main sources of bias:

- **Bird crippling** – Birds that collide with the power line but fall outside the search area, or injured birds that continue flying for some distance beyond the power line before dying (e.g., Bech *et al.* 2012; Murphy *et al.* 2016b; Travers *et al.* 2021);
- **Carcass removal** – Bird carcasses that are completely removed by scavengers or decomposition between carcass searches, being no longer available for detection by the searchers (e.g., Schutgens *et al.* 2014; Costantini *et al.* 2017; Borner *et al.* 2017);
- **Searcher efficiency** – Inability of searchers to locate bird carcasses or their remains within the search area, due to vegetation height and density, carcass size, weather conditions, observer inexperience, etc. (e.g., Ponce *et al.* 2010; Reyes *et al.* 2016; Gómez-Catasús *et al.* 2020).

Raw carcass counts need, therefore, to be corrected for these sources of bias in order to estimate the 'true' number of collision fatalities (Bernardino *et al*. 2013). Carcass removal and searcher efficiency are undoubtedly the sources of bias most studied in power lines, but also in many other infrastructures responsible for bird fatalities, such as wind farms, roads, solar facilities and fences (Barrientos *et al.* 2018). The respective bias corrections – carcass persistence rate and carcass detection probability – are determined through the conduction of site-specific field experiments, which encompass the random distribution of bird carcasses along the power line (to surrogate 'real' bird fatalities). The area is then searched by the observers (humans or dog-handler teams) that usually perform the regular carcass searches to assess their probability of finding a bird carcass. These same placed bird carcasses are then revisited daily or at some other interval established by the study protocol (e.g., daily the first 4 days, and then on day 7, 14 and 21), to determine the proportion of carcasses persisting at the site over time.

The correction factors derived from these carcass persistence and searcher efficiency trials have great impact on the reliability of the bird fatality estimates (Korner-Nievergelt *et al.* 2011; Huso 2019). For instance, Loss *et al.* (2014a) reviewed the bird fatality estimates at US power lines and found that 26.8% of the uncertainty in those estimates arose from bias corrections related to carcass removal and detection. The implementation of well-designed carcass persistence and searcher efficiency trials is, therefore, essential to obtain accurate fatality estimates and, consequently, allow the assessment of the 'true' impacts resulting from individual power lines. Furthermore, it allows the comparison of bird mortality data among projects, the upscale of mortality estimates to broad regions and infer population-level consequences (Loss *et al.* 2012; Huso 2019). Unfortunately, and despite their importance, rigorous experimental designs are not always easy to implement, particularly in the context of post-EIA monitoring, due to logistical and financial constraints (Arnett *et al.* 2008; Conkling *et al.* 2020). A greater understanding of the ecological and methodological drivers of carcass persistence and searcher efficiency is sorely needed to standardise and optimise the field experiments, without compromising the accuracy of the derived bias correction factors.

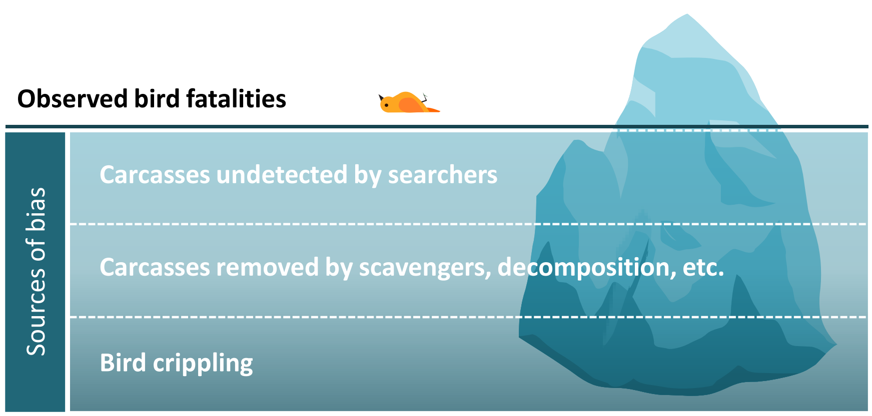


Figure 1.5 - Main sources of bias in bird fatality surveys, as observed carcasses are 'the tip of the iceberg' in the overall number of bird fatalities caused by power lines.

1.2. Thesis aims and outline

The overall goal of this thesis is to increase the understanding of bird collisions with power lines and advance the methods used to quantify and mitigate this impact, in order to better inform the decision-making and monitoring of future T&D developments. More specifically, this work aims to (Figure 1.6):

1) Review the biotic and abiotic drivers of bird collisions with power lines and identify remaining knowledge gaps;
2) Describe the existing mitigation measures and evaluate their effectiveness in reducing bird collisions;
3) Better understand and assess sources of bias in bird fatality assessments, namely carcass persistence and searcher efficiency;
4) Identify the limitations and improve the design of field experiments to quantify bird collisions and assess mitigation effectiveness.

The idea for this thesis arose from the awareness that the research performed on the topic over the last decades and the large amount of data collected in post-EIA monitoring of T&D projects worldwide have not often been assembled and reviewed to inform the “Adaptive Management” cycle, i.e., to better predict, mitigate and monitor bird collisions at power lines. Thus, a significant part of the work presented in this thesis is based on exhaustive literature searches of both R&D and post-EIA monitoring studies, available in peer-reviewed articles but also very often scattered in grey literature. In addition, field experiments were performed to explore topics on which scientific literature is lacking, such as infrastructure effect on vertebrate scavenger behaviour and its consequences for bird fatality assessments.

This thesis is organised into six major sections. This first chapter corresponds to a general introduction, setting the motivation and aims for this research. The next four chapters are independent papers published (three) or to be submitted (one) to international scientific journals (Figure 1.6):

- In **Chapter 2**, we performed a systematic review of the existing literature on bird collisions with power lines to: (*i)* assess the known drivers of bird collision; and *(ii)* summarise the existing mitigation measures and their effectiveness. The current knowledge on each driving factor and mitigation measure was critically evaluated, namely by identifying the most consistently observed effects but also highlighting, whenever appropriate, the different or even contradicting results achieved by the studies and the remaining knowledge gaps. We conclude with suggestions for future research in three main areas: 1) bird behaviour and perception of power lines; 2) impact assessment methods, at project-level and on a broader scale; and 3) mitigation strategies.

Paper #1 - **Bernardino, J.**, Bevanger, K., Barrientos, R., Dwyer, J.F., Marques, A.T., Martins, R.C., Shaw, J.M., Silva, J.P. & Moreira, F. (2018). Bird collisions with power lines: State of the art and priority areas for research. *Biological Conservation*, 222, 1–13. https://doi.org/10.1016/j.biocon.2018.02.029

- In **Chapter 3**, we performed a meta-analysis on wire-marking effectiveness in reducing bird collisions with power lines and explored the potential moderating effects of power line type, habitat and type of BFD. The analysis combined the results of 35 individual studies conducted worldwide, which were published in peer-reviewed journals or available in grey literature. Based on a careful evaluation of the strengths and limitations of the compiled studies, we provide recommendations on how future field experiments should be designed to guarantee reliable results and improve the overall knowledge on wire-marking effectiveness.

Paper #2 - **Bernardino, J.**, Martins, R.C., Bispo, R. & Moreira, F. (2019). Re-assessing the effectiveness of wire-marking to mitigate bird collisions with power lines: A meta-analysis and guidelines for field studies. *Journal of Environmental Management*, 252, 109651. https://doi.org/10.1016/j.jenvman.2019.109651

- In **Chapter 4**, we compiled and re-analysed data from carcass persistence and searcher efficiency trials conducted, between 2005 and 2018, at 36 transmission lines in mainland Portugal. This data was until now unavailable or dispersed in grey literature, as the field experiments were carried out in the framework of separate post-EIA monitoring programmes. Our main objective was to investigate the ecological and methodological factors influencing both sources of bias, to improve future field experiments and, ultimately, bird fatality estimates.

Paper #3 - **Bernardino, J.**, Martins, R.C., Bispo, R., Marques , A.T. & Moreira, F. (in prep.). Ecological and methodological drivers of persistence and detection of bird fatalities at power lines: insights from multiple project monitoring data. To be submitted to *Environmental Impact Assessment Review*.

- In **Chapter 5**, we carried out carcass persistence trials, using camera-trapping methods, in two different Mediterranean agricultural landscapes bisected by linear infrastructures, namely power lines and roads. Our goal was to investigate whether infrastructure presence influenced the identity of the vertebrate scavengers responsible for removing bird carcasses and evaluate its cascading effects on carcass persistence times. Based on the results, we evaluate the implications for the derived bias corrections (carcass persistence probabilities) and bird fatality estimates, and provide recommendations for carcass persistence trials in the context of post-EIA monitoring.

Paper #4 - **Bernardino, J.**, Bispo, R., Martins, R.C., Santos, S. & Moreira, F. (2020). Response of vertebrate scavengers to power line and road rights-of-way and its implications for bird fatality estimates. *Scientific Reports*, 10, 15014. https://doi.org/10.1038/s41598-020-72059-7

Finally, in **Chapter 6**, I discuss the main findings of the previous chapters and contribution of the present research for the "Adaptive Management" cycle of T&D developments and post-EIA monitoring programmes. I finish with an outline of future research possibilities, and some concluding remarks.

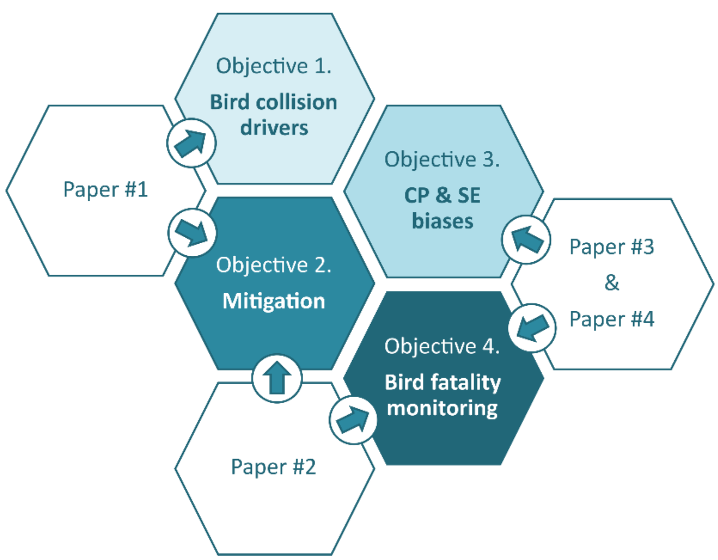


Figure 1.6 - Relationship between the specific objectives of the thesis and the included research papers. CP – Carcass Persistence; SE – Searcher Efficiency.

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Chapter 2

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

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

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 before-after-control-impact [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.

Keywords

Bird mortality, collision risk, Impact assessment and mitigation, energy, knowledge gaps, transmission and distribution lines.

2.1. 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; Rioux *et al.* 2013; Loss *et al.* 2014a, 2015). 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 (Schaub and Pradel 2004; Schaub *et al.* 2010; Loss *et al.* 2012), and red-listed and economically important species are commonly documented casualties (Hobbs 1987; Bevanger 1995a, 1998; 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., Bevanger 1990, 1994; Jenkins *et al.* 2010; Barrientos *et al.* 2011, 2012; 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 (1994, 1998). Since then, there has been no peer-reviewed update of scientific evidence, with the exception of Jenkins *et al.* (2010) which focused 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., Jenkins *et al.* 2010; Barrientos *et al.* 2011).

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:

- 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;
- 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);
- 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;
- We conclude by identifying knowledge gaps and suggesting future research avenues to answer persisting questions.

2.2. 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 Supplementary material, Table S 2.1).

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 Supplementary material, Table S 2.2).

2.3. 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 2.1).

The majority of studies (60.2%), especially those published earlier, focused on quantifying bird fatalities from collisions (Figure 2.2). 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 2.3). 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.

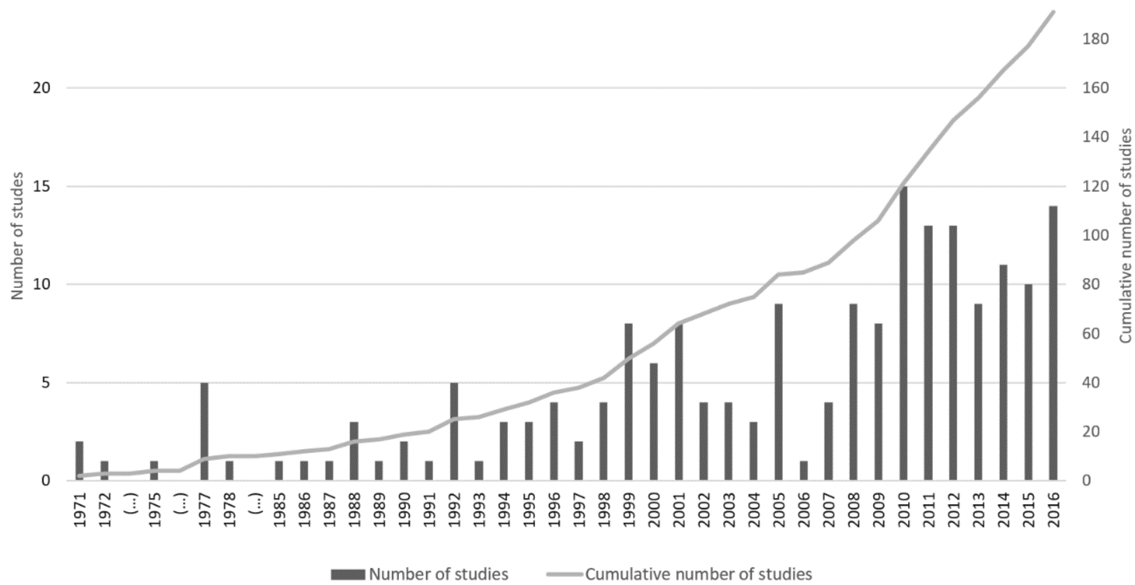

Figure 2.1 - Number of studies per publication year focusing on bird collision with power lines, compiled through a systematic literature search (n = 191). Number of studies found for the years 1973-74, 1976 and 1979-84.

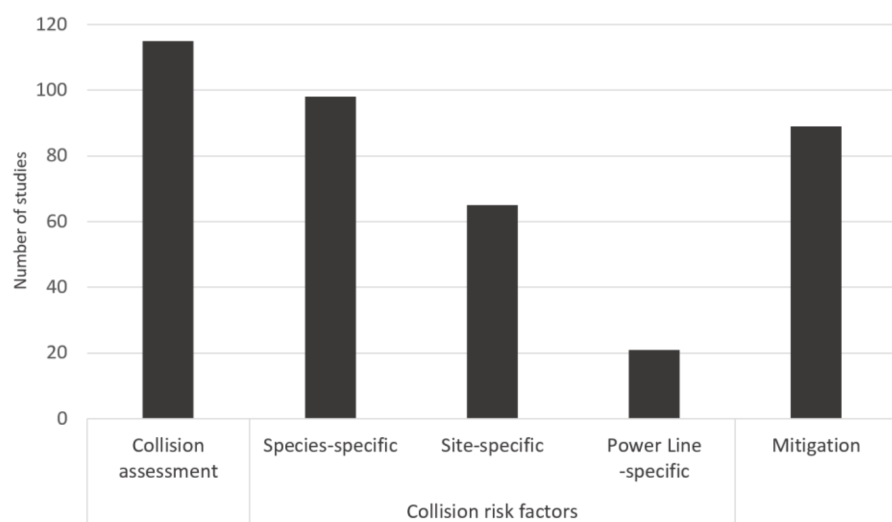

Figure 2.2 - Number of studies addressing each of the main research topics, compiled through a systematic literature search (n = 191). Many studies addressed more than one topic.

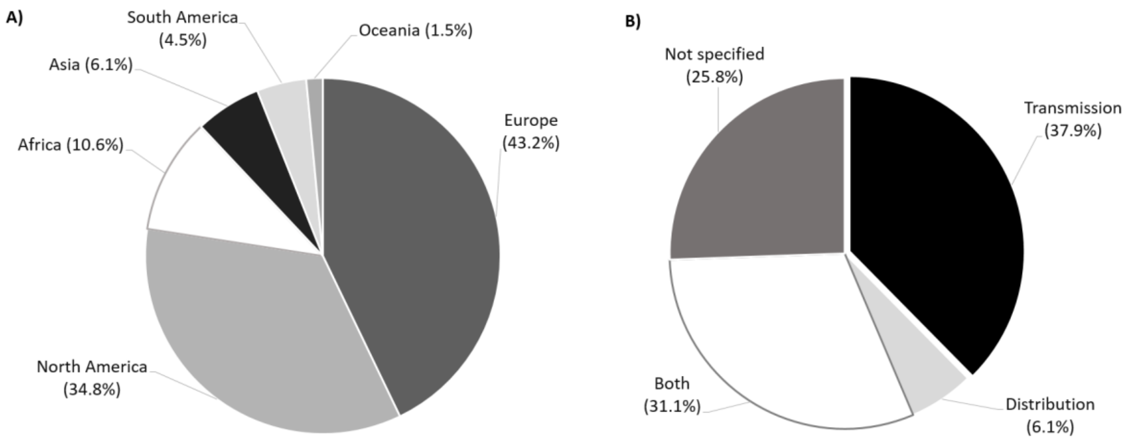

Figure 2.3 - Percentage of studies conducted (A) in each region of the world and (B) on each power-line type, compiled through a systematic literature search and reporting first-hand data on bird collisions with power lines (n=132).

2.4. 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.

2.4.1. 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.

2.4.1.1. 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 (Sillman 1973; Martin 1985, 1990; Martin and Osorio 2008). 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 1985, 1990, 2011), facilitating detection of conspecifics, predators and food (Rogers 2008; Fernández-Juricic *et al.* 2008). However, a very wide visual field may also compromise a bird's ability to detect obstacles in the air. Martin (2009, 2011) 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 and Shaw 2010; Martin 2011, 2012). This may help to explain why even raptors with a visual acuity 2.5-3 times greater than humans (Reymond 1985, 1987), 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 (Sillman 1973; Schmidt-Morand 1992). 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 (Bevanger 1995a, b; Baines and Summers 1997; 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; Zhang 2003; Ödeen *et al.* 2011). 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 weak UV (Lind *et al*. 2014).

2.4.1.2. 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., Rayner 1988; Norberg 1990; Hedenström 2002). 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; Rubolini *et al.* 2005; Rioux *et al. 2013)*. 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., Janss and Ferrer 2000; Reiter 2000; Barrientos *et al.* 2012).

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.

2.4.1.3. Flight behaviour

Collision susceptibility may be influenced by flight behaviour. Gregarious species are generally thought to be more vulnerable than species with solitary habits (Drewitt and Langston 2008; APLIC 2012). 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., Scott *et al.* 1972; Alonso and Alonso 1999). 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 2.4.1.5) 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 2.4.2.3). 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 2.4.2.3), can have a high collision risk, especially if the areas are relatively close together and birds tend to fly between them at lower altitudes (Bevanger 1994; Drewitt and Langston 2008; APLIC 2012). Although raptors are infrequently reported as collision victims, power lines intersecting the home range of some eagle species can be problematic (Mañosa 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.

2.4.1.4. 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 (van Rooyen and Diamond 2008; Shaw 2013). 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., Scott *et al.* 1972; McNeil *et al.* 1985; Janss and Ferrer 2000; Murphy *et al.* 2009; Tere and Parasharya 2011). Nocturnal migrants, such as rails, thrushes, starlings, and other passerines, appear to be more susceptible to collision than diurnal migrants (Scott *et al.* 1972; Drewitt and Langston 2008). 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).

2.4.1.5. 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., Krapu 1974; Anderson 1978; Ward and Anderson 1992; Brown and Drewien 1995; Sundar and Choudhury 2005). 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 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.

2.4.2. 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.

2.4.2.1. 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 (Thompson 1978; Bevanger 1994). 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).

2.4.2.2. 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 (Malcolm 1982; Faanes 1987; Andriushchenko and Popenko 2012), 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.

2.4.2.3. 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 (Drewitt and Langston 2008; APLIC 2012). Heavy fog, rainfall, snow and cloudy conditions (particularly low cloud ceilings), force birds to fly at low altitudes, even close to the ground (Elkins 1988; Bevanger 1994). 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., Ward and Anderson 1992; Savereno *et al.* 1996). 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; Perdeck and Speek 1984; Bevanger 1994). 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 1993, 1995b; Bevanger and Brøseth 2000, 2004). Likewise, waterbirds that fly at night can be less likely to react to a power line (Jie 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).

2.4.2.4. 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., Willard 1978; Brown and Drewien 1995), yet recreational or agricultural activities, and power line maintenance works are also recognised as potential disturbance sources (Thompson 1978; van Rooyen and Diamond 2008; Murphy *et al.* 2009; Sastre *et al.* 2009).

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 (Silva *et al.* 2010; Shaw *et al.* 2018) 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.

2.4.3. 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).

2.4.3.1. 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 (Ward and Anderson 1992; Neves *et al.* 2005; Pandey *et al.* 2008).

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.

2.4.3.2. 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 (Brown *et al.* 1987; Bevanger 1994); see also sections 2.4.1.3 and 2.4.2.2, 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; Murphy *et al*. 2009; Luzenski *et al.* 2016). 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.* 2018). 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).

2.4.3.3. 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 (Martin and Shaw 2010; APLIC 2012); see also section 2.4.1.1). 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 (Scott *et al.* 1972; Meyer 1978; Faanes 1987; Murphy *et al.* 2009), 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 (Scott *et al.* 1972; Meyer 1978; Faanes 1987). 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.

2.5. 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.

2.5.1. 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 2.5.4) 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 (Parsons Brinckerhoff 2012; Hall 2013). 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 (Haas *et al.* 2005; APLIC 2012; SNH 2016).

2.5.2. 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.* 2018). 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 (Shaw *et al.* 2010b; Quinn *et al.* 2011; Silva *et al.* 2014), or simply on species distribution models or locations (e.g., Australian Government 2015; Allinson 2017). 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., Williams 2003; Haas *et al.* 2005; APLIC 2012; SNH 2016). 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 (Darel 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., Thompson 1978; Faanes 1987; Bevanger 1994; Harness and Carlton 2001; SNH 2016). 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., Williams 2003; Prinsen *et al.* 2012; SNH 2016), 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 (Thompson 1978; APLIC 1994; Bevanger 1994). 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.

2.5.3. Power line configuration

Removal of the earth wire can lead to significant reductions in bird collision rates (see section 2.4.3.3). 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 (Bevanger 1994; Haas *et al.* 2005; APLIC 2012). 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 (Shaw *et al.* 2010b; Jenkins *et al.* 2010; APLIC 2012), but we found little scientific evidence that these recommendations are effective (see sections 2.4.3.2 and 2.4.3.3). 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).

2.5.4. 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 (Barrientos *et al.* 2011; APLIC 2012). 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 (Ponce *et al.* 2010; Costantini *et al.* 2017), 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 Supplementary material, Figure S 2.1 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., Sporer *et al.* 2013; Murphy *et al.* 2016a), 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., Scott *et al.* 1972; De La Zerda 2012; 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 (Sporer *et al.* 2013; Dashnyam *et al.* 2016). 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.

2.5.5. 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 2.4.2.2). Thus, a suggested strategy to change local flight paths and prevent bird collisions is the modification of adjacent habitats, land uses or management practices (Thompson 1978; APLIC 2012). 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., Thompson 1978; APLIC 2012) 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) (Thompson 1978; APLIC 2012). 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.

2.6. 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 2.1, divided into three major topics (behaviour aspects, impact assessment and mitigation measures). Here we highlight those we considered of highest priority.

2.6.1. 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 2.6.2).

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).

2.6.2. Impact assessment

Increased knowledge of factors underlying mortality hotspots (e.g., Quinn *et al.* 2011; Prinsen *et al.* 2012) 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., Hernández-Matías *et al.* 2015; Chevallier *et al.* 2015), although a few studies dealing with collisions exist (Schaub and Pradel 2004; Bevanger *et al.* 2014). 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 (Ponce *et al.* 2010; Rioux *et al.* 2013; Murphy *et al.* 2016b). Further research is also needed to refine the estimators used to correct for those biases (Bernardino *et al.* 2013; Stevens and Dennis 2013; Huso *et al.* 2016a).

2.6.3. 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., Yee 2008; Sporer *et al.* 2013), as well on device durability and technical limitations (e.g., Hurst 2004; Dashnyam *et al.* 2016). 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.

Table 2.1 - Identification of knowledge gaps and suggestions of research and innovative approaches to fill those gaps.

Knowledge gaps / Research questions	**Potential research and innovative approaches**
Bird behaviour and perceptions	
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.

Knowledge gaps / Research questions	Potential research and innovative approaches
Assess visual and perceptual aspects	• Experimental approaches to assess 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).
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.
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. • 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).

Knowledge gaps / Research questions	**Potential research and innovative approaches**
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.
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, characterisation of crossing rates is important to evaluate differences.

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2.9. Supplementary material

2.9.1. Studies compiled through systematic literature search

Table S 2.1 - List of studies focusing bird collision with power lines compiled through the systematic literature search.

Type of publication: "paper" – research paper published in scientific journal; "book" – full book; "book chapter" – chapter of a book; "proceedings" – article published in Conference proceedings; "thesis" – thesis submitted to obtain a MSc or PhD degree; "report" – technical report (not peer-reviewed).

Type of work: "original" – original research or dissertation; "review" – review of published literature; "guidelines" – best practice guidelines; "EIA" – Environmental Impact Assessment study.

Research topics: research topics addressed by the manuscript (1 – Yes; 0 – No).

First-hand data: manuscript includes first-hand data on bird collision with power lines (1 – Yes; 0 – No).

Type of power line: T – Transmission, D – Distribution, T&D – Transmission and Distribution; ? - Not specified.

Country: country where the first-hand data was collected.

ID	Authors	Year	Type of publication	Type of work	Research topics					First-hand data	Type of power line	Country
					Collision Assessment	Collision risk factors			Mitigation			
						Species-specific	Site-specific	Power line-specific				
1	Ahlen *et al.*	2013	paper	original	1	1	1	0	0	1	?	Sweden
2	Alonso & Alonso (a)	1999	book chapter	original	1	1	1	0	0	1	T	Spain
3	Alonso & Alonso (b)	1999	book chapter	original	1	0	0	0	1	1	T	Spain
4	Alonso *et al.*	1994	paper	original	1	0	0	0	1	1	T	Spain
5	Anderson	1978	paper	original	1	1	1	0	0	1	T	USA
6	Andrews	1990	paper	review	0	1	1	0	0	0	-	-
7	Antal	2010	paper	original	0	0	0	0	1	0	-	-
8	APLIC	1994	book	review	0	0	1	1	1	0	-	-
9	Ashbrook *et al.*	2015	paper	original	1	0	0	0	0	1	?	UK
10	Avery	1978	proceedings	original	0	1	1	1	1	1	T&D	USA
11	Avery	1979	proceedings	review	1	0	0	0	0	0	-	-
12	Balmer *et al.*	2002	report	original	1	1	1	0	0	1	T	UK
13	Barrientos *et al.*	2011	paper	original	0	0	0	0	1	0	-	-
14	Barrientos *et al.*	2012	paper	original	0	0	0	0	1	1	T&D	Spain
15	Bayle	1999	paper	original	0	1	0	0	0	1	T&D	Western Europe

ID	Authors	Year	Type of publication	Type of work	Research topics: Collision Assessment	Collision risk factors: Species-specific	Collision risk factors: Site-specific	Collision risk factors: Power line-specific	Mitigation	First-hand data	Type of power line	Country
16	Bevanger	1994	paper	review	0	1	1	1	1	0	-	-
17	Bevanger	1995	paper	original	1	1	1	0	0	1	T&D	Norway
18	Bevanger	1995	paper	original	1	1	0	0	0	1	T	Norway
19	Bevanger	1998	paper	review	0	1	0	0	0	0	-	-
20	Bevanger & Brøseth	2001	paper	original	1	1	0	1	0	1	T&D	Norway
21	Bevanger & Brøseth	2004	paper	original	1	1	1	0	0	1	T&D	Norway
22	Bevanger *et al.*	2014	report	original	1	0	0	0	1	1	T&D	Norway
23	Boshoff *et al.*	2011	paper	original	1	0	0	0	0	1	T&D	South Africa
24	Braun *et al.*	1978	paper	original	0	1	1	0	1	0	-	-
25	Breece & Ward	1996	paper	review	0	0	0	0	1	0	-	-
26	Bridges *et al.*	2008	proceedings	review	0	0	0	0	1	0	-	-
27	Brown & Drewien	1992	proceedings	original	0	0	1	0	1	1	?	USA
28	Brown & Drewien	1995	paper	original	1	1	1	0	1	1	T&D	USA
29	Brown & Lawson	1989	paper	original	1	0	0	0	0	1	T&D	Namibia
30	Brown *et al.*	1992	paper	original	1	1	0	0	0	1	?	UK
31	Burd & Resto-Spotts	2014	paper	original	0	0	0	0	1	0	-	-
32	Burke & Rodwell	2000	newsletter	original	1	1	0	0	0	0	-	-
33	Burnham *et al.*	2004	paper	review	0	0	0	1	1	0	-	-
34	Burnside *et al.*	2012	paper	original	1	0	0	0	0	1	?	UK
35	Cadbury & Olney	1978	paper	original	1	1	0	0	0	1	T	UK
36	Calvert *et al.*	2013	paper	original	1	0	0	0	0	0	-	-
37	Clancy	2010	paper	original	1	0	0	0	0	1	T&D	Australia
38	Australian Government	2015	report	guidelines	0	0	0	0	1	0	-	-
39	Cochrane *et al*.	1991	paper	original	1	1	0	0	1	1	D	South Africa
40	Cooper & Day	1998	paper	original	1	1	1	0	0	1	?	USA
41	Cornwell & Hochbaum	1971	paper	original	1	1	1	0	0	1	?	USA
42	Costantini *et al.*	2016	paper	original	1	0	1	0	0	1	T	Italy
43	Crivelli *et al.*	1988	paper	original	1	1	1	0	0	1	T	Greece
44	Cruz-Delgado	2010	paper	original	1	0	0	0	0	1	?	Equator
45	Darel Tracy *et al.*	2012	proceedings	review	0	0	0	0	1	0	-	-
46	De La Zerda & Rosselli	2002	proceedings	original	1	0	0	0	1	1	T	Colombia
47	De La Zerda & Rosselli	2003	paper	original	1	0	1	0	1	1	T	Colombia
48	De La Zerda	2012	proceedings	original	0	0	0	0	1	1	T	Colombia
49	Demerdzhiev	2014	paper	original	1	0	1	0	0	1	D	Bulgaria

ID	Authors	Year	Type of publication	Type of work	Research topics					First-hand data	Type of power line	Country
					Collision Assessment	Collision risk factors			Mitigation			
						Species-specific	Site-specific	Power line-specific				
50	Demerdzhiev *et al.*	2009	paper	original	1	0	1	0	0	1	D	Bulgaria
51	Dillingham & Fletcher	2008	paper	original	0	1	0	0	0	0	-	-
52	Donázar *et al.*	2002	paper	original	1	1	0	0	0	1	T&D	Spain
53	Dorin *et al.*	2005	report	review	0	0	1	1	1	0	-	-
54	Dray *et al.*	2016	report	EIA	0	1	0	0	1	0	-	-
55	Drewitt & Langston	2008	paper	review	0	1	1	1	1	0	-	-
56	Erickson *et al.*	2005	paper	review	1	0	0	0	0	0	-	-
57	Faanes	1987	report	original	1	1	1	1	1	1	T	USA
58	Faanes & Johnson	1992	proceedings	original	1	1	1	0	0	1	T	USA
59	Fengshan *et al.*	2011	paper	original	1	0	1	0	0	1	T	China
60	Fernie & Bird	2001	paper	original	0	1	0	0	0	0	-	-
61	Fernie *et al.*	2000	paper	original	0	1	0	0	0	0	-	-
62	Folk *et al.*	2008	proceedings	original	1	1	0	0	0	1	T	USA
63	Frederick & Jie	1997	report	original	1	1	1	0	1	1	T	USA
64	Frost	2008	paper	original	1	1	0	0	1	1	T	UK
65	Gahbauer *et al.*	2015	paper	original	1	0	0	0	0	1	?	Canada
66	Garcia-del-Rey & Rodriguez-Lorenzo	2011	paper	original	1	1	0	0	0	1	T	Spain
67	Garrido & Fernandés-Cruz	2003	paper	original	1	1	1	0	0	1	T&D	Spain
68	Gerdzhikov & Demerdzhiev	2009	paper	original	1	0	1	0	0	1	D	Bulgaria
69	Gibbons	2011	paper	original	1	0	0	0	0	1	T&D	South Africa
70	González *et al.*	2007	paper	original	1	1	0	0	0	1	?	Spain
71	Goodrich-Mahoney *et al.*	2008	proceedings	original	1	0	0	0	1	0	-	-
72	Haas *et al.*	2005	book	review	0	0	1	0	1	0	-	-
73	Harmata *et al.*	1999	paper	original	1	0	0	0	0	1	?	USA
74	Harmata *et al.*	2001	paper	original	1	0	0	0	0	1	?	USA
75	Harness & Carlton	2001	report	review	0	0	0	1	1	0	-	-
76	Harness *et al.*	2003	report	original	1	0	0	0	0	1	T	USA
77	Heck	2007	thesis	original	0	1	1	1	0	1	T	USA
78	Henderson *et al.*	1996	paper	original	1	1	1	0	1	1	T	UK
79	Hovick *et al.*	2014	paper	review	0	1	0	0	0	0	-	-
80	Ingrassia	2016	thesis	original	0	1	0	0	0	1	T&D	USA
81	Janss	2000	paper	original	1	1	0	0	0	1	?	Spain
82	Janss & Ferrer	1998	paper	original	1	1	0	0	1	1	T&D	Spain
83	Janss & Ferrer	2000	paper	original	1	1	0	0	0	1	T&D	Spain

ID	Authors	Year	Type of publication	Type of work	Research topics					First-hand data	Type of power line	Country
					Collision Assessment	Collision risk factors			Mitigation			
						Species-specific	Site-specific	Power line-specific				
84	Jenkins *et al.*	2010	paper	review	0	1	1	1	1	0	-	-
85	Jenkins *et al.*	2011	paper	original	1	1	0	0	0	1	T	South Africa
86	Jenkins *et al.*	2015	report	guidelines	0	0	0	0	1	0	-	-
87	Jie & Frederick	2001	paper	original	1	1	1	0	0	1	T	USA
88	Kalkani *et al*	1996	paper	review	0	0	0	0	1	0	-	-
89	Kalpakis *et al.*	2009	paper	original	1	0	0	0	0	1	T&D	Greece
90	Kelly & Kelly	2005	paper	original	1	1	0	0	0	1	T	UK
91	Klaassen *et al.*	2014	paper	original	1	0	0	0	0	1	?	Europe
92	Kroodsma	1978	thesis	review	0	1	1	1	1	0	-	-
93	Lambertucci *et al.*	2015	paper	other	0	0	0	0	1	0	-	-
94	Larsen & Madsen	2000	paper	original	0	1	0	0	0	1	T	Denmark
95	Ledger & Hobbs	1999	paper	review	0	1	0	0	0	0	-	-
96	Lewis *et al.*	1992	proceedings	original	1	1	0	0	0	1	?	USA
97	Liguori	2009	proceedings	review	0	0	1	0	1	0	-	-
98	Lobermeier *et al.*	2015	paper	original	0	0	0	0	1	1	T	USA
99	Loss	2016	paper	other	1	0	0	0	1	0	-	-
100	Loss *et al.*	2014	paper	original	1	0	0	0	0	0	-	-
101	Loss *et al.*	2015	paper	review	1	0	0	0	0	0	-	-
102	Luzenski *et al.*	2016	paper	original	0	0	0	0	1	1	T	USA
103	Manville II	2005	report	review	1	0	0	1	1	0	-	-
104	Manville II	2016	book chapter	review	0	1	0	1	0	0	-	-
105	Martin	2010	proceedings	original	0	1	0	0	1	0	-	-
106	Martin	2011	paper	review	0	1	0	0	1	0	-	-
107	Martin	2012	paper	review	0	1	0	0	0	0	-	-
108	Martin & Shaw	2010	paper	original	0	1	0	0	0	1	T&D	South Africa
109	Martin & Wanless	2015	paper	original	0	1	0	0	0	1	T&D	UK
110	Martin *et al*.	2012	paper	original	0	1	0	0	0	1	T&D	UK
111	Martinez *et al.*	2016	paper	original	1	0	0	0	0	1	?	Spain
112	Martínez-Abraín *et al.*	2012	paper	original	1	0	0	0	0	1	T	Spain
113	Mathiasson	1993	paper	original	1	1	1	0	0	1	?	Sweden
114	Mathiasson	1999	book chapter	original	1	1	1	1	0	1	T	Sweden
115	McCann	2005	report	EIA	0	0	1	0	1	0	-	-
116	McNeil *et al.*	1985	paper	original	1	1	1	0	0	1	T&D	Venezuela
117	Miller *et al.*	2010	proceedings	original	1	0	0	0	0	1	T&D	USA
118	Milsom *et al.*	2000	paper	original	0	1	0	0	0	1	?	USA

ID	Authors	Year	Type of publication	Type of work	Research topics					First-hand data	Type of power line	Country
					Collision Assessment	Collision risk factors			Mitigation			
						Species-specific	Site-specific	Power line-specific				
119	Miquet	1990	paper	original	1	0	0	0	0	1	?	France
120	Mojica *et al.*	2009	paper	original	0	0	1	0	0	1	D	USA
121	Murphy *et al.*	2009	report	original	0	0	1	1	1	1	T	USA
122	Murphy *et al.*	2016	paper	original	1	0	0	0	1	1	T	USA
123	Murphy *et al.*	2016	paper	original	1	0	1	0	1	1	T	USA
124	Newman *et al.*	2007	paper	original	1	1	0	0	0	1	?	USA
125	Owen & Cadbury	1975	paper	original	1	1	1	0	0	1	T&D	UK
126	Palacín *et al.*	2017	paper	original	0	1	0	0	0	1	T&D	Africa
127	Pande *et al*.	2013	paper	original	1	0	0	0	0	1	T	India
128	Patten *et al.*	2005	paper	original	1	1	1	0	0	1	?	USA
129	Pavez & Estades	2016	paper	original	1	0	0	0	0	1	T&D	Chile
130	Podolsky *et al.*	1998	paper	original	1	1	1	0	0	1	?	USA
131	Pruett *et al.*	2009	paper	original	0	0	1	0	0	1	T	USA
132	Purevdorj & Sundev	2012	paper	original	1	0	0	0	0	1	T&D	Mongolia
133	Quinn *et al.*	2011	paper	original	1	0	1	0	1	1	T	USA
134	Raab *et al*.	2011	paper	original	0	0	1	0	0	1	T	Austria
135	Raab *et al.*	2012	paper	original	0	0	0	0	1	1	T	Austria
136	Raab *et al.*	2014	paper	review	0	1	0	0	1	0	-	-
137	Radler & Bergerhausen	1988	proceedings	original	1	1	0	0	0	1	?	Europe
138	Real *et al.*	2001	paper	original	1	1	0	0	0	1	?	Spain
139	Rideout *et al.*	2012	paper	original	1	0	0	0	0	1	?	USA
140	Rioux *et al.*	2013	paper	review	1	0	0	0	0	0	-	-
141	Rodríguez *et al.*	2010	paper	original	1	0	0	0	0	1	T	Spain
142	Rollan *et al.*	2010	paper	original	0	1	1	0	0	1	T&D	Spain
143	Rubolini *et al.*	2001	paper	original	1	1	0	0	0	1	D	Italy
144	Rubolini *et al.*	2005	paper	original	1	1	0	0	0	1	T&D	Italy
145	Rusz *et al.*	1986	paper	original	1	1	1	0	0	1	T	USA
146	Sánchez-Zapata *et al.*	2016	book chapter	review	0	1	1	0	1	0	-	-
147	Savereno *et al.*	1996	paper	original	1	0	1	0	1	1	T	USA
148	Schaub & Pradel	2004	paper	original	1	0	0	0	0	1	?	Switzerland
149	Schaub *et al.*	2010	paper	original	1	0	0	0	0	1	T&D	Switzerland
150	Scott *et al.*	1972	paper	original	1	1	1	1	1	1	T	UK
151	Shaw	2009	thesis	original	1	0	1	0	0	1	T&D	South Africa
152	Shaw	2013	thesis	original	1	1	1	1	1	1	T&D	South Africa

ID	Authors	Year	Type of publication	Type of work	Research topics					First-hand data	Type of power line	Country
					Collision Assessment	Collision risk factors			Mitigation			
						Species-specific	Site-specific	Power line-specific				
153	Shaw *et al.*	2010	paper	original	1	0	0	0	0	1	T&D	South Africa
154	Shaw *et al.*	2010	paper	original	0	0	1	0	0	1	T&D	South Africa
155	Shaw & Smallie	2013	report	EIA	1	0	0	0	1	0	-	-
156	Shimada	2001	paper	original	0	1	1	0	0	1	?	Japan
157	Shobrak	2012	paper	original	1	0	0	0	0	1	T	Saudi Arabia
158	Silva *et al.*	2010	paper	original	0	0	1	0	0	1	T	Portugal
159	Silva *et al.*	2014	paper	original	0	0	0	0	1	1	D	Portugal
160	Simmons	2011	paper	original	0	1	0	0	0	0	-	-
161	Smallie	2008	report	EIA	0	0	0	0	1	0	-	-
162	Smallie	2012	thesis	original	0	1	0	0	0	1	T&D	South Africa
163	Smallie	2013	report	EIA	0	0	0	0	1	0	-	-
164	Smallie	2014	report	EIA	0	0	0	0	1	0	-	-
165	Smallie & Virani	2010	paper	original	1	0	0	0	0	1	T&D	Kenya
166	Smith & Dwyer	2016	paper	review	1	1	1	0	0	0	-	-
167	Smith & Willebrand	1999	paper	original	0	1	0	0	0	0	-	-
168	SNH	2016	report	guidelines	0	0	0	0	1	0	-	-
169	Söderman	2006	paper	original	0	0	0	0	1	0	-	-
170	Spalding *et al.*	2010	proceedings	original	1	0	0	0	0	1	?	USA
171	Sporer *et al.*	2013	paper	original	0	1	0	0	1	1	T	USA
172	Stehn & Wassenich	2008	paper	original	1	1	1	0	1	1	T	USA
173	Sundar & Choudhury	2005	paper	original	1	1	0	0	0	1	T	India
174	Taylor & Walker	2015	report	original	0	1	1	0	0	1	T	Canada
175	Tere & Parasharya	2011	paper	original	1	1	0	0	0	1	T&D	India
176	Tobolka	2014	paper	original	1	0	0	0	0	1	?	Poland
177	Tyler *et al.*	2014	paper	other	0	1	0	0	0	0	-	-
178	van Rooyen & Diamond	2008	newsletter	review	0	1	1	1	1	0	-	-
179	van Rooyen & Legder	1999	book chapter	original	1	1	0	0	0	1	T	South Africa
180	Voronova *et al.*	2012	paper	original	1	0	0	0	0	1	T&D	Kazakhstan
181	Ward & Anderson	1992	proceedings	original	1	1	0	1	0	1	T&D	USA
182	Watts *et al.*	2015	paper	original	0	1	0	0	0	1	T&D	USA
183	Weir	1971	paper	original	1	1	0	0	0	1	?	UK
184	Wendell *et al.*	2002	paper	original	1	1	0	0	0	1	?	USA
185	Williams	2003	proceedings	review	0	0	1	1	1	0	-	-
186	Windingstad	1988	paper	original	1	1	0	0	0	1	?	USA

ID	Authors	Year	Type of publication	Type of work	Research topics: Collision Assessment	Collision risk factors: Species-specific	Collision risk factors: Site-specific	Collision risk factors: Power line-specific	Mitigation	First-hand data	Type of power line	Country
187	Winkleman	2012	report	EIA	0	1	1	0	1	0	-	-
188	Winning & Murray	1997	paper	original	1	1	1	0	0	1	T	Australia
189	Wolfe *et al.*	2007	paper	original	1	1	0	0	0	1	?	USA
190	Wright *et al.*	2009	paper	original	1	0	0	0	0	1	T	USA
191	Yee	2008	report	original	1	0	0	0	1	1	D	USA

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2.9.2. Additional studies included in the review

Table S 2.2 - List of additional studies included in the review, besides the studies compiled through the systematic literature search.

Type of publication: "paper" – research paper published in scientific journal; "book" – full book; "book chapter" – chapter of a book; "proceedings" – article published in Conference proceedings; "thesis" – thesis submitted to obtain a MSc or PhD degree; "report" – technical report (not peer-reviewed).

Type of work: "original" – original research or dissertation; "review" – review of published literature; "guidelines" – best practice guidelines; "EIA" – Environmental Impact Assessment study.

ID	**Authors**	**Year**	**Title**	**Type of publication**	**Type of work**
192	Allison	2017	Introducing a New Avian Sensitivity Mapping Tool to Support the Sitting of Wind Farms and Power Lines in the Middle East and Northeast Africa	proceedings	original
193	Anderson	2002	The effectiveness of two different marking devices to reduce large terrestrial bird collisions with overhead electricity cables in the eastern Karoo, South Africa	report	original
194	Andriushchenko & Popenko	2012	Birds and Power Lines in Steppe Crimea: Positive and Negative Impacts, Ukaine	proceedings	original
195	APLIC	2006	Suggested Practices for Avian Protection on Power lines: The State of the Art in 2006	report	guidelines
196	APLIC	2012	Reducing Avian Collisions with Power Lines: The State of The Art in 2012	report	guidelines
197	Avery *et al.*	1977	Weather Influences on Nocturnal Bird Mortality at a North Dakota Tower	paper	original
198	Bagli *et al.*	2011	Routering of power lines through least-cost path analysis and multicretria evaluation to minimise environmental impacts	paper	original
199	Beaulaurier	1981	Mitigation of bird collisions with transmission lines	report	original
200	Bergman	1978	Effects of wind conditions on the Autumn Migration of Waterfowl between the White Sea Area and the Baltic Region	paper	original
201	Bevanger	1993	Bird collisions with a 220 kV transmission line in Polmak, Finnmark	report	original
202	Bevanger & Broseth	2000	Reindeer *Rangifer tarandus* fences as a mortality factor for ptarmigan *Lagopus* spp.	paper	original
203	Bevanger & Refsnæs	2013	Possibilities and constraints in reducing bird collision and electrocution in the existing power-line grid in Norway	report	review
204	Borner	2016	Apports méthodologiques à l'étude des interactions des oiseaux avec le réseau de transport d'électricité en France	thesis	original
205	Brockbank	2014	Environmental effects of underground and overhead transmission line construction and maintenance	proceedings	original
206	Brown *et al.*	1987	Mortality of cranes and waterfowl from power line collisions in the San Luis Valey, Colorado	proceedings	review
207	Calabuig & Ferrer	2009	Análisis de la eficacia y la vida útil de la señalización anticolisión "salvapájaros" en líneas de transporte de energía eléctrica	report	original
208	Chevallier *et al.*	2015	Retrofitting of power lines effectively reduces mortality by electrocution in large birds: an example with the endangered Bonelli's eagle	paper	original
209	Crowder	2000	Assessment of devices designed to lower the incidence of avian power lines strikes	thesis	original

ID	Authors	Year	Title	Type of publication	Type of work
210	Cuthill	2000	Ultraviolet Vision in Birds	paper	review
211	D'Amico *et al.*	2018	Bird on the wire: Landscape planning considering costs and benefits for bird populations coexisting with power lines	paper	review
212	Dashnyam *et al.*	2016	Malfunction Rates of Bird Flight Diverters on Powerlines in the Mongolian Gobi	paper	original
213	Doucet	2016	Proceedings of the 11th International Symposium Environmental Concerns in Rights-of-Way Management	proceedings	original
214	European Commission	2011	EU Guidance on wind energy development in accordance with the EU nature legislation	report	guidelines
215	EirGrid	2013	SEA Statement of the Grid25: Implementation Programme 2011-2016	report	EIA
216	Fengshan *et al.*	2011	Power line strikes by Black-necked Cranes and Bar-headed Geese in Tibet Autonomous Region	paper	original
217	Fernández-Juricic *et al.*	2008	The visual fields of two ground-foraging birds, House Finches and House Sparrows, allow for simultaneous foraging and anti-predator vigilance	paper	original
218	Geyr von Schweppenburg	1963	Zur Terminologie und Theorie der Leitlinie	paper	original
219	Hall	2013	Out of Sight, Out of Mind 2012: An Updated Study on the Undergrounding of Overhead Power Lines	report	original
220	Hanssen *et al.*	2014	A Least Cost Path (LCP) Toolbox for Optimal Routing of High Voltage Power Lines for a Sustainable Future	proceedings	original
221	Hedenstrom	2002	Aerodynamics, evolution and ecology of avian flight	paper	original
222	Heijnis	1980	Bird mortality from collision with conductors for maximum tension	book chapter	original
223	Hernández-Matías *et al.*	2015	Electrocution threatens the viability of populations of the endangered Bonelli's eagle (*Aquila fasciata*) in Southerns Europe	paper	original
224	Hüppop *et al.*	2016	Bird collisions at an offshore platform in the North Sea	paper	original
225	Hurst	2004	Corona Testing of Devices Used to Mitigate Bird Collisions	report	original
226	Infante	2011	Estudo de avaliação da eficácia de dispositivos anti colisão	report	original
227	Infante *et al.*	2005	Estudo sobre o Impacto das Linhas Eléctricas de Média e Alta Tensão na Avifauna em Portugal	report	original
228	James & Haak	1979	Factors affecting avian flight behaviour and collision mortality at transmission lines	report	original
229	Janss *et al.*	1999	Use of raptor models to reduce avian collisions with powerlines	paper	original
230	Lind *et al.*	2014	Ultraviolet vision in birds: the importance of transparent eye media	proceedings	original
231	Lisney *et al.*	2012	Interspecifc variation in eye shape and retinal topography in seven species of galliform bird (Aves: Galliformes: Phasianidae)	paper	original
232	Mahood *et al.*	2018	Proposed power transmission lines in Cambodia constitute a significant new threat to the largest population of the Critically Endangered Bengal florican *Houbaropsis bengalensis*	paper	original
233	Malcolm *et al.*	1982	Bird Collisions with a Power Transmission Line and Their Relation to Botulism at a Montana Wetland	paper	original
234	Mañosa & Real	2001	Potential negative effects of collisions with transmission lines on a Bonelli's eagle population	paper	original
235	Martin *et al.*	2007	Sex-biased juvenile survival in a bird with extreme size dimorphism, the great bustard *Otis tarda*	paper	original
236	Meyer	1978	Effects of Transmission Lines on Bird Flight Behavior and Collision Mortality	report	original
237	Morkill & Anderson	1991	Effectiveness of Marking Powerlines to Reduce Sandhill Crane Collisions	paper	original
238	Mueller & Berger	1967	Wind drift, leading lines and diurnal migration	paper	review

ID	**Authors**	**Year**	**Title**	**Type of publication**	**Type of work**
239	Neves *et al.*	2005	Estudo sobre o Impacto das Linhas Eléctricas de Muito Alta Tensão na Avifauna em Portugal	report	original
240	Newton	2010	The Migration Ecology of Birds	book	review
241	Odeen *et al.*	2011	Evolution of ultraviolet vision in the largest avian radiation - the passerines	paper	original
242	Palacin *et al.*	2017	Changes in bird-migration patterns associated with human-induced mortality	paper	original
243	Pandey *et al.*	2008	Bird strike indicator field deployment at the Audubon National Wildlife Refuge in North Dakota - Phase Tow	report	original
244	Parco Delta de Po	2005	Free skies over the Delta: a Sustainable Electricity Network in the Regional Park Area	report	original
245	Perrins & Sears	1991	Collisions with overhead wires a cause of mortality in Mute Swans *Cygnus olor*	paper	original
246	Piorkowski *et al.*	2012	Research Priorities for Wind Energy and Migratory Wildlife	paper	guidelines
247	Prinsen *et al.*	2011	Review of the conflict between migratory birds and electricity power grids in the African-Eurasian region	report	review
248	Prinsen *et al.*	2012	Guidelines on How to Avoid or Mitigate Impact of Electricity Power Grids on Migratory Birds in the Africa-Eurosian Region	report	guidelines
249	Rayner	1988	Form and Function in Avian Flight	paper	original
250	Reiter	2000	Casualties of Great Bustards (*Otis tarda* L.) on overhead power lines in the wertern Weinviertel (Lower Austria)	paper	original
251	Reymond	1985	Spatial visual acuity of the eagle Aquila audax: A behavioural, optical and anatomical investigation	paper	original
252	Reymond	1987	Spatial visual acuity of the falcon, Falco berigora: A behavioural, optical and anatomical investigation	paper	original
253	Richardson *et al.*	2017	Review of impact of pipelines and powerlines on biodiversity and strategies for mitigation	paper	review
254	Rogers	2008	Development and function of lateralization in the avian brain	paper	original
255	Sastre *et al.*	2009	Disturbance to great bustards (Otis tarda) in central Spain: human activities, bird responses and management implications	paper	original
256	Schaub & Pradel	2004	Assessing the relative importance of different sources of mortality from recoveries of marked animals	paper	original
257	Schoroeder	1977	Geese Hit Power Transmission Line	magazine article	original
258	Shaw *et al.*	2018	High power line collision mortality of threatened bustards at a regional scale in the Karoo, South Africa	paper	original
259	Swaddle & Ingrassia	2017	Using a Sound Field to Reduce the Risks of Bird-Strike: An Experimental Approach	paper	original
260	Tryjanowski *et al.*	2014	A Paradox for Conservation Electricity Pylons May Benefit Avian Diversity in Intensive Farmland	paper	original
261	Tyrrell & Fernandez-Juricic	2017	Avian binocular vision: It's not just about what birds can see, it's also about what they can't	paper	original
262	Ventana Wildlife Society	2009	Evaluating Diverter Effectiveness in Reducing Avian Collisions With Distribution Lines at San Luis National Wildlife Refuge Complex, Merced County, California	report	original
263	Zhang	2003	Paleomolecular biology unravels the evolutionary mystery of vertebrate UV vision	paper	original

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2.9.3. Examples of wire-markers

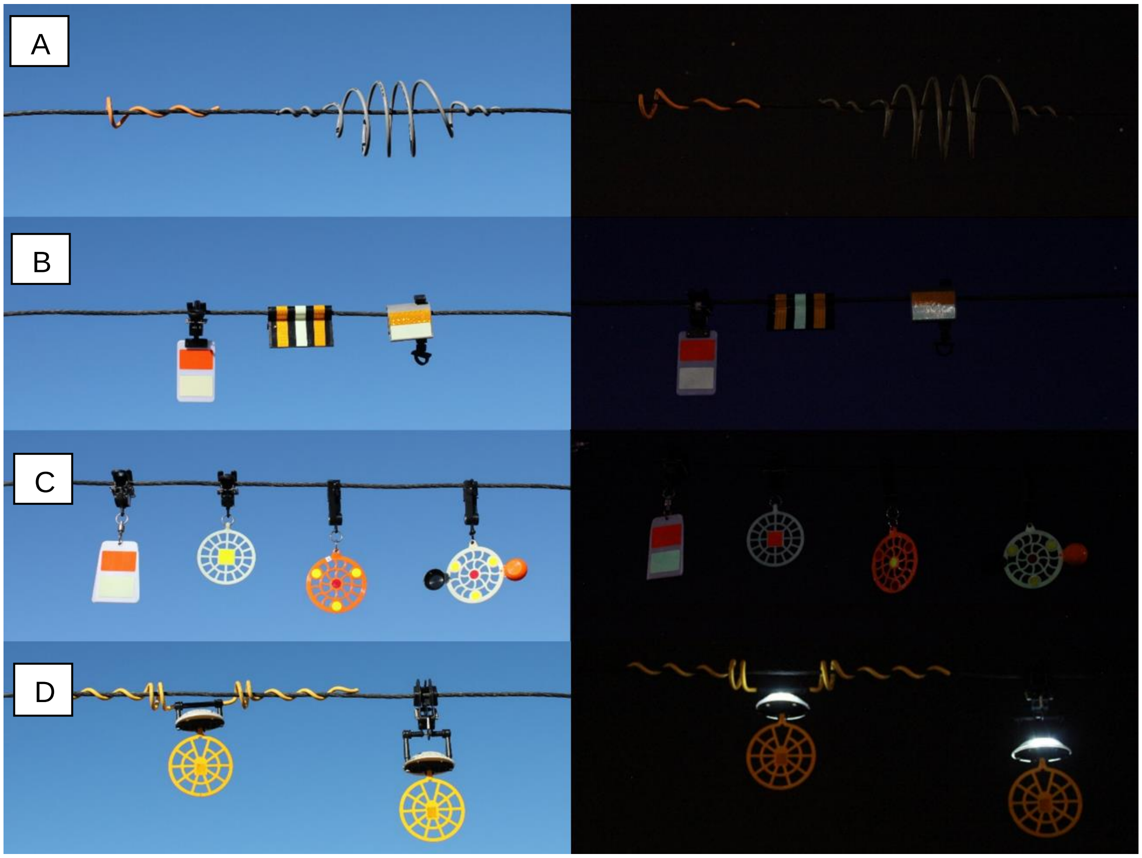
Figure S 2.1 – Examples of some common line markers currently available on the market, and how they look under sunlight (left side) and during night-time (right side).

A) Small spirals and large double spiral; no glow in the dark, no motion;

B) Clamps without moving parts; glow in the dark, no motion;

C) Flappers and other clamps with moving parts; some glow in the dark, all motion;

D) Flappers with solar powered light emitting diodes; all lighted, some motion.



Chapter 3

Re-assessing the effectiveness of wire-marking to mitigate bird collisions with power lines: A meta-analysis and guidelines for field studies

Joana Bernardino, Ricardo C. Martins, Regina Bispo and Francisco Moreira

3. Re-assessing the effectiveness of wire-marking to mitigate bird collisions with power lines: A meta-analysis and guidelines for field studies

Abstract

The expansion of overhead power lines worldwide challenges companies of energy transmission and distribution, regulators and environmental consultants, among other stakeholders, to effectively mitigate their negative impacts on wildlife. Wire-marking is currently the most widespread and recommended measure to reduce bird collisions with these infrastructures. Nevertheless, and despite its importance for a bird-friendly development of energy projects, there is still much uncertainty about what explains wire-marking effectiveness.

We performed an extensive literature review and meta-analysis to evaluate the overall effectiveness of wire-marking in reducing bird collisions with power lines, including the possible influencing factors of power line voltage, habitat and type of device. We gathered data from 35 field studies across the world (which included 66 trials) assessing the effectiveness of wire-marking based on regular carcass searches beneath power lines.

Overall, wire-marking reduced bird collisions with power lines by half (50.4%; 95% Confidence Interval Estimate: 40.4 – 58.8%), although this estimate of effectiveness is lower than the one reported in a meta-analysis performed in 2011. Despite the effort to include both peer-reviewed and grey literature studies in the present meta-analysis, the risk of publication bias could not be entirely excluded and may be still overestimating the true overall effect of wire-marking. High heterogeneity among the study outcomes hindered the power to detect clear moderating effects, with none of explanatory variables being statistically significant. Large between-study heterogeneity is (to some extent) explained by the variety of anti-collision devices available, wire-marking intensities used and ecological circumstances in which the experiments were carried out. Nonetheless, it may be also related to within-study methodological biases and reporting gaps in the existing field studies.

Robust experimental designs (ideally using *Before-After-Control-Impact* approaches), comprehensive reporting of results and broad dissemination of study findings are needed to increase the statistical power of future meta-analyses. Ways to achieve these improvements in field studies are presented in detail. Their inclusion in future meta-analyses will increase the knowledge on the drivers of wire-marking effectiveness, which is critical to better inform decision-making processes and environmental management plans.

Keywords

Energy, linear infrastructure, bird mortality, environmental impact assessment, mitigation, bird flight diverter.

3.1. Introduction

Global demand for energy and the need to accomplish climate targets in the next decades will promote a rapid deployment of renewable energy generation and decarbonisation of the electricity grid (IRENA 2017). The energy sector will continue, nevertheless, to rely on extensive networks of power lines to ensure the supply of electricity worldwide, despite their negative impacts on natural ecosystems (Biasotto and Kindel 2018; D'Amico *et al.* 2018).

Bird mortality due to collisions with overhead wires has long been recognized as one of the most important negative impacts associated to both transmission and distribution lines (Bernardino *et al.* 2018). The most susceptible species to collision, in terms of expected population-level impacts, seem to be "poor fliers" (due to their heavy body and/or low manoeuvrability), often habitat specialists with hazardous behavioural traits (especially flight height and flocking flight) and/or species with unfavourable conservation status (Jenkins *et al.* 2010; Bernardino *et al*. 2018; D'Amico *et al.* 2019). To address this problem, a wide variety of mitigation measures have been proposed and implemented over the last 30 years, such as underground cabling, optimization of power line routing and configuration, and/or wire-marking (Bernardino *et al.* 2018). The latter is currently the most widespread and recommended measure to reduce bird collisions with power lines (e.g., APLIC 2012; SNH 2016), mostly because it can be applied with minimal costs and engineering (compared to other mitigation strategies). Wire-marking consists in the attachment of different types of devices (e.g., spirals, plates, crossed bands, stripes or spheres) to the conductors and/or earth-wires, in an attempt to increase their visibility and divert birds from these obstacles.

Several field studies have been conducted to assess the effectiveness of this measure, although few have been published in peer-reviewed journals (e.g., Alonso *et al.* 1994; Barrientos *et al.* 2012; Sporer *et al.* 2013). In many occasions, results are only reported in grey literature documents (e.g., thesis and dissertations, book chapters, EIA monitoring reports, government/NGO publications), which are often scattered and difficult to access. Furthermore, estimates of wire-marking effectiveness are mainly done by comparing spatial and/or temporal variations in bird mortality rates (by collision with power lines), using three types of experimental design: *Control-Impact* (CI), *Before-After* (BA) and *Before-After-Control-Impact* (BACI). The validity of these approaches to measure mitigation effectiveness is based, however, on assumptions (like environmental similarity between *treatment* and *control* groups) which, if not fulfilled, affect the reliability of the conclusions (Christie *et al.* 2019).

Regardless of these constrains, the synthesis of evidence from existing studies is crucial to inform the decision-making process and future management actions by regulators, project developers, environmental consultants and other stakeholders. The first attempt to quantitatively summarize the effectiveness of wire-marking was done by Barrientos *et al.* (2011). Their meta-analysis showed that wire-marking had an overall positive effect in reducing bird collision rates by 55 – 94%. However, differences among types of anti-collision devices, power-line features and site-specific factors (apart from the number of species) were not tested. Since then, several more field studies have been conducted (or made publicly available) on this topic and, although evidence suggests that this mitigation measure works, there is still much uncertainty about what explains the large observed variability in wire-marking effectiveness.

Over the years, a wide range of devices and wire-marking intensities (i.e., combination of spacing between devices, number and position of wires marked, and portion of the power line span marked) have been implemented in power lines worldwide. Devices can be static (e.g., spirals) or, on the other hand, have dynamic features (e.g., rotating suspended plates), the latter being developed based on the general concept that devices with moving parts are more likely to draw birds' attention (Martin 2010, 2011; Martin and Shaw 2010). The shape, size and colour of the devices available on the market also varies a lot, with some devices also incorporating some type of luminescence (e.g. reflective or glow in the dark properties) (Bernardino *et al.* 2018). All these device characteristics are expected to influence the way birds perceive the power line and to have a moderating effect on wire-marking effectiveness (e.g., Anderson 2002; Murphy *et al.* 2016a). Moreover, the effectiveness of each type of device is likely to be affected by the regional particularities of habitats and bird communities bisected by the power line, and its features (e.g., wires arrangement and height). Therefore, scientific evidence on what type of device should be implemented depending on the project characteristics and location, is particularly relevant for both electricity transmission and distribution operators.

Here, we carry out an updated meta-analysis of studies assessing the effectiveness of wire-marking in reducing bird collisions with power lines, including a number of studies published (or made available) since Barrientos *et al.* (2011), and pooling a large amount of data from grey literature. Our main objectives are to: (1) estimate the overall effect of wire-marking on the rate of bird collisions and evaluate the impact of including grey literature in the estimated effectiveness; (2) assess the moderating effect of site- and project-specific factors, namely habitat, power line voltage and type of device, on wire-marking effectiveness; and (3) identify the limitations of existing field studies and provide guidelines for future monitoring programmes of wire-marking effectiveness.

3.2. Methods

3.2.1. Literature review and inclusion criteria

Studies were first searched by examining the reference lists of three key systematic reviews on bird collision with power lines and its mitigation: Jenkins *et al.* (2010), Barrientos *et al.* (2011) and Bernardino *et al.* (2018) (see PRISMA flow diagram in Supplementary material Figure S 3.1). Full-text of potentially relevant articles, including grey literature (e.g., books, technical reports, dissertations and conference proceedings), were retrieved after screening of title and abstract. This initial list was then expanded through the screening of citations included in this first set of articles and so forth, until no new relevant articles were discovered. In addition, we conducted targeted searches (in Google Scholar and Web of Science search engines) of articles published after the systematic searching done by Bernardino *et al.* (2018), using the keywords “bird collision”, “power line” and/or “wire-marking”. No language or date restrictions were imposed to the search strategy. Articles unavailable online were obtained through contact of organizations and experts on the subject.

The preliminary literature search resulted in 58 full-text articles (hereafter called studies) of which 35 were considered eligible for the meta-analysis (see Supplementary material Table S 3.1). Only studies that assessed wire-marking effect based on measured rates of bird mortality by collision (e.g., not based just on flight behaviour characterization) were included in the analyses. Exclusion criteria were: 1) studies testing the effect of aviation balls or a mix of different types of devices (attached to a same wire); and 2) studies that did not report mean (or raw) counts of bird mortality and associated sample sizes, since these are necessary for calculating the weighted effect size (see below, 3.2.2 Effect size calculations and adjustments).

Whenever studies included results from multiple experiments (e.g., comparison of the effect of different types of wire-markers in separate sections of a power line, and/or testing of a same wire-marker in power lines located in different habitats), these were considered separate trials. Conversely, for studies reporting the effects of a same experiment for the entire bird community and/or separately for target species, we only included the results for the entire bird community (or consolidated the data from the different species/groups into a single trial), because data reported for target species are usually based on extremely low numbers of observed mortalities.

The final database comprised a total of 66 trials conducted in several countries (see Supplementary material Table S 3.2), although the majority of the trials was from Europe (n=45, 68.2%), followed by North America (n=11, 16.7%), Africa (n=8, 12.1%) and, finally, South America (n=2, 3.0%). Depending of the trial, one of following experimental designs was used: *Control-Impact* (CI; 39.4%), *Before-After* (BA; 33.3%), and *Before-After-Control-Impact* (BACI; 27.3%). CI trials provided a comparison of bird mortality between "impact" sites (i.e., power line sections with wire-markers) and "control" sites (i.e., without wire-markers). BA trials compared the same sections of a power line "before" and "after" the installation of wire-markers. In BACI trials, sampling is conducted at "impact" and "control" sites in simultaneous time periods, namely "before" and "after" implementation of the *treatment* (i.e., installation of wire-markers). CI or BA approaches rely on the assumption (often not verified) that environmental factors affecting the mortality estimates do not significantly differ between "impact" and "control" sites, or between "before" and "after" periods, respectively. In BACI approach eventual differences between "impact" and "control" sites (not related with wire-marking effect) are accepted, as long as they remain the same between the "before" and "after" periods.

3.2.2. Effect size calculations and adjustments

The log response ratio ($\ln \mathrm{R}$), which is one of the metrics most commonly used in ecological meta-analyses (Nakagawa and Santos 2012), was used to estimate the effect size (Hedges *et al.* 1999) and defined as:

$$ln\ R = ln\left(\frac{\bar{X}_T}{\bar{X}_C}\right) \quad (1)$$

where $\bar{X}_T$ and $\bar{X}_C$ are, respectively, the means of the response variable (bird mortality rate, expressed as number of bird carcasses/Km/search) for the *treatment* and *control* groups; i.e., in wire-marked and control sites (CI design), or before and after the installation of the wire-markers (BA design).

Our meta-analysis was inverse-variance weighted, meaning that variance was taken into account when calculating effect sizes for each trial (Hedges *et al.* 1999). We calculated the variance of $\ln R$ as:

$$var(\ln R) = \frac{{s_T}^2}{n_T\ {\bar{X}_T}^2} + \frac{{s_C}^2}{n_C\ {\bar{X}_C}^2} \tag{2}$$

where $\bar{X}_T$ and $\bar{X}_C$ are the means of the response variable on *treatment* and *control* groups, respectively; ${s_i}^2$ $(i = T, C)$ is their sampling variance; and n_i $(i = T, C)$ is the sample size of each site.

Estimates of sampling variance (either for *treatment* or *control* groups) were often not reported in the studies. However, raw mortality rates are counts per time/area unit (e.g., number of death birds/Km/year). Therefore, this variable was assumed to be Poisson distributed, which means that its variance equals the mean (Koricheva *et al.* 2013). Hence, the variance of the response variable on *treatment* and *control* groups (${s_T}^2$ and ${s_c}^2$) was always estimated by the observed mean of bird mortality ($\bar{X}_T$ and $\bar{X}_c$, respectively), even on the few occasions that it was originally reported.

Thus, to estimate $\ln R$, and the corresponding variance for each trial, we extracted mean bird mortality rates and the corresponding sample size of wire-marked and control sites, and/or before and after the installation of the wire-markers. Few studies (15%) provided bird mortality estimates properly adjusted by the potential biases (e.g., scavenger removal, searcher efficiency), thus calculations of mean mortality rates were mainly based on raw data from carcass searches. Sample size was defined as the accumulated number of Kms surveyed in each site (i.e., the number of carcass searches times the number of Kms surveyed in each search).

Studies with BACI design are expected to achieve more robust results (compared to BA or CI designs; Christie *et al.* 2019), as it allows to account for differences between *treatment* and *control* groups not related to wire-marking. In such cases, $\ln R$ was calculated as if it was a BA study (see Equation 1), but the mean mortality rates registered "before" and "after" wire-marking ($\bar{X}_C$ and $\bar{X}_T$, respectively) were first adjusted by the mortality rates registered in control sites (in the same corresponding periods). Whenever studies used BA or CI designs but data on bird flight crossing rates were also available for the same sites or periods, the ratio of crossing rates registered in *treatment* and *control* groups was used to previously adjust the mean mortality rate registered in the *control* group ($\bar{X}_C$).

3.2.3. Extraction of moderators

Information on wire-marking intensities, study area and power line features was not always provided in detail by the primary studies. To maximize the use of available data, we narrowed down the moderators to three variables: i) Voltage (<110 kV and ≥110 kV); ii) Habitat (Grasslands, Wetlands, Shrublands and Forest-farmland mosaics); and iii) Type of device (Small spirals, Large spirals and Flappers).

Power line voltage is a binary moderator that aims to embody a set of voltage-related features, such as the pylon height, thickness of conductors, presence/absence of earth wires, distances between different conductors and between conductors and earth wires, and placement of wire-marking devices (see Supplementary material Table S 3.3). We considered two voltage levels, below and above 110 kV, which can be generally considered distribution and transmission power lines, respectively, although the voltage threshold between these categories is variable across countries (CIGRE 2018).

Habitat is a four-level moderator with categories defined based on the main characteristics of the landscapes bisected by the power lines: (1) Grasslands - open and rather flat areas with cereal farmlands and/or extensively grazed grasslands; (2) Wetlands - areas permanently or temporally flooded, such as lakes, rivers and estuaries, marshes and coastal lagoons; (3) Shrublands – semi-arid areas dominated by grassy, low-shrub vegetation; and (4) Forest-farmland mosaics – Native forests and/or tree plantations, interspersed with agricultural areas (often with trees) and/or occasional shrubs.

Wire-markers were categorized in three main types, depending mainly on their size and static/dynamic features: (1) Small spirals – static devices with spiral shape, single-side attachment (to the wires) and small dimensions (20-35 cm long, 6-18 cm in diameter) - also called “pigtails”; (2) Large spirals – static devices with spiral shape, double-side attachment (to the wires) and large dimensions (60-100 cm long, 20-35 cm in diameter) - also called “swan flight diverters”; and (3) Flappers – devices with moving parts (due to wind action), including clamps with rotating planes or discs (e.g., Firefly) and devices with relatively limited dynamics (e.g., crossed bands, RIBE’s and other stripes, as well as clamps with suspended non-rotating plates or discs).

3.2.4. Statistical analysis

The analysis was carried out in R statistical computing language (R Core Team 2018), using the $metaphor$ package (Viechtbauer 2010). To quantify heterogeneity among effect sizes, we fitted three-level random-effects models using the restricted (or residual) maximum likelihood (REML) estimation approach (Nakagawa and Santos 2012; Koricheva *et al.* 2013). All fitted models contained the effect size ($\ln R$) as the response variable weighted by its inverse-variance (Borenstein *et al.* 2009), and "trial ID" and "study ID" as random factors (Assink and Wibbelink 2016). Random effects were included at trial-level to account for the potential effect of unreported covariates (that may have contributed to differences in effect sizes); and at a study-level to account for non-independency between values extracted from the same study (Nakagawa *et al.* 2017).

Using the multi-level models described above, we started by fitting a random-effects model to the complete dataset (n=66). Normality assumption and outlier detection were assessed through graphical residual analysis (Viechtbauer and Cheung 2010). Five cases (7.5%) were defined as outliers and excluded from the dataset (n=61, see Supplementary material Table S 3.2), as these extreme values are likely explained by study limitations and may have a disproportionate influence on the analysis. The random-effects model was then refitted to estimate the overall weighted-mean effect size of wire-marking, accompanied by its 95% Confidence Interval Estimates (CIE). Heterogeneity was assessed by inspection of forest plots and Cochran's Q statistics (Nakagawa and Santos 2012). Total heterogeneity was then partitioned into the proportion of variance explained by the random factors in the model (between- and within-study heterogeneity), and residual error variance (within-trial heterogeneity). Potential publication bias was assessed in three different ways: (1) visual examination of the funnel plot of raw effect sizes ($\ln R$) against its inverse variance (as a proxy for sampling effort) (Sterne and Egger 2001); (2) performance of Egger's regression test applied to model residuals, accompanied with their original variance (Egger *et al.* 1997; Nakagawa and Santos 2012); and (3) comparison of weighted average effect sizes estimated solely based on peer-reviewed studies, versus grey literature.

Next, we investigated if heterogeneity between trials could be partially explained by the compiled moderators. We started by fitting three separate univariate mixed-effects models to the subset of trials with complete information for each candidate moderator: voltage (n=58), habitat (n=52) and type of device (n=58). The significance of fixed effects was determined using Wald-type statistics with asymptotic chi-square distribution (Koricheva *et al.* 2013). Then, we conducted a multivariate model selection analysis based on the subset of trials with complete information for all moderators (n=47). We used $glmulti$ R package (Calcagno and de Mazancourt 2010) to automatically fit all possible model combinations involving the three moderators, compare all candidate models and rank them based on their corrected Akaike's Information Criterion (AICc) value. The significance of each moderators in equally–plausible models (i.e., models with value differing less than two units from the higher–ranked model) was tested using a likelihood ratio test, and moderators were dropped from the final model when not significant. Fixed and random effects were estimated through maximum likelihood, to allow a meaningful comparison between models (Koricheva *et al.* 2013).

Finally, a sensitivity analysis was conducted to assess the robustness of the meta-analytic findings, which included the repetition of the primary analysis with altered datasets (Bown and Sutton 2010), namely: (1) “Calibrated” - exclusion of trials perceived to be of lower quality (i.e., using BA or CI designs); (2) “Sample size ≥30 “ - exclusion of trials with low sample size (i.e., No. of Accumulated Kms <30, either for *treatment* or *control* groups); (3) “With outliers” - inclusion of trials identified as outliers; and (4) “Without influential cases” - exclusion of influential cases identified through Cook’s distance statistics (Cook and Weisberg 1982; Viechtbauer and Cheung 2010). See sub-section 3.8.5 (Supplementary material) for more details about the rationale behind and methods used in the creation of the altered datasets.

Whenever appropriate, estimated effect sizes ($\ln \mathrm{R}$) and associated 95% CIE were transformed into percent reduction in bird collision rate (that is, $[(1 - e^{\ln \mathrm{R}}) \times 100]$), for easier interpretation of results.

3.3. Results

3.3.1. Overall size effect and publication bias

Overall, wire-marking had a significant (positive) effect on reducing bird collisions with power lines (Figure 3.1). The overall estimated log response ratio ($\ln R$) was -0.70 (95% CIE: -0.89, -0.52), corresponding to an overall wire-marking effectiveness of 50.4% (95% CIE: 40.4 – 58.8%) in reducing bird collision rates with power lines. There was, however, significant amount of (residual) heterogeneity with respect to effect sizes (Q = 480.5, df = 60, p < 0.001; see Supplementary material Table S 3.4). Most of the heterogeneity was explained by variance within- ($I^2_{(level\ 2)}$ = 49.6%) or between-studies ($I^2_{(level\ 3)}$ = 41.3%), rather than within trials ($I^2_{(level\ 1)}$ = 9.1%). The mean effect sizes of the 61 trials included in the meta-analysis ranged between -2.36 and 0.72, which means that the reduction in bird collision rates varied between 90.5% and -104.8% (Figure 3.1).

Sensitivity analyses were performed, and the results remained similar after (1) removing studies with lower samples sizes (i.e., number of accumulated Kms <30, either for *treatment* or *control* groups) and/or weaker experimental designs (namely, CI or BA designs), (2) excluding influential cases, and (3) re-including outliers (see Supplementary material Table S 3.6). The corresponding overall estimated $\ln R$ ranged between -0.64 and -0.81, which corresponds to a reduction in bird collision rates ranging between 47.0 and 55.4%.

There was no evidence of publication bias in the meta-analysis (Egger's regression test result: z = -0.50; p = 0.61), which is consistent with the apparent symmetry of the funnel plot (Figure 3.2). However, if only peer-reviewed studies had been included in the meta-analysis (n=12), the overall estimated reduction in bird collision rate would be of 56.4% (95% CIE: 29.3 – 73.2%), which corresponds to an increased estimate of wire marking effectiveness compared to the one estimated solely based on grey literature (48.7%; 95% CIE: 37.7 – 57.2%) (Figure 3.2).

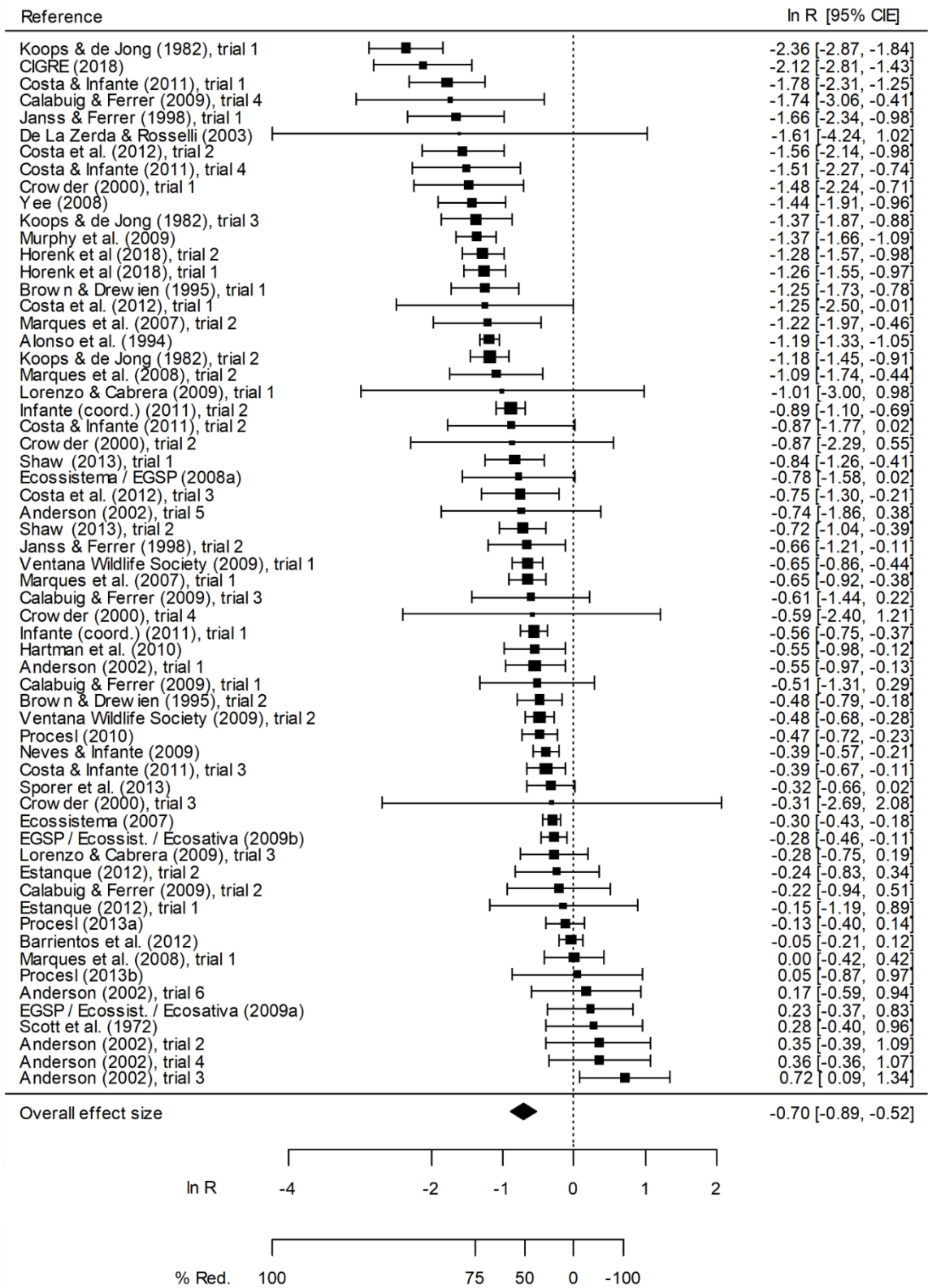


Figure 3.1 - Forest plot of effect sizes and 95% Confidence Interval Estimates (CIE) of each individual trial (n = 61).

The “diamond” on last row shows the overall mean effect size (central tips of diamond) and associated 95% CIE (lateral tips of diamond) estimated based on the random effect model. Primary and secondary x-axis represent the log response ratio (ln R) and percent reduction in bird collision rates (% Red.), respectively. Negative values of ln R indicate that wire-marking had a positive effect in reducing bird collisions with power lines, positive values indicate the opposite (increased collision rates). ln R = 0 means no effect.

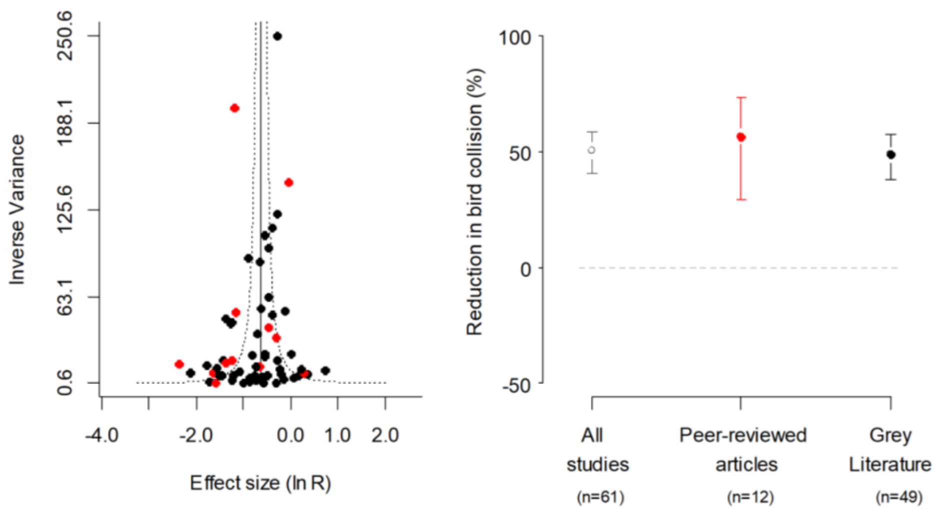


Figure 3.2 - Funnel plot of effect sizes ($\ln R$) of each individual trial from the complete dataset (on the left) and overall percent reduction in bird collision rates (± 95% Confidence Interval Estimates), estimated based on trials retrieved from peer-reviewed articles, grey literature studies or all types of studies (on the right). Red and black dots indicate, respectively, the effect sizes retrieved from peer-reviewed articles and grey literature.

3.3.2. Moderators of wire-marking effectiveness

Univariate analyses revealed that none of the moderators had a significant effect on wire-marking effectiveness (Voltage: $Q_{M\,(df=1)}$ =0.2, p=0.63; Habitat: $Q_{M\,(df=3)}$ =3.6, p=0.31; and Type of device: $Q_{M\,(df=2)}$ =2.2, p=0.32; see Supplementary material Table S 3.4). These findings were corroborated by the multivariate analysis, with two models fitting the sub-dataset equally well (Null model: AICc=91.1, Akaike weight=0.38; *versus* Model with Habitat as single-moderator: AICc=91.6, Akaike weight=0.29) (see Supplementary material Table S 3.5). The likelihood ratio test showed no significant differences between both models (p=0.06), so the null model was selected. The test for residual heterogeneity (Q_E) was significant for all mixed-effects models (see Supplementary material Table S 3.4), indicating that variability among the effect sizes might be explained by (unaccounted) moderators. Once again, all meta-analytic findings were generally consistent with the ones achieved in the sensitivity analyses (see Supplementary material Table S 3.7).

Despite its non-significance as a moderator, all types of devices significantly decreased bird collisions with power lines, with a tendency for flappers to be more effective than spirals (either small or large) (Figure 3.3). Wire-marking also appears to be slightly more effective in wetlands, compared to the other habitat categories, and in distribution lines (<110kV), compared to transmission lines (≥110kV) (Figure 3.3).

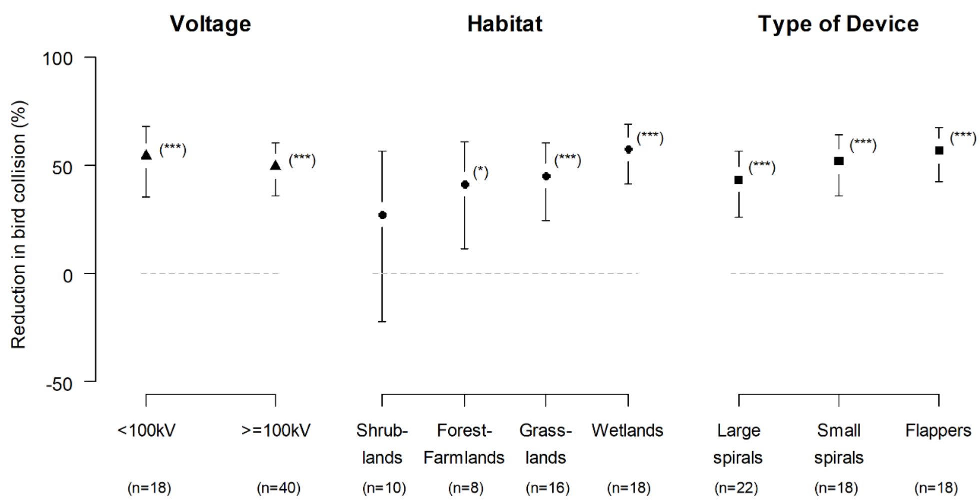


Figure 3.3 - Effectiveness of wire-marking in reducing bird collision rates (mean percent reduction ± 95% Confidence Interval Estimates) depending on power line voltage, habitat and type of device, estimated by the univariate mixed-effects models. Significance levels (* indicates p<0.05, and *** p<0.001) near the effect size symbols denote a significant difference from zero (no effect).

3.4. Discussion

3.4.1. Overall size effect and publication bias

The results of our meta-analysis corroborate the general perception that wire-marking is effective in reducing bird collisions with power lines (e.g., Jenkins *et al.* 2010; APLIC 2012; Williams *et al.* 2018). The estimate of the overall mean effect size shows that the number of bird collisions was reduced almost by half (50.4%; 95% CIE: 40.4 – 58.8%) in marked power lines, after diverter installation and/or compared to controls. Although this is a substantial reduction, the effectiveness estimate is considerably lower than the one estimated by Barrientos *et al.* (2011) (78%; 95% CIE: 55 – 94%), who performed the first meta-analysis on the topic. The difference in the results is probably explained by: (1) the additional number of studies and, consequently, number of trials included in the present study; and (2) the latest methodological advances in biological meta-analysis, such as accounting for non-independency between experiments from a same study (Nakagawa and Santos 2012; Nakagawa *et al.* 2017).

We found no evidence of clear publication bias within our systematic review, which is probably explained by the high number of trials retrieved from grey literature (76%), compared to trials published in peer-reviewed journals (24%). Still, we cannot exclude the possibility of such bias. First, the estimated wire-marking effectiveness was lower in grey literature studies, compared to the one estimated in peer-reviewed studies. Second, many studies are carried out internally by energy companies or under the scope of EIA processes, and only reported in grey literature that is difficult to access. And, third, energy companies tend to be less supportive of publishing studies with negative results (i.e., showing that the mitigation measure was not effective and/or highlighting the study limitations). This suggests that the true wire-marking effectiveness may probably be lower than the one estimated in this study.

Concerns about the quality of grey literature are often raised, usually due to limitations on study design and relatively low sample sizes (Lajeunesse 2013). This was not the case for several grey literature studies compiled in the present meta-analysis (e.g., Marques *et al.* 2007; Calabuig and Ferrer 2009). Nonetheless, low statistical power of individual studies was fairly addressed in the weighted meta-analysis conducted, as studies with a large sampling error contributed less to the estimates of overall effect (using the inverse variance of each effect size as a weight) (Lajeunesse 2013). Conversely, well-conducted studies with tight control of measurement variation and/or larger sample sizes contributed more to estimates of effect size, independently of where they were published.

3.4.2. Moderators of wire-marking effectiveness

To the best of our knowledge, no previous study has conducted a meta-analysis to quantify the moderating effect of project- and site-specific factors on wire-marking effectiveness. None of the moderators (type of device, habitat or power line voltage) was found significant in our meta-analytic models. The lack of a statistically evidence towards a significant result does not necessarily mean that these three moderators have no influence on wire-making effectiveness, being most likely a consequence of the high heterogeneity (i.e. variation of effect size estimates) among the pooled studies, as the power to detect moderator effects in meta-analyses is largely determined by the degree of (residual) heterogeneity present in the dataset (Hempel *et al.* 2013). This large variability might be explained by within-study methodological biases (see next section, 4.3 Study limitations), but also by confounding variables that could not be examined independently. For instance, a limited number of studies provided comprehensive information about: (1) the wires arrangement and, consequently, the number of collision levels for birds; (2) which wires were marked; and/or (3) what was the spacing between markers. Thus, neither power line configuration nor wire-marking intensity could be examined as separate moderators of wire-marking effectiveness.

We found a weak evidence that devices with moving parts (here called “Flappers”) may be more effective than static devices (like spirals), as hypothesised by Martin (2010, 2011) and Martin & Shaw (2010). According to these authors, frontal/binocular vision in birds is primarily concerned with near tasks (e.g., control of bill in foraging; chick provisioning; nest building) and more tuned for the detection of movement (rather than spatial detail); thus, devices with moving parts are more likely to draw birds’ attention. There were, however, device characteristics which could not be evaluated in the present meta-analysis, due to the lack of detailed information in the studies and/or small number of trials available for each factor level. These include colour (e.g. all white, grey, red, or mix of colours), luminescence (e.g., reflective or glow-in-the-dark properties) and type of flapper (e.g., Fireflies, suspended discs, crossed bands), expected to influence the way birds perceive the power line during daylight, but also at night or in low visibility conditions (e.g., during migration periods) (Murphy *et al.* 2016a).

3.4.3. Study limitations

The limitations of our review and meta-analysis are partially related to reporting gaps in the existing studies and the variety of anti-collision devices and installation intensities tested so far. First, summary statistics (e.g., means and associated variances) and/or sample sizes were often difficult to extract from studies and, in some few occasions, not reported at all, which led to the exclusion of the studies from the weighted meta-analysis. Second, as mentioned above, candidate explanatory variables were also often poorly reported, which limited the number of moderators included in the analysis and our ability to assess (or control) the effect of potential confounding factors, such as power line configuration and wire-marking intensity. Lastly, the variety of devices developed and tested in the studies and, consequently, the limited number of trials available for each type, forced a simplification of the moderator levels of the Type of device. For instance, the group named "Flappers" includes a wide variety of devices, whose particularities (e.g., shape, size, colour and luminescent properties) can affect the way birds perceived them. We had, however, to gather them in a single category, to guarantee that a minimum number of trials was available per moderator level.

The variety of wire-marking devices available, wire-marking intensities used and ecological circumstances in which the experiments were carried out, necessarily inflates the heterogeneity present in the dataset and limits the moderator analyses (Hempel *et al.* 2013). Nonetheless, there are other sources of between-study heterogeneity that are not related to true diversity among study outcomes, but to within-study methodological biases (Higgins *et al.* 2009). In our meta-analysis, the presence of such biases is evidenced by the existence of study trials in which the number of bird collisions with wire-marked power lines increased, compared to controls ($\ln R > 0$; Figure 3.1). We cannot discard the possibility that self-illuminated markers (e.g., with LEDs) or those that glow in the dark (with luminescent properties) may attract birds to the power line, but so far there is no published evidence that it might occur. Moreover, in our meta-analysis, none of the trials that obtained negative results was testing the effectiveness of luminescent (or illuminated) devices. This result is, therefore, potentially explained by within-study limitations, namely:

- **Stochastic nature of bird collision with power lines and biases in carcass detection** – With some exceptions (e.g., Murphy *et al.* 2016b), the occurrence of a bird collision with an infrastructure followed by its detection (by observers) is, generally, regarded as a stochastic event (Korner-Nievergelt *et al.* 2011, 2013). Bird collisions may be highly concentrated in time and/or space, e.g., due to habitat features, intensive migration episodes and adverse weather conditions or other stochastic events (Bernardino *et al.* 2018). Moreover, no or few carcasses may be found either because few animals were actually killed, or because they were missed in the carcass detection process due to crippling bias, limited survey coverage, carcass removal (by scavengers or decay), and searcher efficiency (Bernardino *et al.* 2013; Korner-Nievergelt *et al.* 2015), which increases the uncertainty in the mortality estimates both for wire-marked sections and controls.
- **Study design characteristics** – BACI designs encompass considerably less risks of violating the underlying assumptions than CI or BA designs, thus have higher power to

detect true treatment effects, in particular if paired control-impact designs are adopted (i.e., with spatial alternation between wire-marked and control sections) (e.g., Yee 2008). In practice, their implementation is often limited by the fact that mitigation measures are, for precautionary reasons, usually applied (1) during the project construction phase (e.g., SNH 2016; EC 2018), making it impossible to collect mortality data before the wire-marking treatment; and/or (2) in power line sections foreseen to be more sensitive for birds, which limits the selection of (true) control sections (e.g., SNH 2016; Rytwinski *et al.* 2016). Therefore, sub-optimal study designs, like CI trials or BACI trials without paired control-impact design, are often adopted. In our meta-analysis, 6 of the 7 study trials which estimated implausible negative effects on bird collision rates ($\ln R > 0$) were CI trials.

- **Limitations of methods used to correct observed mortality rates** – In sub-optimal study designs, observed mortality rates in wire-marked sections and controls should ideally be adjusted by the corresponding bird crossing rates and/or bias correction factors for imperfect carcass detection (e.g., due to carcass removal and searcher efficiency), to control for potential temporal-spatial differences in bird mortality rates - not related to wire-marking treatment. Unfortunately, bird surveys to determine flight crossing rates, as well as carcass removal and searcher efficiency trials also encompass several methodological limitations (Bernardino *et al.* 2013; Urquhart *et al.* 2015; Murphy *et al.* 2016b; Smallwood *et al.* 2018), which can inflate the biases associated with the adjusted mortality rates and, consequently, the estimated effect size, especially if those methods are implemented with low sampling effort.

3.5. Conclusions and guidelines for future field studies

Wire-marking is responsible for a significant reduction in bird collisions with power lines (on average, by 50%), although its positive effect seems to be lower than the one reported in the meta-analysis performed by Barrientos *et al.* (2011). The drivers of wire-marking effectiveness are still not clear due to the high variability in study outcomes, although we found a weak evidence that devices with moving parts (flappers) tend to be more effective. More studies are needed to confirm this result and further investigate the effectiveness of the different types of flappers (e.g., Fireflies, suspended discs, crossed bands), and how it may vary depending on target species, wire-marking intensity, etc. It is important to note that, flappers are particularly exposed to wind action and seem to lose their functionality faster than static devices (Dashnyam *et al.* 2016), which compromises their long-term effectiveness and entails additional costs with device replacement (Lobermeier *et al.* 2015). Studies evaluating the cost-effectiveness of the different types of devices available on the market (and/or currently being developed) are, therefore, also needed.

The statistical power of future meta-analyses depends mostly on the quality of data used to estimate effect sizes and variances in field studies (Lajeunesse 2013; Hempel *et al.* 2013). This can be achieved namely through (1) the conduction of more well-designed experiments; and (2) the control of potential confounders of effect size differences between studies. Therefore, we strongly recommend the adoption of BACI approaches with fine spatial-scale alternation between wire-marked and control sections ('paired samples' approach), to guarantee their similarity in terms of habitats, bird communities and carcass detection probability, among other confounding factors. The adoption of such experimental design allows the assessment of wire-marking effectiveness solely based on observed mortality rates, without the need for additional bias corrections (e.g., bird crossing rates, searcher efficiency, carcass persistence rates); which would also be beneficial and appropriate for the assessment of the effectiveness of alternative strategies to increase the visibility of the wires, like the use of lasers and U.V light (KIUC 2015; Dwyer *et al.* 2019). If only sub-optimal designs can be adopted (i.e., BA or CI design), the conduction of additional field experiments (namely carcass removal/detection trials, and surveys to determine bird-crossing rates and/or flight behaviour) is important, first, to account for variations in bird mortality arising from external factors not related to wire-marking (e.g., Savereno *et al.* 1996) and, second, to link mortality rates to bird behavioural responses, in terms of reaction distances and manoeuvres to avoid the power line (e.g., Dwyer *et al.* 2019). Improvements in the quality of field studies can also be achieved with increased sample sizes (per combination of moderators tested) and proper control of potential confounding variables, even if (for logistic/financial reasons) it implies a reduction in the number of different type of devices, wire-marking intensities, power line features, habitats, etc. tested in a single study. In other words, it is preferable to use the available resources to implement a focused experiment (e.g., focused on one habitat type and wire marking device) rather than using a multi-objective approach trying to address at the same time different habitats and types of devices, which will result in small samples sizes for each of the moderators.

The impact of each individual study can then be maximized through its inclusion in meta-analyses. For that, it is crucial a broad dissemination of the study findings, together with a comprehensive reporting of the methods and results, even if wire-marking had weak or no significant effect on reducing bird collisions (Gerstner *et al.* 2017). A greater sharing of study results is extremely important, not only because it minimizes the risk of publication bias in meta-analyses and increases their power to detect moderator effects, but also because it prevents redundancy among research studies.

All these recommendations and important caveats to bear in mind in their implementation are summarized in Table 3.1, as well as the underlying weaknesses of the existing field studies identified through the present systematic review. With this exercise, we sought to increase the quality of future studies and maximize their contribution for the overall knowledge about wire-marking effectiveness, by facilitating their inclusion in meta-analyses. Finally, we highlight the importance of transferring this new knowledge to energy companies, policy makers and other stakeholders, so that it can be incorporated into EIA practice and contribute to an effective mitigation of bird collisions with power lines.

Table 3.1 - Summary of the main limitations of field studies and recommendations to maximize their individual power and improve the overall knowledge on wire-marking effectiveness. BACI – Before-After-Control-Impact, BA - Before-After; CI - Control-Impact.

Topic	Main limitations in existing studies	Recommendations for future research
Experimental design	• Adoption of sub-optimal experimental designs (e.g., BA or CI), due to restrictions on the collection of mortality data prior to wire-markers installation and/or selection of (true) controls. • Increased biases in effect size estimates, due to limitations in the field methods used to determine the bias correction factors of bird mortality (e.g., bird crossing rates, removal and detection rates).	• Perform dedicated studies to assess wire-marking effectiveness, in order to enable the adoption of a BACI design. • Select a relatively fine spatial-scale alternation between marked (impact) and non-marked (control) sections (‘paired samples’ approach) to perform the mortality surveys. Each pair of control-impact sections should not be too far apart to ensure that their differences (in terms of habitat, bird communities, scavengers’ community, carcass detection, etc.) are neglectable. This allows the evaluation of wire-marking effect solely based on observed mortality rates, without the need for additional corrections. • If only sub-optimal designs can be adopted (i.e., BA or CI design), conduct additional field experiments (namely carcass removal/detection trials and surveys to determine bird-crossing rates) to account for variations in bird mortality arising from external factors not related to wire-marking.

Topic	Main limitations in existing studies	Recommendations for future research
		Ensure that robust sampling schemes are adopted in order to minimize the uncertainty associated with the estimation of those correction factors. • Ideally, carcass searches should be performed by the same observer(s).
Sampling effort	• Conduction of short-term studies, which fail to detect temporal changes (seasonal or inter-annual) in bird mortality rates. • Adoption of low-effort carcass search protocols (in terms of search frequency and length of power line surveyed), which can lead to biased bird mortality estimates due to the stochasticity nature of bird collision events and limitations in carcass detection.	• Guarantee that seasonal and between-year variations in bird mortality are properly surveyed, both in wire-marked and control sections. Each experiment should cover, at least, one year prior to wire-marking treatment plus 2-3 years post-treatment. • Ensure that, within the study seasons, the survey effort is appropriate for the study-site and/or target species, in terms of the expected number of bird collisions and/or carcass detection probability. Whenever these are expected to be low, the survey effort (carcass search frequency and extension of power line surveyed) should be increased in order to guarantee reliable conclusions.
Confounding variables	• Mix of potential ecological and/or project-related confounders (e.g., mix of different types of devices or habitats) in a same experiment. • Insufficient number of experiments per combination of moderators, which limits the statistical power of meta-analyses.	• Avoid the mix of wire-marking treatments (combinations of different devices and/or wire-making intensities) in a same experiment, to prevent confounding effects and increase the survey effort (per treatment sections and controls). • Test the effectiveness of a same wire-marking treatment (type of device and wire-marking intensity) in different ecological circumstances (e.g., habitat types, bird communities).
Reporting	• Unclear and/or selective reporting of study details and results, which hampers the calculation of effect size statistics and/or extraction of covariates (moderators) required for meta-analyses. • Reporting of effect size statistics only for trials which evidenced	• Describe clearly the experimental design, study temporal/spatial coverage and survey methods used. • Discriminate the survey effort (e.g. number of carcass searches and kms searched) for each treatment and control section, and/or before-after study periods.

Topic	Main limitations in existing studies	Recommendations for future research
	statistically significant effectiveness ('p-hacking'), despite the informative value of non-significant results.	• Provide complete information about study area (e.g., habitat, target bird species), power line features (voltage, dimensions, wire arrangement, etc.) and wire-making details (devices characteristics and wire-marking intensity). • Report all study outcomes, regardless of statistical significance and direction of the effect. • Present either raw bird mortality counts or summary effect size statistics, including mean mortality rates, associated variation measures and sample size. • Report summary effect size statistics separately for each treatment and control section, and for each study period (i.e., before and after treatment).
Dissemination and access to study findings	• Publication bias towards studies showing positive wire-marking effectiveness, or novel findings; • Limited access to studies conducted internally by the energy companies or under EIA processes (i.e. studies which were not conducted primarily with a scientific purpose).	• Promote study publication, ideally, in peer-review journals, even those with negative (or not significant) effects; • Ensure access and dissemination of study results, by making grey literature reports openly available online; • Carefully choose the title, abstract content and keywords, to maximize study retrieval in systematic literature searches (e.g., using Google Scholar).

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3.8. Supplementary material

3.8.1. PRISMA diagram

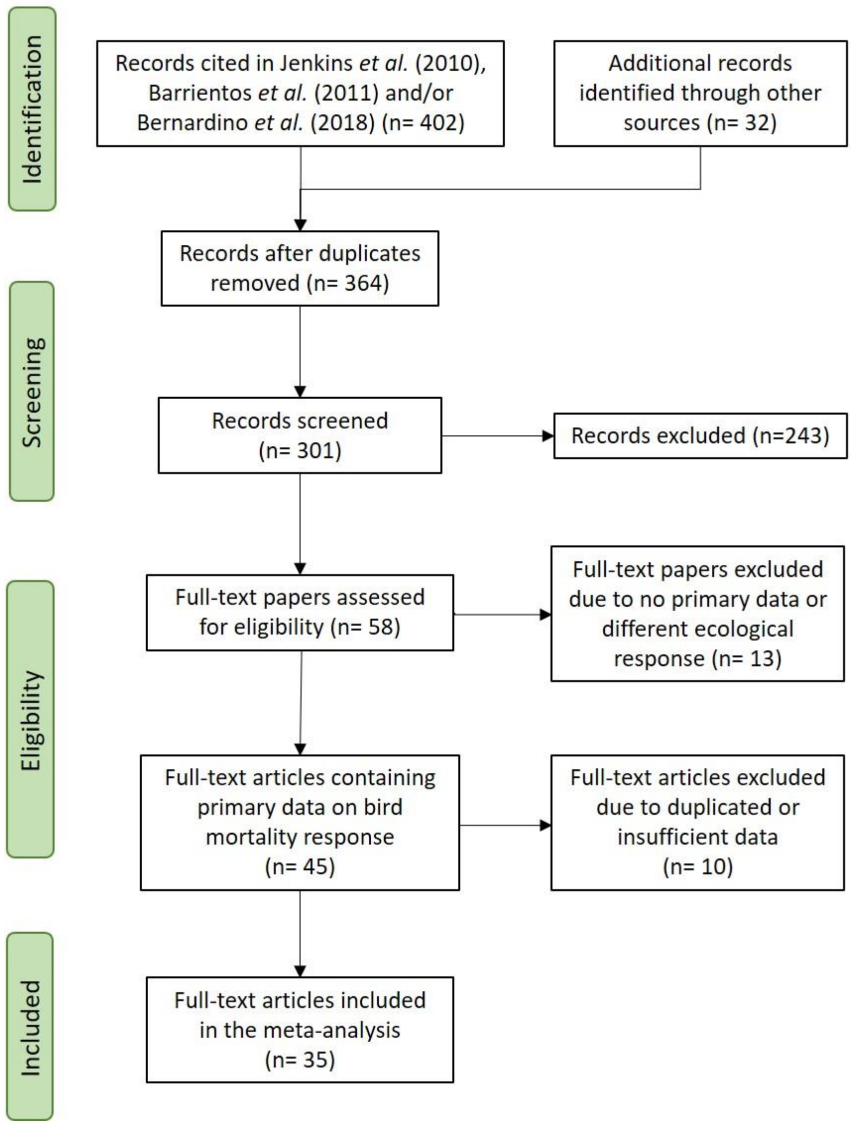

Figure S 3.1 - PRISMA flow diagram of literature search and selection process.

3.8.2. Articles assessed for eligibility and trials included in the meta-analysis

Table S 3.1 - Full-text articles assessed for eligibility (n= 58), compiled through the systematic literature search.

Type of publication: "paper" – research paper published in scientific journal; "book" – full book; "book chapter" – chapter of a book; "proceedings" – article published in Conference proceedings; "thesis" – thesis submitted to obtain a MSc or PhD degree; "report" – technical report or brochure (not peer-reviewed).

Country: country where the data was collected.

#	Reference	Title	Type of publication	Country	Included in the meta-analysis
1	Alonso *et al.* (1994)	Mitigation of bird collisions with transmission lines through groundwire marking	paper	Spain	X
2	Alonso & Alonso (1999)	Mitigation of bird collisions with transmission lines through groundwire marking	book chapter	Spain	
3	Anderson (2002)	The effectiveness of two different marking devices to reduce large terrestrial bird collisions with overhead electricity cables in the eastern Karoo, South Africa	report	South Africa	X
4	Barrett & Weseloh (2008)	Bird mortality near high voltage transmission lines in Burlington and Hamilton, Ontario, Canada	proceedings	Canada	
5	Barrientos *et al.* (2012)	Wire marking results in a small but significant reduction in avian mortality at power lines: a BACI designed study	paper	Spain	X
6	Biasotto *et al.* (2017)	Comportamento de voo de aves em resposta ao uso de sinalizadores em linhas de transmissão de energia elétrica	paper	Brazil	
7	Brauneis et al (2003)	Das Verhalten von Vögeln im Bereich eines ausgewählten Trassenabschnittes der 110 kV-Leitung Bernburg - Susigke (Bundesland Sachsen-Anhalt) - Flugreaktionen, Drahtanflüge, Brutvorkommen	paper	Germany	X
8	Brown & Drewien (1992)	Marking power lines to reduce avian collision mortality in the San Luis Valley, Colorado	proceedings	USA	
9	Brown & Drewien (1995)	Evaluation of two power line markers to reduce crane and waterfowl collision mortality	paper	USA	X
10	Calabuig & Ferrer (2009)	Análisis de la eficacia y la vida útil de la señalización anticolisión "salvapájaros" en líneas de transporte de energía eléctrica	report	Spain	X
11	CIGRE (2018a)	Case Study Belgium - Assessing the efficiency of curls	report	Belgium	
12	CIGRE (2018b)	Case Study Brazil - b) Case Serra da Mesa Transmissora de Energia S.A. – Transmission (Maio, 2010) – State of Goiás	report	Brazil	X
13	Costa & Infante (2011)	Monitorização e minimização dos impactes negativos resultantes da interacção da avifauna e as linhas eléctricas aéreas de alta e média tensão da EDP Distribuição - Protocolo Avifauna III	report	Portugal	X
14	Costa *et al.* (2012)	Protocolo Avifauna IV (2012) - Relatório das actividades desenvolvidas	report	Portugal	X
15	Crowder (2000)	Assessment of devices designed to lower the incidence of avian power lines strikes	thesis	USA	X
16	Dashnyam *et al.* (2016)	Malfunction Rates of Bird Flight Diverters on Powerlines in the Mongolian Gobi	paper	Mongolia	
17	De La Zerda & Rosselli (2002)	Mitigating collision of birds against transmission lines in wetland areas in Colombia by marking the ground	proceedings	Colombia	

#	Reference	Title	Type of publication	Country	Included in the meta-analysis
18	De La Zerda & Rosselli (2003)	Mitigation of collisions of birds with high-tension electric power lines by marking the ground wire	paper	Colombia	X
19	De La Zerda (2012)	Testing the effectiveness of a Colombian-designed bird flight diverter to mitigate collisions with transmission lines	proceedings	Colombia	
20	Ecossistema (2007)	Linhas de Alta Tensão Alqueva-Ferreira do Alentejo e Ferreira do Alentejo-Sines 2, a 400 kV – Monitorização de impactes na avifauna	report	Portugal	X
21	Ecossistema / EGSP (2008a)	Monitorização de Vertebrados Voadores na "Linha Batalha-Pego, a 400 kV" – 2º Relatório Anual	report	Portugal	X
22	Ecossistema / EGSP (2008b)	Monitorização de Vertebrados Voadores na "Linha Bodiosa-Paraimo, a 400 kV" – Relatório Anual	report	Portugal	
23	EGSP / Ecossistema / Ecosativa (2009a)	Monitorização de Vertebrados Voadores – Linha Sines-Portimão 3, a 400 kV – Relatório Final	report	Portugal	X
24	EGSP / Ecossistema / Ecosativa (2009b)	Monitorização de Vertebrados Voadores – Linha de Alta Tensão Tunes-Estói, a 150 kV – Relatório Final	report	Portugal	X
25	Estanque (2012)	Projeto LIFE Estepárias - Conservação da Abetarda, Sisão e Peneireiro-das-torres nas estepes cerealíferas do Baixo Alentejo (LIFE07/NAT/P/654), Relatório Final da Ação E4 – Monitorização do Projeto	report	Portugal	X
26	Ferrer, M. (2012)	Birds and power lines: from conflict to solution	book	Spain	
27	Frost (2008)	The use of 'flight diverters' reduces mute swan *Cygnus olor* collision with power lines at Abberton Reservoir, Essex, England	paper	UK	X
28	Hartman *et al.* (2010)	Are bird flaps effective wire markers in a hightension power line? – Field study of collision victims and flight movements at a marked 150 kV power line	report	Netherlands	X
29	Horenk et al (2018)	Effectiveness of markers for bird protection (bird flight diverter fittings) on an overhead powerline in the national park "Lower Oder Valley" – Minimisation of the risk of collision by markers for bird protection	proceedings	Germany	X
30	Infante (coord.) (2011)	Estudo de avaliação da eficácia de dispositivos anti colisão	report	Portugal	X
31	Janss & Ferrer (1998)	Rate of Bird Collision with Power Lines: Effects of Conductor-Marking and Static Wire-Marking	paper	Spain	X
32	Koops & de Jong (1982)	Vermindering van draadslachtoffers door markering van hoogspanningsleiden in de omgeving van Heerenveen	paper	Netherlands	X
33	Lobermeier *et al.* (2015)	Mitigating avian collision with power lines: a proof of concept for installation of line markers via unmanned aerial vehicle	paper	USA	
34	Lorenzo & Cabrera (2009)	Estudio de la mortalidad de aves por los tendidos eléctricos en los ambientes no esteparios de Lanzarote y Fuerteventura, y valoración de las medidas correctoras instaladas en Fuerteventura.	report	Spain	X
35	Luzenski *et al.* (2016)	Collision avoidance by migrating raptors encountering a new electric power transmission line	paper	USA	
36	Marques *et al.* (2007)	Monitorização dos Efeitos da Linha de Muito Alta Tensão Ferreira do Alentejo - Ourique sobre Espécies Prioritárias, Mortalidade e Taxas de Voo	report	Portugal	X
37	Marques *et al.* (2008)	Estudo de consolidação da avaliação da problemática das linhas eléctricas na conservação da Abetarda (Otis tarda) e Sisão (*Tetrax tetrax*) na ZPE de Castro Verde	report	Portugal	X
38	Masatomi (1991)	Population dynamics of Red-crowned Cranes in Hokkaido since the 1950s	proceedings	Japan	
39	McCann (2001)	Eskom/EWT partnership: the wattled crane marking project in South Africa	proceedings	South Africa	
40	Morkill & Anderson (1991)	Effectiveness of Marking Powerlines to Reduce Sandhill Crane Collisions	paper	USA	

#	Reference	Title	Type of publication	Country	Included in the meta-analysis
41	Murphy *et al.* (2009)	Effectiveness of avian collision averters in preventing migratory bird mortality from powerline strikes in the central Platte River, Nebraska	report	USA	X
42	Murphy *et al.* (2016a)	Crippling and Nocturnal Biases in a Study of Sandhill Crane (*Grus canadensis*) Collisions with a Transmission Line	paper	USA	
43	Murphy *et al.* (2016b)	Reactions of Sandhill Cranes Approaching a Marked Transmission Power Line	paper	USA	
44	Neves & Infante (2009)	Monitorização e minimização dos impactes das linhas eléctricas aéreas de alta e média tensão e a avifauna, Relatório técnico final – Protocolo Avifauna II	report	Portugal	X
45	Onrubia *et al.* (1996)	La eficacia de las señales de visualización sobre colisión y electrocución de aves en tendidos eléctricos de Madrigal de las Altas Torres (Ávila)	book chapter	Spain	
46	Procesl (2010)	Linha de Transporte de Energia Alqueva-Brovales, a 400 kV – Relatório Final de Monitorização e Medidas Compensatórias Dirigidas ao Grou e ao Sisão	report	Portugal	X
47	Procesl (2013a)	Monitorização de Avifauna e Quirópteros na Linha Macedo de Cavaleiros-Valpaços a 220 (400) kV – Relatório Anual, Primavera 2012 / Inverno 2012-2013	report	Portugal	X
48	Procesl (2013b)	Monitorização de Avifauna e Quirópteros no Ramal da Linha Lares-Lavos 1, a 400 kV, para a subestação de Paraimo – Relatório Anual, Outono 2012 / Verão 2013	report	Portugal	X
49	Raab *et al.* (2012)	Underground cabling and marking of power lines: conservation measures rapidly reduced mortality of West-Pannonian Great Bustards *Otis tarda*	paper	Austria	
50	Rasmussen (2001)	Problem resolutions for avian interactions at two NSP facilities	proceedings	USA	
51	Savereno *et al.* (1996)	Avian behavior and mortality at power lines in coastal South Carolina	paper	USA	
52	Scott *et al.* (1972)	Bird deaths from power lines at Dungeness	paper	UK	X
53	Shaw (2009)	The end of the line for South Africa's national bird? Modelling power line collision risk for the Blue Crane	thesis	South Africa	
54	Shaw (2013)	Power line collisions in the Karoo conserving Ludwig's bustard	thesis	South Africa	X
55	Sporer *et al.* (2013)	Marking power lines to reduce avian collisions near the Audubon National Wildlife Refuge, North Dakota	paper	USA	X
56	Sudman *et al.* (2000)	Das Anflugverhalten von überwinternden, arktischenWildgänsen im Bereich von markierten und unmarkierten Hochspannungsfreileitungen am Niederrhein	report	Germany	
57	Ventana Wildlife Society (2009)	Evaluating Diverter Effectiveness in Reducing Avian Collisions with Distribution Lines at San Luis National Wildlife Refuge Complex, Merced County, California	report	USA	X
58	Yee (2008)	Testing the effectiveness of an avian flight diverter for reducing avian collisions with distribution power lines in the Sacramento Valley, California	report	USA	X

Table S 3.2 - Characteristics of trials included in the primary meta-analysis ("primary" dataset) and following sensitivity analysis ("Calibrated", "Sample size ≥30", "With outliers" and "Without influential cases" datasets).

Candidate moderators: "Voltage" – voltage of the power line where the trial was conducted; Habitat – main features of the landscape present in the study area; Device – Type of wire-marker tested in the trial. Study design: BACI - Before-After-Control-Impact; BA - Before-After; CI - Control-Impact; BA or CI (adjust.) – studies with BA or CI design, which used bird flight crossing rates to control for differences on mortality rates (not related to wire-marking). Effect size: lnR - log response ratio; Var (ln R) – Variance of lnR. Datasets: "Primary" – dataset used in the primary analysis, after exclusion of trials identified as outliers; "Calibrated" - exclusion of trials perceived to be of lower quality (namely, using BA or CI designs); "Sample size ≥30" - exclusion of trials with low sample size (i.e., No. of Accumulated Kms <30, either for treatment or control sites); "With outliers" – re-inclusion of trials identified as outliers in the primary analysis; "Without influent. cases" - exclusion of influential cases identified through Cook's distance statistics (for more details see Supplementary material, section 3.8.5).

#	Reference	Country	Trial no.	Candidate moderators			Study design	Effect size		Datasets				
				Voltage	**Habitat**	**Device**		**ln R**	**Var (ln R)**	**Primary**	**Calibrated**	**Sample size ≥30**	**With outliers**	**Without influent. cases**
1	Alonso *et al.* (1994)	Spain	-	≥110kV	Grasslands	Large spirals	BACI	-1.19	0.01	X	X	X	X	X
2	Anderson (2002)	South Africa	1	≥110kV	Shrublands	Small spirals	BA	-0.55	0.05	X		X	X	X
3			2	≥110kV	Shrublands	Large spirals	CI	0.35	0.14	X		X	X	X
4			3	≥110kV	Shrublands	Small spirals	CI	0.72	0.10	X			X	X
5			4	≥110kV	Shrublands	Small spirals	CI	0.36	0.13	X			X	X
6			5	≥110kV	Shrublands	Flapper	CI	-0.74	0.33	X			X	X
7			6	≥110kV	Shrublands	Flapper	CI	0.17	0.15	X			X	X
8	Barrientos *et al.* (2012)	Spain	-	n.a.	Grasslands	n.a	BACI	-0.05	0.01	X	X	X	X	X
9	Brauneis *et al.* (2003)	Germany	-	≥110kV	Forest-Farmlands	Flapper	CI	-3.58	0.07				X	
10	Brown & Drewien (1995)	USA	1	n.a.	Wetlands	Small spirals	CI (adjust.)	-1.25	0.06	X	X	X	X	X
11			2	n.a.	Wetlands	Flapper	CI (adjust.)	-0.48	0.02	X	X	X	X	X
12	Calabuig & Ferrer (2009)	Spain	1	≥110kV	Grasslands	Large spirals	CI (adjust.)	-0.51	0.17	X	X	X	X	X
13			2	≥110kV	Grasslands	Large spirals	CI (adjust.)	-0.22	0.14	X	X	X	X	X
14			3	≥110kV	Grasslands	Large spirals	CI (adjust.)	-0.61	0.18	X	X	X	X	X
15			4	≥110kV	Grasslands	Flapper	CI (adjust.)	-1.74	0.46	X	X	X	X	X
16	CIGRE (2018b)	Brazil		≥110kV	Forest-Farmlands	n.a	CI	-2.12	0.12	X			X	
17	Costa & Infante (2011)	Portugal	1	<110kV	n.a.	Flapper	BA	-1.78	0.07	X			X	X

#	Reference	Country	Trial no.	Candidate moderators			Study design	Effect size		Datasets				
				Voltage	Habitat	Device		ln R	Var (ln R)	Primary	Calibrated	Sample size ≥30	With outliers	Without influent. cases
18			2	<110kV	n.a.	Large spirals	BA	-0.87	0.21	X			X	X
19			3	<110kV	n.a.	Small spirals	BA	-0.39	0.02	X		X	X	X
20			4	<110kV	n.a.	Flapper	BA	-1.51	0.15	X		X	X	X
21	Costa *et al.* (2012)	Portugal	1	<110kV	n.a.	Flapper	BA	-1.25	0.40	X			X	X
22			2	<110kV	n.a.	Flapper	BA	-1.56	0.09	X		X	X	X
23			3	<110kV	n.a.	Large spirals	BA	-0.75	0.08	X		X	X	X
24	Crowder (2000)	USA	1	≥110kV	Wetlands	Small spirals	BA (adjust.)	-1.48	0.15	X	X		X	X
25			2	≥110kV	Wetlands	Small spirals	BA (adjust.)	-0.87	0.53	X	X		X	X
26			3	≥110kV	Wetlands	Large spirals	BA (adjust.)	-0.31	1.48	X	X		X	X
27			4	≥110kV	Wetlands	Large spirals	BA (adjust.)	-0.59	0.85	X	X		X	X
28	De La Zerda & Rosselli (2003)	Colombia	-	≥110kV	Wetlands	Large spirals	BACI	-1.61	1.80	X	X		X	X
29	Ecossistema (2007)	Portugal	-	≥110kV	Forest-Farmlands	Small spirals	CI (adjust.)	-0.30	0.00	X	X	X	X	X
30	Ecossistema / EGSP (2008a)	Portugal	-	≥110kV	Forest-Farmlands	Large spirals	CI	-0.78	0.17	X		X	X	X
31	EGSP / Ecossist. / Ecosativa (2009a)	Portugal	-	≥110kV	Forest-Farmlands	Large spirals	CI (adjust.)	0.23	0.09	X	X	X	X	X
32	EGSP / Ecossist. / Ecosativa (2009b)	Portugal	-	≥110kV	Forest-Farmlands	Large spirals	BACI	-0.28	0.01	X	X	X	X	X
33	Estanque (2012)	Portugal	1	<110kV	Grasslands	Large spirals	BA	-0.15	0.28	X		X	X	X
34			2	<110kV	Grasslands	Flapper	BA	-0.24	0.09	X		X	X	X
35			3	<110kV	Grasslands	Flapper	BA	-3.04	0.49				X	
36	Frost (2008)	UK	-	≥110kV	Wetlands	Small spirals	BA (adjust.)	-3.17	0.85				X	
37	Hartman *et al.* (2010)	Nether-lands	-	≥110kV	Wetlands	Flapper	BACI	-0.55	0.05	X	X	X	X	X
38	Horenk et al (2018)	Germany	1	≥110kV	n.a.	Small spirals	BA	-1.26	0.02	X		X	X	X
39			2	≥110kV	n.a.	Flapper	BA	-1.28	0.02	X		X	X	X
40	Infante (coord.) (2011)	Portugal	1	≥110kV	Grasslands	Flapper	BACI	-0.56	0.01	X	X	X	X	X
41			2	≥110kV	Grasslands	Large spirals	BACI	-0.89	0.01	X	X	X	X	X
42	Janss & Ferrer (1998)	Spain	1	≥110kV	Grasslands	Large spirals	BACI	-1.66	0.12	X	X		X	X
43			2	≥110kV	Grasslands	Flapper	BACI	-0.66	0.08	X	X	X	X	X

				Candidate moderators				Effect size		Datasets				
#	**Reference**	**Country**	**Trial no.**	**Voltage**	**Habitat**	**Device**	**Study design**	**ln R**	**Var (ln R)**	**Primary**	**Calibrated**	**Sample size ≥30**	**With outliers**	**Without influent. cases**
44			3	<110kV	Wetlands	Flapper	BACI	2.08	0.96				X	
45	Koops & de Jong (1982)	Nether-lands	1	≥110kV	Wetlands	Small spirals	BACI	-2.36	0.07	X	X	X	X	X
46			2	≥110kV	Wetlands	Small spirals	BACI	-1.18	0.02	X	X	X	X	X
47			3	≥110kV	Wetlands	Large spirals	BACI	-1.37	0.06	X	X	X	X	X
48	Lorenzo & Cabrera (2009)	Spain	1	<110kV	Shrublands	Small spirals	CI	-1.01	1.03	X			X	X
49			2	<110kV	Shrublands	Large spirals	CI	-4.61	65.32				X	
50			3	<110kV	Shrublands	Flapper	CI	-0.28	0.06	X		X	X	X
51	Marques *et al.* (2007)	Portugal	1	≥110kV	Grasslands	Small spirals	BA	-0.65	0.02	X		X	X	X
52			2	≥110kV	Forest-Farmlands	Small spirals	BA	-1.22	0.15	X		X	X	X
53	Marques *et al.* (2008)	Portugal	1	<110kV	Grasslands	Small spirals	CI	0.00	0.05	X		X	X	X
54			2	<110kV	Grasslands	Small spirals	CI	-1.09	0.11	X		X	X	X
55	Murphy *et al.* (2009)	USA	-	<110kV	Wetlands	Flapper	BA	-1.37	0.02	X			X	X
56	Neves & Infante (2009)	Portugal	-	<110kV	Wetlands	Small spirals	BACI	-0.39	0.01	X	X	X	X	X
57	Procesl (2010)	Portugal	-	≥110kV	Grasslands	Large spirals	BA	-0.47	0.02	X		X	X	X
58	Procesl (2013a)	Portugal	-	≥110kV	Forest-Farmlands	Large spirals	CI (adjust.)	-0.13	0.02	X	X	X	X	X
59	Procesl (2013b)	Portugal	-	≥110kV	Forest-Farmlands	Large spirals	CI (adjust.)	0.05	0.22	X	X		X	X
60	Scott *et al.* (1972)	UK	-	≥110kV	Wetlands	Flapper	BACI	0.28	0.12	X	X	X	X	X
61	Shaw (2013)	South Africa	1	≥110kV	Shrublands	Flapper	BACI	-0.84	0.05	X	X	X	X	X
62			2	≥110kV	Shrublands	Large spirals	BACI	-0.72	0.03	X	X	X	X	X
63	Sporer *et al.* (2013)	USA	-	≥110kV	Wetlands	n.a	CI	-0.32	0.03	X		X	X	X
64	Ventana Wildlife Society (2009)	USA	1	<110kV	Wetlands	Small spirals	CI	-0.65	0.01	X			X	X
65			2	<110kV	Wetlands	Large spirals	CI	-0.48	0.01	X			X	X
66	Yee (2008)	USA	-	<110kV	Wetlands	Flapper	BACI	-1.44	0.06	X	X	X	X	X
TOTAL No. of trials included										61	31	42	66	60

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3.8.3. Power line features

Table S 3.3 - Power line features typically associated with the two levels defined for the moderator “Voltage” (<110 kV and ≥110 kV, which roughly represents distribution and transmission lines, respectively).

Presented values (of height, thickness or distance) are merely indicative for most of the lines in each category (i.e., may not be valid for voltage levels near the 110 kV threshold).

Power line features	**Power line Voltage**	
	<110 kV	**≥110 kV**
Type of pylon	Concrete or wood poles shorter than 15-20 m;	Metal lattice towers taller than 20-25 m;
Wires’ arrangement and thickness	Each phase is composed by a single conductor, thinner than 1.5-2 cm, thus with similar diameter of earth wires (when present); Distance between phases: ≤3 m;	Each phase is composed by one or more conductors (in bundles), thicker than 2-2.5 cm (each wire), thus typically contrasting with earth wires (always present, on top; c.a. 1.5 cm or less in diameter); Distance between phases: ≥ 5 m;
Wire-marking	Wire-markers are installed in all cables or only on earth wires (above ~60 kV).	Wire-markers are usually only installed on earth wires.

3.8.4. Model fit and heterogeneity

Table S 3.4 - Model fit results and heterogeneity associated to the random- and mixed-effects models using the complete dataset, the sub-datasets of trials with complete information for each candidate moderator and sub-dataset with complete information for all three moderators.

The multivariate mixed-effects model corresponds to one higher-ranked (based on AICc value) from the set of candidate models (see Table S 3.5). k = sample size; AICc – corrected Akaike's Information Criterion; Q_E - Test for Residual Heterogeneity; Q_M - Test of moderators.

Analysis / moderator	**k**	**AICc**	**Q_E**	**Q_M**
Random-effects model				
Null model	61	119.8	480.5 (df=60, p < 0.001)	-
Univariate mixed-effects models				
Voltage	58	115.6	420.2 (df=56, p < 0.001)	0.2 (df=1, p=0.63)
Habitat	52	103.1	344.9 (df=48, p < 0.001)	3.6 (df=3, p=0.31)
Device	58	111.8	388.2 (df=55, p < 0.001)	2.2 (df=2, p=0.32)
Multivariate mixed-effects model				
Null model	47	90.0	328.9 (df=46, p < 0.001)	-

Table S 3.5 - Rank of all candidate models (based on AICc values), using the sub-dataset with complete information for all three moderators (n=47).

Candidate models	**AICc**	**Weights**
lnR ~ 1	91.10690	0.379278175
lnR ~ 1 + habitat	91.61698	0.293897261
lnR ~ 1 + voltage + habitat	93.32049	0.125395917
lnR ~ 1 + voltage	93.43550	0.118388533
lnR ~ 1 + device	95.32722	0.045975606
lnR ~ 1 + habitat + device	97.21869	0.017856704
lnR ~ 1 + voltage + device	97.96171	0.012315594
lnR ~ 1 + voltage + habitat + device	99.12266	0.006892211

3.8.5. Sensitivity analysis

To assess the robustness of the meta-analytic findings, we conducted a sensitivity analysis which consisted in the repetition of the primary analysis with altered datasets (Bown and Sutton 2010). The altered datasets were created based on the notion that lower quality experiments (e.g. with small sample sizes or weak experimental designs), and the presence of outliers or influential cases can lead to different conclusions about the overall effect size estimated and/or moderating effect of the included co-variables (Viechtbauer and Cheung 2010; Lajeunesse 2015).

The results of the analyses using each altered dataset were confronted with the ones obtained in the primary analysis. If the pooled effect sizes and overall conclusions are the same, one can be more confident that the meta-analytic findings achieved in the primary analysis are robust (Viechtbauer and Cheung 2010).

Definition of the altered datasets

The following altered datasets were created:

1) **“Calibrated”** - exclusion of trials perceived to be of lower quality (namely, using BA or CI designs), compared to trials that used a BACI design or used bird flight crossing rates to control for differences on mortality rates not related to wire-marking;

2) **“Sample size ≥30”** - exclusion of trials with low sample size (i.e., No. of Accumulated Kms <30, either for *treatment* or *control* sites);

3) **“With outliers”** – re-inclusion of trials identified as outliers in the primary analysis, using graphical residual analysis;

4) **“Without influential cases”** - exclusion of influential cases identified through Cook’s distance statistics (Cook and Weisberg 1982).

The Cook’s distance statistics summarizes how much the, overall, estimated effect size changes when the i^{th} trial is removed from the complete dataset. The cut-off value used to determine if a trial is to be considered as an influential case was $4/(n-p)$, where n is the total number of trials and p is the number of moderators included in the model (Bollen and Jackman 1990). One influential case was identified and excluded from the primary dataset (Figure S 3.2).

For detailed information about which trials were included (or not) in each altered dataset and in the following sensitivity analyses, see Table S 3.2.

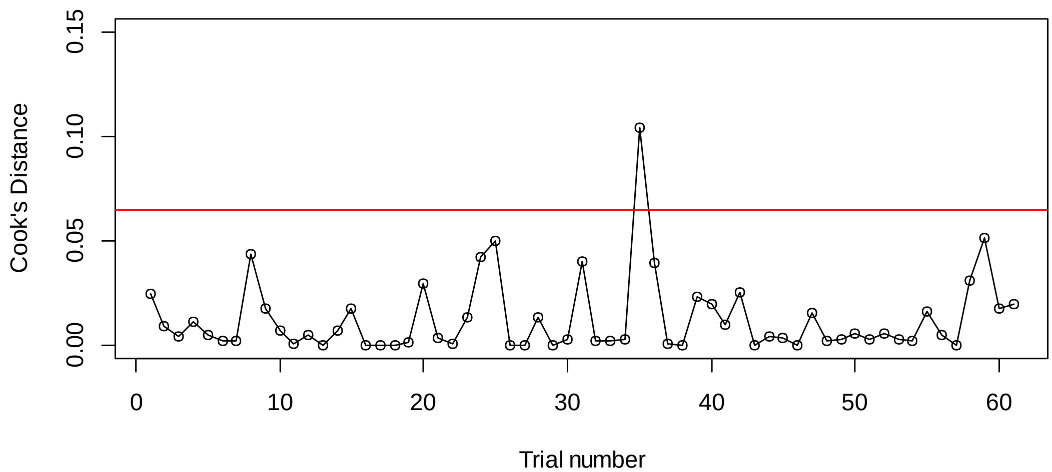

Figure S 3.2 - Difference between the average effect size estimated by random-effect model, once before and after deletion of the ith study ("Cook's distance"). Red line shows the cut-off value used to identify influential cases.

Sensitivity analysis of overall effect size

The estimated effect sizes, based on the altered datasets, ranged between -0.64 and -0.81, which corresponds to a 47.0% and 55.4% reduction in bird collisions at marked power lines (Table S 3.6).

Table S 3.6 - Overall effect size [95% CIE] and corresponding % reduction in bird mortality rates, estimated based on the primary dataset and each of the altered datasets.

Datasets	**No. Trials**	**LnR [95% CIE]**	**% Reduction [95% CIE]**
Primary dataset	61	-0.70 [-0.89; -0.52]	50.4 [40.4;58.8]
Altered datasets			
Calibrated	31	-0.66 [-0.91; -0.41]	48.3 [33.9;59.6]
Sample size ≥30	42	-0.64 [-0.82; -0.45]	47.0 [36.5;55.8]
With outliers	66	-0.81 [-1.03; -0.59]	55.4 [44.3;64.2]
Without Influential cases	60	-0.67 [-0.85; -0.49]	48.9 [38.9;57.3]

Sensitivity analysis of moderator effects

The meta-analytic findings using the altered datasets were generally consistent with the ones achieved based on the primary dataset (see section 3.8.4), with all models showing high (residual) heterogeneity (Q_E) and with none of the moderators being significant (Q_M) (Table S 3.7).

Table S 3.7 - Model fit results and heterogeneity associated to the random and mixed-effects models, using the altered datasets. k = sample size; AICc – corrected Akaike's Information Criterion; QE - Test for Residual Heterogeneity; QM - Test of moderators.

Altered dataset / Moderator	**k**	**AICc**	**Q_E**	**Q_M**
"Calibrated" dataset				
Null model	31	64.0	300.6 (df=30, p < 0.001)	-
Voltage	28	61.0	242.3 (df=26, p < 0.001)	0.3 (df=1, p=0.61)
Habitat	31	63.9	228.0 (df=27, p < 0.001)	7.3 (df=3, p=0.06)
Device	30	64.2	239.9 (df=27, p < 0.001)	2.3 (df=2, p=0.31)
"Sample size ≥30" dataset				
Null model	42	74.3	368.5 (df=41, p < 0.001)	-
Voltage	39	71.2	306.3 (df=37, p < 0.001)	0.1 (df=1, p=0.86)
Habitat	36	66.3	257.2 (df=32, p < 0.001)	3.1 (df=3, p=0.37)
Device	40	73.1	307.3 (df=37, p < 0.001)	2.5 (df=2, p=0.28)
"With outliers" dataset				
Null model	66	169.8	637.0 (df=65, p < 0.001)	-
Voltage	63	164.8	571.8 (df=61, p < 0.001)	0.1 (df=1, p=0.72)
Habitat	57	153.1	526.3 (df=53, p < 0.001)	3.1 (df=3, p=0.38)
Device	63	160.3	523.6 (df=60, p < 0.001)	3.6 (df=2, p=0.16)
"Without Influential cases" dataset				
Null model	60	113.8	462.5 (df=59, p < 0.001)	-
Voltage	57	109.6	403.3 (df=55, p < 0.001)	0.5 (df=1, p=0.46)
Habitat	51	94.6	318.2 (df=47, p < 0.001)	6.4 (df=3, p=0.09)
Device	58	111.8	388.2 (df=55, p < 0.001)	2.2 (df=2, p=0.33)

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Chapter 4

Ecological and methodological drivers of persistence and detection of bird fatalities at power lines: insights from multiple project monitoring data

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4. Ecological and methodological drivers of persistence and detection of bird fatalities at power lines: insights from multiple project monitoring data

Abstract

Environmental impact assessment (EIA) follow-up monitoring in energy projects, such as wind farms, solar facilities and power lines, frequently encompasses bird fatality surveys based on regular carcass searches. Since a large number of bird carcasses are often not found, field experiments to determine carcasses persistence (CP) and searcher efficiency (SE) biases in fatality surveys are typically performed for every single project. These data are, however, rarely used beyond the scope of each original project. We compiled data from CP and SE trials performed under 36 independent monitoring programmes aiming to assess bird mortality at transmission lines in Portugal, whose results were until now unavailable or dispersed in grey literature. We used survival analysis and generalized linear mixed-effects models to investigate the ecological and methodological factors influencing CP times and SE rates. Bird carcass size was a key driving factor of both CP times and SE rates of human observers, which were consistently outperformed by scent detection dogs. Season and habitat interactions had also an important role in CP patterns, while variations in SE rates by human observers were largely influenced by ground visibility (i.e., a combination of ground cover and vegetation height). Our results reinforce previous studies indicating that CP and SE biases are site-specific and determined by a wide range of ecological and methodological factors not always accounted in standard trial designs. Overall, our study demonstrates that data routinely collected under bird monitoring programmes from multiple projects can be combined to identify broad ecological patterns, limitations of current studies and, ultimately, improve EIA follow-up practice.

Keywords

Transmission lines, EIA follow-up, experimental design, carcass removal, searcher efficiency, bird carcass surrogate.

4.1. Introduction

Environmental Impact Assessment (EIA) is a globally used procedure to ensure that a proposed infrastructure or human activity is developed in an environmentally sustainable way (Ott *et al.* 2012). In practice, EIA consists in evaluating the expected environmental impacts of a proposed development and identify solutions to mitigate its adverse impacts on the environment. Although legislation and practice vary around the world, it is important that, once the EIA procedure is completed, a *monitoring programme* is implemented to determine whether the predicted impacts occurred and the proposed mitigation measures were implemented, and whether or not the latter are working effectively (Marshall *et al.* 2005).

The development of infrastructures such as power lines, roads, wind farms and solar facilities has well-documented negative impacts on bird communities (Benítez-López *et al.* 2010; Marques *et al.* 2014; Bernardino *et al.* 2018; Kosciuch *et al.* 2020). Among those of greatest concern is direct mortality, so post-EIA monitoring programmes often include regular searches of bird carcasses along or around the different infrastructures (Loss *et al.* 2015). However, assessing direct mortality effects through simple field-based searches holds several challenges as the number of carcasses found greatly depends on the chance of a carcass not having been removed (e.g., by scavengers) between searches (hereafter "carcass persistence") and, then, on searcher's ability to detect a carcass (hereafter "searcher efficiency") (Barrientos *et al.* 2018). Therefore, bird fatality monitoring programmes also often include experimental trials to estimate site-specific correction values for carcass persistence (CP) and searcher efficiency (SE) biases. In energy infrastructure projects like overhead power lines (where assessing bird fatalities due to collision or electrocution is the main concern), CP trials typically involve the placement of bird carcasses (usually reared specimens) along the power line corridor and then follow-up visits (e.g., on days 1, 3, 7, 15 and 30) to determine the time until removal (i.e., the persistence time of carcasses or any detectable remains, such as feather spots, in the field) (e.g., Costantini *et al.* 2017; Gómez-Catasús *et al.* 2020). SE trials usually take place immediately after the placement of these carcasses along the power line corridor, which is then searched by human observers or dog-handler teams to assess the probability of carcasses detection (Reyes *et al.* 2016). In SE trials with human observers, bird decoys or other objects (hereafter "dummies") can alternatively be used as surrogates of 'real' bird carcasses, to increase the trial sample size and the robustness of the derived SE bias correction, without the unnecessary sacrifice of a high number of animals (Moreira 2018; Hallingstad *et al.* 2018).

Well-designed CP and SE trials are essential to ensure the reliability of the bias correction values and, consequently, of the adjusted bird fatality estimates (Loss *et al.* 2014a; Huso 2019). Only accurate estimates that account for CP and SE biases allow (1) the adequate estimation of the (true) mortality levels caused by a given infrastructure; (2) the comparability of bird fatality estimates from different projects; and, ultimately, (3) the evaluation of their cumulative mortality and consequences at population-level (Loss *et al.* 2014a; Erickson *et al.* 2014; Katzner *et al.* 2020). Thus, the most recent national and international guidelines for monitoring bird fatality highlight the importance of undertaking CP and SE trials, and provide recommendations on how they should be designed (e.g., Strickland *et al.* 2011; Birdlife International 2015; Huso *et al.* 2016b). Ideally, the bird carcasses used in the trials should be representative of the bird species (e.g., differences in size, colours, etc.) that occur in the study area and might be victims of the infrastructure. The trials should also, as much as possible, account for spatial and/or temporal variations that may affect the CP and SE rates, such as differences in habitat or topography within the search area, seasonal variations on scavenger activity, vegetation height/cover and weather conditions (Turner *et al.* 2017; Barrientos *et al.* 2018). Taking all these into consideration implies rigorous experimental designs sometimes hard to implement within the framework of post-EIA monitoring studies (Conkling *et al.* 2020). Moreover, any increase in the number of factors tested (e.g., carcass size, habitat and season, and categories therein) has an immediate impact on the number of animals that need to be sacrificed for the trials, which raises additional ethical concerns. Consequently, there is a lack of standardization in the ecological and methodological aspects considered in CP and SE trial designs among projects, regions and countries (Barrientos *et al.* 2018).

Due to the high number of post-EIA monitoring studies undertaken worldwide, a large amount of data on CP and SE biases has been produced in the last years. However, it has rarely been used outside the scope of each individual project (Smallwood 2007, 2013; Bispo *et al.* 2013a; Barrientos *et al.* 2018), although these data could hold the potential to derive generic models applicable to specific regions, and avoiding the ethical and financial hurdles of having to undertake CP and SE trials for every single study. Compiling and integrating data from multiple projects is not straightforward. First, requirements for public disclosure of study findings vary greatly among countries, so most monitoring results are only available as grey literature, scattered across different institutional or company archives, and often not readily accessible for researchers or practitioners (Zwart *et al.* 2015; Fernández-Bellon 2020; Conkling *et al.* 2020). Second, the majority of the studies is only available in the native language of the country where it took place, which undermines their identification via web search engines (typically using English search-terms) and/or interpretation by non-native speakers (Amano *et al.* 2016; Fernández-Bellon 2020). Third, data extraction and integration is often constrained by the variety of experimental designs and methods used in the trials, and/or by incomplete reporting of the methods and results (Barrientos *et al.* 2018; Bernardino *et al.* 2019). However, the combined analysis of data from multiple projects can contribute for a broader and more robust understanding of the ecological and methodological drivers of CP and SE biases. This evidence-based knowledge, difficult to achieve through data from single projects due to the limited sample size and number of factors that can be tested, can then be used to improve current post-EIA monitoring practice (Zwart *et al.* 2015).

Here, we integrate and analyse data from CP and SE trials carried out under 36 monitoring programmes aiming to assess bird mortality (by collision) at transmission (150-400 kV) overhead power lines in Portugal. To our knowledge, this is the largest compiled CP and SE dataset related to one type of infrastructure in a single country. Almost all trials were performed within the framework of distinct post-EIA monitoring programmes whose results were until now unavailable or dispersed in grey literature. In addition to quantifying the overall CP and SE rates, our main objective is to investigate the ecological and methodological factors influencing CP and SE biases. We are particularly interested in assessing: (1) the effect of season, habitat and carcass size on CP times; and (2) the effect of object type (carcass vs. dummy), object size, ground visibility and type of observer (human vs. dog-handler team) on SE rates. Our ultimate goal is to promote the improvement of future CP and SE trials, taking advantage of the integration and the analysis of multiple project data conducted, for the first time, on a national scale.

4.2. Methods

4.2.1. Compilation of studies

With the collaboration of REN - Redes Energéticas Nacionais, the company responsible for the development and operation of the Portuguese electricity transmission network (150-400 kV), we performed an exhaustive search on its digital archive to identify and collect the available reports of all bird mortality monitoring programmes including CP and/or SE field trials. This was done 2016, with a further update in 2020. The reports were then screened in detail to identify which ones allowed the extraction or reconstruction of the raw data. For those that did not, additional requests for raw data were made directly to the environmental consulting companies or other entities that carried out these studies.

In total, we managed to compile raw data from CP and/or SE trials conducted, between 2005 and 2018, under 36 bird mortality monitoring programmes at transmission power lines in mainland Portugal (Supplementary Figure S 4.1). The complete list of projects from which data was retrieved is available in Table S 4.1 (see Supplementary material), also including information on which projects provided CP data, SE data or both. Almost all bird monitoring programmes included only one set of CP and/or SE trials, typically performed in the first post-construction monitoring year.

4.2.2. Data extraction and categorization

4.2.2.1. Carcass persistence

For each bird carcass used in the CP trials, we extracted and tabulated information on the time until carcass removal (in days). Depending on the study, difference schemes of follow-up visits were used to check the persistence of the carcass or any detectable remains (e.g., bones, feather spots) in the field. Some examples include: (i) daily visits for 10 days; (ii) visits on day 2, 5, 10 and 15; or (iii) visits solely on day 1 and 7, after carcass placement. This means that whatever the scheme adopted, the CP time (i.e., time until removal) is not known exactly but it is known to have occurred between two consecutive follow-up visits (interval-censored data) or, for the carcasses that persisted until the end of the trial, to have occurred after the last follow-up visit (right-censored data). Thus, for each bird carcass, we extracted information on between which follow-up visits the carcass removal occurred (e.g., between day 2 and 5) or, for carcasses persisting until the end of the trial, on when the last follow-up visit occurred (e.g., day 15).

To explain the variation of CP time, we extracted information, for each bird carcass, on the following potential explanatory variables:

i. **Season** in which the field experiment was conducted, classified as *Spring* (March to May), *Summer* (June to August), *Fall* (September to November) and *Winter* (December to February).

ii. **Habitat**, classified as *Agroforestry, Annual crops, Permanent crops, Forests* and *Scrublands*. This classification was based on the immediate surrounding of the power line right-of-way where the carcass was placed according to the reported in the study. If not provided but the GPS location of the carcass was known, information on habitat type was retrieved from the official Land Use and Land Cover maps of Continental Portugal for 2007, 2010 or 2015 (DGT 2018; shapefiles publicly available at https://snig.dgterritorio.gov.pt/), depending on the closest year to the CP trial date.

iii. **Carcass size**, classified as *Small* (< 200 g), *Medium* (200–1000 g), and *Large* (> 1000 g). Some examples of small-, medium- and large-sized specimens used in the trials are, respectively, common quails *(Coturnix coturnix)*, red-legged partridges (*Alectoris rufa*) and domestic chickens (*Gallus gallus*) (for more examples, see Supplementary Table S 4.2). Each bird carcass was classified based on the body-weight values and other morphological traits reported in each individual study. If not available, body-weight values were retrieved from the species profile information on the Cornell Laboratory of Ornithology (http://www.birds.cornell.edu).

4.2.2.2. Searcher efficiency

For each bird carcass or dummy placed in the SE trials, we extracted information on whether it was found or not by the observer (registered as a binary variable: "1" for detected, "0" for not detected) and on the following potential explanatory variables:

i. **Observer type** (*human* vs. *dog*), depending on whether carcass searches were carried out by a human observer or dog-handler team.

ii. **Object type** (*carcass* vs. *dummy*), depending on whether a 'real' bird carcass or a cryptic foam dummy (Supplementary Table S 4.2 and Figure S 4.2) was used in the trial to assess SE by human observers. Note that dogs rely mostly on olfactory cues to find the carcass (Beebe et al. 2016), so dummies were never used in SE trials for dog-handler teams.

iii. **Visibility** (*high*, *intermediate*, *low*), based on the reported habitat characteristics surrounding the carcass, mainly ground cover and vegetation height. We collapsed these two features into visibility classes that reflect their combined influence on observer's ability to find a carcass and were also frequently used in the compiled SE trials:

- 'High', <50% ground cover, and vegetation height typically <20 cm;
- 'Intermediate', 50-75% vegetation cover, and vegetation height typically 20-40 cm;

- ‘Low’, >75% vegetation cover, and vegetation height typically >40 cm.

iv. Object size (*small*, *medium*, *large*), using the same categories and information sources described above for ‘carcass size’ in CP data. For dummies, the three size classes corresponded always to objects with lengths of 12.0 cm, 18.5 cm and 38.0 cm (Supplementary Figure S 4.2).

4.2.3. Statistical analysis

All analyses were performed in R version 4.0.2 (R Core Team 2020).

4.2.3.1. Carcass persistence

Bird carcass persistence times were assessed with survival analysis techniques to accommodate interval-censored and right-censored time-to-event data (Gutierrez 2002). To determine which factors explain the variation of carcass persistence time, we built an accelerated failure time (AFT) regression model in three steps. First, considering the exponential, Weibull, log-logistic and log-normal candidate models (Bispo *et al.* 2013a) we selected the parametric distribution that best fitted the CP time density, based both on the Akaike Information Criterion (AIC) and on the graphical comparison between the empirical and the fitted distributions (Supplementary Table S 4.3 and Figure S 4.4). Second, we built an AFT model including all the covariates of interest, namely ’Season’, ‘Habitat’, ‘Carcass size’ and their two-way interactions, as fixed-effect terms; and “Project_ID” as a frailty term (equivalent to the inclusion of a random effect) to account for non-independence between carcasses used in each CP trial from a same bird monitoring programme. Third, we selected the best model using a stepwise backward elimination method. Term removal was based on likelihood-ratio tests (with 0.05 as the level of significance), until reaching the most parsimonious adequate model.

Overall model performance was assessed using the generalized R^2 statistics (proportion of variation explained by the model) proposed by Nagelkerke (1991). The empirical CP curves and median CP times were estimated using Kaplan-Meier method (Kaplan and Meier 1958).

4.2.3.2. Searcher efficiency

To evaluate the effect of different ecological and methodological factors on carcass detection probability, we created the following two datasets: (1) ‘Humans’ dataset, which included data where carcass/dummy searches were conducted only by human observers; and (2) ‘Humans vs. Dogs’ dataset, with data only from SE trials that used ‘real’ bird carcasses (i.e., trials using dummies were excluded) to allow true comparisons between the carcass detection probability for humans and dog-handler teams.

For each sub-dataset, we fitted a generalized linear mixed-effects model (GLMM), with a logit link function and a binomial error distribution (according to the response variable). All models included “Object_detection” (“1” for detected, or “0” for not detected) as the response variable and included “Project_ID” as a random effect to account for non-independence between objects used in the SE trials from a same bird mortality monitoring programme. Although we analysed the two sub-datasets similarly, there were specificities regarding the fixed-effects included in each model. In the first model, we investigated the probability of carcass detection by human observers as a function of ‘Object type’, ‘Object size’, ‘Visibility’ and their two-way interactions. Objects for which there was no comprehensive information on ground visibility were excluded from the multivariate analysis. In the second model, the probability of carcass detection was modelled as a function of ‘Observer type’, ‘Object size’ and their two-way interactions. ‘Visibility’ was not included as potential explanatory variables because SE trials using dog-handler teams occurred only in “intermediate” visibility areas.

For each SE model built, the best model was selected using stepwise backward procedure, based on a series of likelihood ratio tests (with $P < 0.05$ as removal criterion) for nested models. The performance of each model as a binary classifier was assessed by calculating the Area Under (the receiver operating characteristic) Curve (AUC; with values ranging from 0 to 1). An AUC value of 0.50 indicates that model did not perform better than random, whereas a value of 1.0 indicates perfect discrimination (Streiner and Cairney 2007).

4.3. Results

4.3.1. Summary of trial designs

A total of 3214 bird carcasses were placed in the CP trials compiled from 30 different bird mortality monitoring programmes. Most CP trials (53.3%) included ‘Season’ and ‘Carcass size’ in their experimental design, followed by trials (26.7%) that only tested ‘Season’ effect on CP rates (Figure 4.1 A). In all these trials, carcasses were randomly placed along the power line sections regularly surveyed by the observers (under the framework of each bird mortality monitoring programme). The effect of 'Habitat' on CP rates was, however, formally tested in the remaining trials (20.0%), by including this factor in the experimental design along with 'Season' and 'Carcass size' (Figure 4.1 A). On average, 9.9 carcasses (standard deviation, s.d.: 6.4; range: 1 - 20) were placed per combination of factor level tested. The follow-up schemes of the placed carcasses varied considerably among bird monitoring programmes, although the vast majority (93.3%) monitored the carcasses for at least 10 days (Supplementary Figure S 4.3).

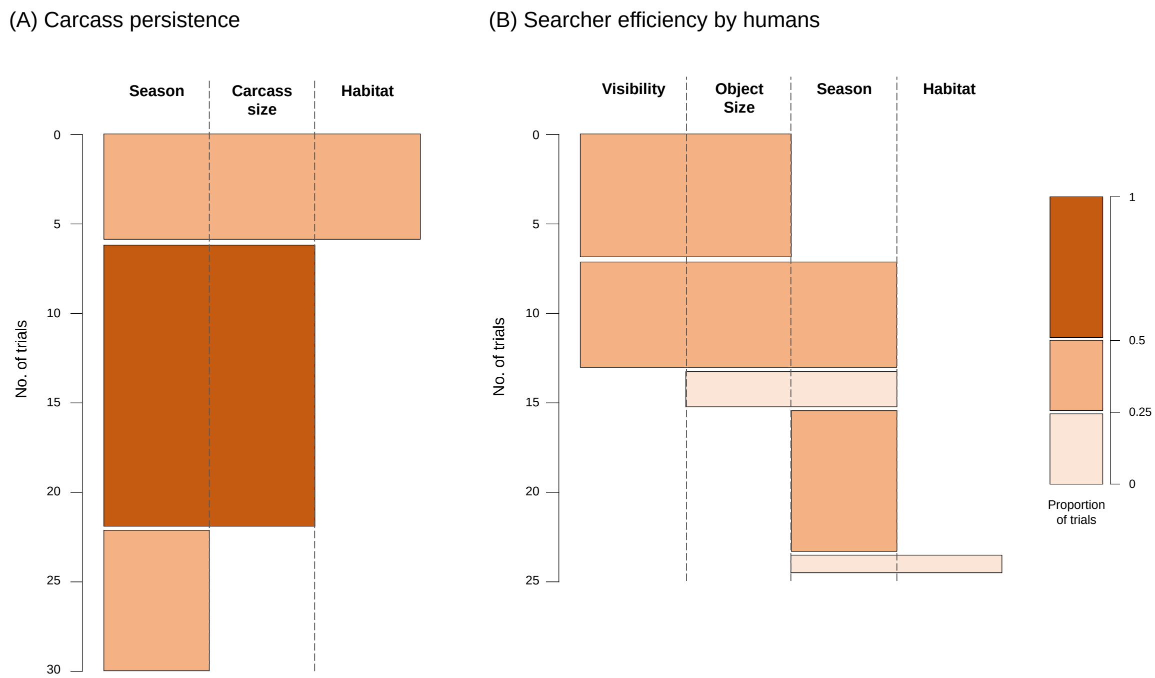

Figure 4.1 - Schematic representation of the experimental design used in the compiled (A) carcass persistence trials [n = 30] and (B) searcher efficiency trials for humans [n = 24].

Bars' width defines the variables included in the experimental design; bars' height represents the number of trials that included each combination of variables. Colour scale shows the proportion of trials that included a given combination of variables.

A total of 5950 objects (bird carcasses or dummies) were used in SE trials with human observers compiled from 24 different monitoring programmes. One third (33.3%) of those trials only included the factor 'Season' in their experimental design, followed by trials that tested 'Visibility' and 'Object size' effects (29.2%), and trials that tested the latter two together with 'Season' effects (25.0%) (Figure 4.1 B). The average sample size per combination of factor level tested was 8.6 (s.d.: 5.6; range: 2 – 21) in trials using 'real' bird carcasses and 16.6 (s.d.: 12.0; range: 10 – 48) when using dummies. Only two of the monitoring programmes conducted SE trials with dog-handler teams. Both SE trials assessed the effect of 'Season', 'Carcass size' and 'Habitat' on the probability of carcass detection for dogs, and had a sample size of 10 bird carcasses per combination of factor level tested.

4.3.2. Carcass persistence

From the total 3214 bird carcasses used in the CP trials, more than a fourth (26.0%) was removed during the first 24 hours, almost half (49.3%) within the first 3 days and 71.7% within a one-week period. Bird carcasses or their remains had a median persistence time of 3.5 days (95% CI: 0.6 – 7.5), with CP times highly variable among projects.

Likelihood-ratio tests showed that carcass persistence times were best predicted by the log-normal AFT model that included the three main effects ('Season', 'Habitat', 'Carcass size'), as well as the interactions 'Season x Habitat' and 'Season x Size' (Table 4.1; Nagelkerke's R^2 = 0.22). The frailty effect was highly significant (χ^2 =300.49, p <0.001). CP times varied with carcass size, except during Spring when carcasses were quickly removed regardless of their size (Figure 4.2 A). During the other seasons, larger carcasses tend to have higher persistence times. However, these differences were only significant between small-medium and large carcasses in the Fall (details in Supplementary Table S 4.4). During Fall and Winter seasons, differences between habitats were also significantly more pronounced (Figure 4.2 B; details in Supplementary Table S 4.4). Bird carcasses in scrublands and mostly in forests tended to persist longer, particularly when compared to agroforestry systems.

Table 4.1 - Final Accelerated Failure Time (AFT) model to predict carcass persistence times.

All AFT models included "Project_ID" as a frailty term. Explanatory variables: Se – Season; Ha – Habitat; Si – Carcass size. LRT – Results of nested likelihood-ratio test against the Full model (with P < 0.05 as the removal criterion). For further details see section 4.2.3.1.

Model	Terms included in the model	Removed Term	LRT	P-value	Nagelkerke R^2
1	Full model	-	-	-	0.22
2	Se + Ha + Si + Se:Ha + Se:Si	Ha:Si	12.15	0.1447	0.22
3	Se + Ha + Si + Se:Ha + Ha:Si	Se:Si	33.05	< 0.001	0.21
4	Se + Ha + Si + Se:Si + Ha:Si	Se:Ha	48.89	< 0.001	0.20

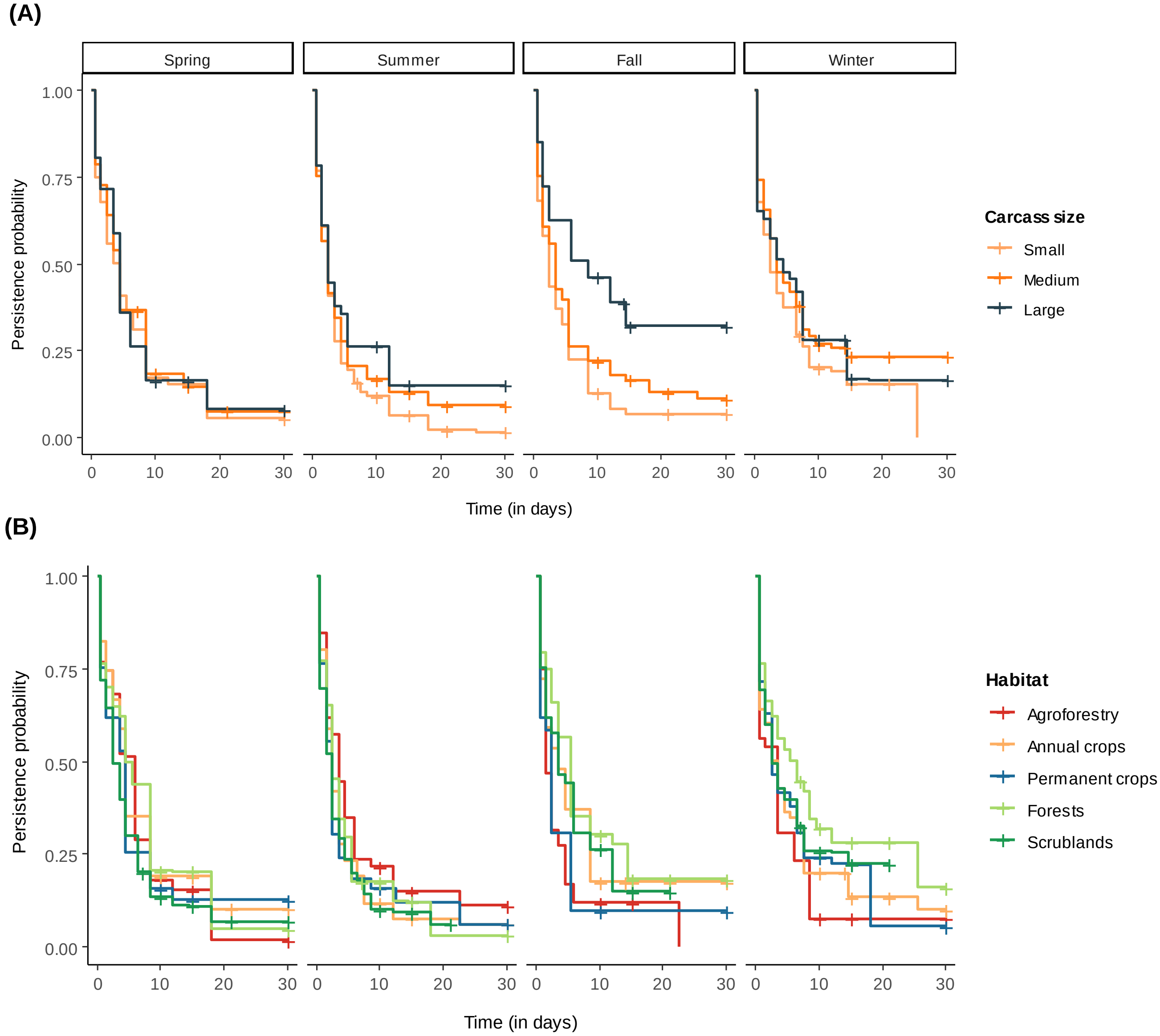

Figure 4.2 - Kaplan-Meier curves of carcass persistence probability as a function of (A) season and carcass size, and (B) season and habitat. Crosses represent censored data.

4.3.3. Searcher efficiency

Human searchers found 58.7% of all bird carcasses or dummies (n = 5950) used in SE trials compiled. Detection by humans was best predicted by the model that included the three variables of interest as predictors (‘Visibility’, ‘Size’ and ‘Type’), as well as the interactions ‘Visibility x Size’ and ‘Visibility x Type’ (Table 4.2 A; AUC = 0.81). Detection probabilities increased with visibility and object size (Figure 4.3 A; details in Supplementary Table S 4.5). Smaller objects were consistently harder to detect (regardless of the visibility class), but, on average, differences between detection rates of medium and large objects tend to decrease as visibility increased. Detection probabilities for dummies were consistently lower than those for 'real' bird carcasses, with differences between both types being more pronounced in 'intermediate' visibility areas (Figure 4.3 B; details in Supplementary Table S 4.5).

For the "Humans vs. Dogs" sub-dataset, the best model included 'Observer type' and 'Object size' as predictors (Table 4.2 B). The model was found to be moderately accurate (AUC = 0.76) in predicting the detection of carcasses. The inclusion of the interaction terms 'Observer x Size" did not significantly improve model fit (LRT, p-value = 0.101). However, the observed pattern (Figure 4.4) suggests an interaction effect, as differences between humans and dogs are larger for small carcasses. Search dogs located 84.2% (n = 600) bird carcasses (all in 'intermediate' visibility areas), while human searchers found 68.2% (n = 734) in the same conditions (visibility class). On average, detection probabilities increased with carcass size, although this effect was considerably less marked for dogs than for human searchers (Figure 4.4; details in Supplementary Table S 4.6).

Table 4.2 - Final logistic regression models to predict (A) object detection probability for human searchers and (B) carcass detection probability for dog-handler teams and humans in 'intermediate' visibility areas.

All models included "Project_ID" as a random factor. Explanatory variables: Vi – Visibility; Si – Object size; Ty – Object type; Ob – Observer type. LRT – Results of likelihood-ratio test against the nested model (with P < 0.05 as the removal criterion). AUC - area under the receiver operating characteristic curve. For further details see section 4.2.3.2.

Model	**Terms included in the model**	**Removed Term**	**LRT**	**P-value**	**AUC**
A. Detection probability for human searchers					
A1	Full model	-	-	-	0.81
A2	Vi + Si + Ty + Vi:Si + Vi:Ty	Si:Ty	2.41	0.299	0.81
A3	Vi + Si + Ty + Vi:Ty + Si:Ty	Vi:Si	10.00	0.040	0.81
A4	Vi + Si + Ty + Vi:Si + Si:Ty	Vi:Ty	14.67	< 0.001	0.80

Table 4.2 (continued).

Model	Terms included in the model	Removed Term	LRT	P-value	AUC
B. Detection probability for dog-handler teams and humans					
B1	Full model	-	-	-	0.76
B2	Ob + Si	Ob:Si	4.58	0.101	0.76
B3	Si	Ob	8.125	0.046	0.76
B4	Ob	Si	36.42	< 0.001	0.73

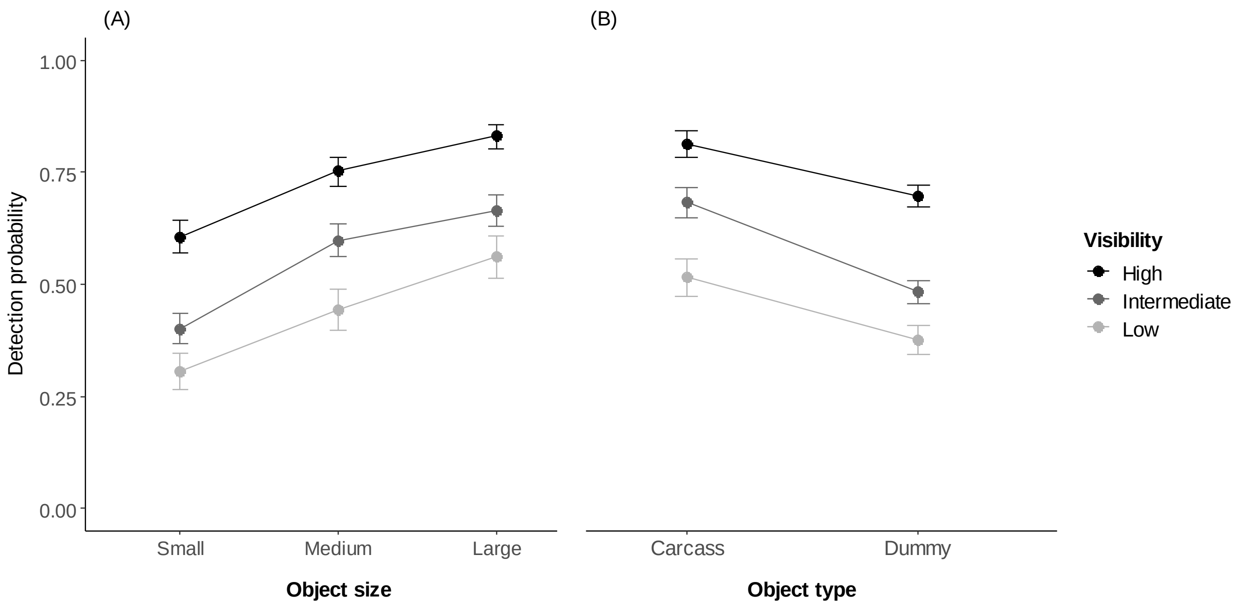

Figure 4.3 - Mean detection probability (± 95% confidence interval) for humans as a function of (A) ground visibility and object size, and (B) ground visibility and object type.

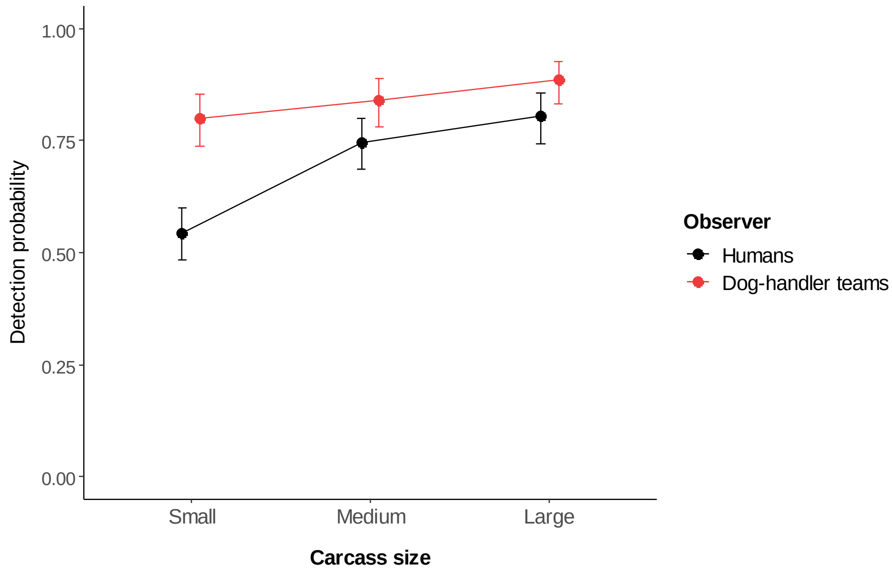

Figure 4.4 - Mean detection probability (± 95% confidence interval) for humans and dog-handler teams as a function of carcass size.

4.4. Discussion

4.4.1. Carcass persistence patterns

Despite the potential effect that different experimental designs may have on CP estimates (see section 4.4.3), our results are comparable with the ones achieved by Barrientos *et al.* (2018), which compiled persistence rates in the first 24h for different carcass taxon and types of infrastructures worldwide. The authors estimated a mean persistence rate of 75.6% for power lines, likewise in our study where, on average, 74.0% of the bird carcasses persisted after 24h. In our study, however, we intended to further explore the influence of ecological factors on the overall bird CP times (not only on the first 24h), as well as to exclude potential confounding effects resulting from underlying differences in CP patterns at power lines and other type of infrastructures (e.g., roads).

Our results show that the factors typically included in the trial experimental designs (size, season and habitat) indeed influence CP times at power lines. As expected, on average, persistence times increased with carcass size (e.g., Ponce *et al.* 2010; Costantini *et al.* 2017; Farfán *et al.*

2017). This is usually explained by the fact that small to medium-sized carcasses can be exploited by a greater number of species and be removed at once by scavengers, while larger carcasses require greater effort to be completely removed and are more likely to be scavenged *in situ*, leaving readily observable carcass remains (DeVault *et al.* 2003; Schutgens *et al.* 2014).

Carcass size effects varied across seasons, with maximum differences between sizes during the Fall and reduced differences during the other seasons, but particularly during Spring. Previous studies have demonstrated that carcass removal patterns are frequently modulated by seasonality (e.g., Prosser *et al.* 2008; Bernardino *et al.* 2011; Borner *et al.* 2017). In temperate regions, competition for carrion between vertebrate scavengers, invertebrates and microbes tend to increase during spring and summer (DeVault *et al.* 2004; Henrich *et al.* 2017; Turner *et al.* 2017), which can lead to the rapid disappearance of bird carcasses regardless of their size (at least up to 1-2 Kg). Moreover, the detection of carcasses seems to be easier during warmer months for scavengers that rely mainly on olfactory cues, in opposition to rainy and/or very windy periods (Ruzicka and Conover 2012; Paula *et al*. 2015; Henrich *et al.* 2017), which may explain why bird carcasses overall persisted longer during Fall and Winter periods.

Habitat and landscape features determine the composition and abundance of scavenger communities, at local- and regional-scales, with consequent effects on bird carcass removal rates (Costantini *et al.* 2017; Borner *et al.* 2017; Bernardino *et al.* 2020; Clarke *et al.* 2020). Such effects can, however, be difficult to predict due to the complexity of scavenger-carrion dynamics and their response to abiotic factors (e.g., weather conditions, distance to water, roads, etc.) (Ruzicka and Conover 2012; Turner *et al.* 2017; Moleón *et al.* 2019). In our case, habitat effects on CP times depended on season. In Spring and Summer, bird carcasses were removed similarly fast in any of the compared habitat categories, while during the fall and winter months, carcass removal rates tended to be slower in areas dominated by scrublands and forests. This pattern might be explained by combined effects of seasonal shifts on scavenger dynamics, weather conditions and/or carcass visibility (due to changes on vegetation density). The transmission projects that bisect forests and scrublands are located mainly in central and northern Portugal, characterized for harsher weather conditions during Fall-Winter periods that can promote slower scavenging processes (Bernardino *et al.* 2011; Paula *et al.* 2015). Conversely, agroforestry systems and annual crops are located mainly in south Portugal, where weather conditions are milder and undercover vegetation is less dense in cold seasons (Simionesei *et al.* 2018), which may facilitate carcass detection and removal both by avian and mammalian scavengers.

4.4.2. Searcher efficiency patterns

In our study, average SE rates of human observers steadily increased with the increase of the object size and ground visibility, although differences between medium and large-sized carcasses/dummies were less marked in ‘intermediate’ and ‘high’ visibility areas. Previous studies also found strong ground visibility effects on carcass detection (e.g., Schutgens *et al.* 2014; Hallingstad *et al.* 2018). For instance, SE trials conducted in Sagebrush steppes demonstrated that increasing the mean vegetation height from 16.5 to 36.0 cm reduced the detection probability of large bird carcasses (ring-necked pheasant, *Phasianus colchicus*) by approximately 30% (Stevens *et al.* 2011). Similar or even greater reductions in detection probabilities would, therefore, be expected for medium-sized carcasses (e.g., pigeons or partridges) or for small-sized carcasses (e.g., warblers or finches). Nonetheless, as vegetation height and ground cover decreases, medium to large carcasses can become considerably easier to find by the observers and differences in detection probabilities tend to be less marked, while small carcasses continue to show considerably lower detection probabilities (Smallwood 2007, 2013).

SE rates for human observers were also affected by methodological aspects, namely the use of dummies instead of “real” bird carcasses. The available literature regarding the use of dummies in SE trials for any type of infrastructure is very scarce (Moreira 2018; Hallingstad *et al.* 2018) and none of the studies assessed detection probabilities of dummies compared to ‘real’ bird carcasses. In our case, ‘real’ bird carcasses had, on average, 40% higher detection probabilities than dummies. This may be due to the latter having green to brown cryptic colours (that blend into the vegetation; see Supplementary Figure S 4.2), being less conspicuous than the ‘real’ bird carcasses used in the SE trials compiled (mostly reared specimens; see next section 4.4.3). We may not, however, exclude the possibility that the observed differences between the detectability of dummies and ‘real’ bird carcass may be partially explained by the variety of bird specimens used across the different SE trials compiled. For the purpose of our analysis, ‘real’ bird carcasses had to be grouped into three size categories, each including a relatively wide range of carcass weights (small, <200g; medium, 200-1000g; large, >1000g), while the dummies used to represent each carcass size category had all the same volume and length (small, 12.0 cm; medium, 18.5 cm; large, 38.0 cm. Thus, dummy size categories may not completely match the corresponding size categories established for ‘real’ bird carcasses, which might explain some of the differences observed between the detection probabilities of the two types of objects.

Our results confirm that dog-hander teams consistently out-perform human observers at detecting bird carcasses of all sizes, but particularly for small-sized carcasses (mean detection rate: 80.0% versus 54.2%, respectively). In our study, we could only compare carcass detection probabilities between dogs and humans for areas with intermediate ground visibility, however the dog-human differential is likely to increase even more in low visibility areas like tall and dense grasslands (Arnett 2006; Domínguez del Valle *et al.* 2020). It is undeniable that dog-handler teams increase carcass detection probabilities, with great impact on the accuracy of bird fatality estimates, and also improve search efficiency as dogs can survey larger areas per unit of time (Paula *et al.* 2011b; Reyes *et al.* 2016; Smallwood *et al.* 2020). However, the selection, purchase and training of scent detection dogs, as well as the maintenance of their search skills, heath care and housing may be still financially and logistically demanding (Mathews *et al.* 2013; Beebe *et al.* 2016), which inhibits their more widespread use in bird fatality assessments.

4.4.3. Potential causes of high heterogeneity in observed patterns

The amount of variation in CP times and detection probability unexplained by our models suggests that factors other than the predictor variables are also influencing the response variables. The observed within- and between-study differences may be partly attributed to differences in vegetation structure, the local identity and abundance of scavengers, and their specific foraging routes (DeGregorio *et al.* 2014; Borner *et al.* 2017; Clarke *et al.* 2020). Additionally, our dataset is the compilation of records from independent field trials conducted by different entities over more than a decade. Inter-annual variations in weather conditions (temperature and precipitation, for example) and prey availability can determine scavenger activity and, consequently, contribute for differences in carcass removal rates among studies (Kostecke *et al.* 2001; Hallingstad *et al.* 2018).

Heterogeneity in CP times and detection probabilities may, nonetheless, be also caused by unaccounted factors that are not related to site-specific biotic and abiotic conditions, but to methodological differences between studies. Some of these differences were included as explanatory variables in our analyses (e.g., dogs vs. human observers, real carcasses vs. dummies), but others could not. For instance, ‘carcass origin’ (wild vs. reared specimens) could not be included in our multivariate analysis because the total number of wild carcasses in the CP dataset was relatively small (n = 111; vs. n = 3103 for reared specimens), and even more if sub-divided per combination of season, habitat and carcass size tested. Reared birds are often used in CP trials because carcasses of wild birds are more difficult to obtain. This option may, however, affect CP times, as reared birds due to differences e.g. in scent and colour may misrepresent wild bird carcasses in their attractiveness to scavengers (Prosser *et al.* 2008; Urquhart *et al.* 2015; DeVault *et al.* 2017; Hallingstad *et al.* 2018). The diversity of reared birds used (Supplementary Table S 4.2) can also inflate the differences in SE rates between studies, namely because a carcass with a cryptic plumage (e.g. quail) is harder to detect than a bright yellow chick (Witmer *et al.* 1995; Prosser *et al.* 2008). Lastly, in our analysis, the number of categories established for each explanatory variable was limited by the diversity of trial designs used in the original studies and/or by the detail of the methods reported. The categories (e.g., of habitat or ground visibility) used may, therefore, be too broad for an effective prediction of CP times and SE rates.

Regardless of the causes, substantial variation in SE rates and, most particularly, in CP times is unaccounted by our best mixed-effects models. This means that their ability to predict 'reference' CP and SE bias corrections applicable to specific regions or transmission projects is reduced. Therefore, our results reinforce previous studies indicating that CP and SE rates are, to some extent, unpredictable on a small scale, and that field trials should be carried out to estimate site-specific bias corrections (Prosser *et al.* 2008; Ponce *et al.* 2010; Borner *et al.* 2017; Bernardino *et al.* 2020). Nonetheless, it is important to bear in mind that the implementation of site-specific trials has itself several practical / logistical limitations (e.g., limited number of factors that can be included in the experimental design; difficulty in finding good surrogates of wild bird fatalities). The derived CP and SE bias corrections will, therefore, always be an approximation of the 'true' biases in bird mortality surveys.

4.5. Conclusions

The need to quantify CP and SE biases in carcass searches is a transversal challenge to studies investigating avian mortality caused by human-made structures. This study is one of the first to compile, on a national scale, data from CP and SE trials conducted in a single type of infrastructure (transmission power lines). Combining and re-analysing data from multiple projects is an important, but often overlooked, opportunity to zoom out from individual study findings and identify broad patterns.

We found that most ecological variables typically included in the design of the field experiments indeed influence the derived CP and SE bias corrections. Carcass size was a key driving factor of both CP times and SE rates (most particularly for human observers, but also for dog-handler teams). Season and habitat interactions had also an important role in CP patterns, while variations in carcass (or dummy) detection rates by human observers were largely influenced by the different levels of ground visibility. In both CP and SE trials, it is important to ensure that bird fatality surrogates fairly mimic (in size, colour, scent, etc.) the wild bird species exposed to collision in each specific power line project. The use of dummies may be a viable option to increase the robustness of SE trials with human observers, without the unnecessary sacrifice of a high number of reared birds. However, studies that compare detection probabilities of dummies and 'real' bird carcasses under the exact same conditions are still needed, to determine which dummies are truly reasonable surrogates of wild bird fatalities at power lines or other infrastructures.

Despite the broad patterns observed, carcass removal and detection varied greatly between projects within a same region and bisecting similar habitats. SE rates and, most particularly, CP times were frequently site-specific, which supports current best practice recommendations to perform CP and SE trials in every post-EIA bird mortality monitoring programme (e.g., Strickland *et al.* 2011; Birdlife International 2015; Huso *et al.* 2016b). Notably, substantial variation in CP times and SE rates was not explained by the variables included in our models, which suggests that both biases are influenced by a myriad of variables not formally included in the design of the field trials typically conducted. Any increase in the environmental factors accounted (and/or categories within) has, however, implications on the logistics and costs of the trials, and may also raise ethical issues due to a minimum sample size required per combination of factors tested. Therefore, the final decision on which factors (and/or how many factor levels) to formally include in the design of field trials conducted under post-EIA monitoring framework should always take into consideration the specificities of each power line project and location (e.g., power line length, target bird species/groups, habitat complexity, expected seasonal variations in scavenger activity and weather conditions).

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4.8. Supplementary material

4.8.1. List of transmission projects

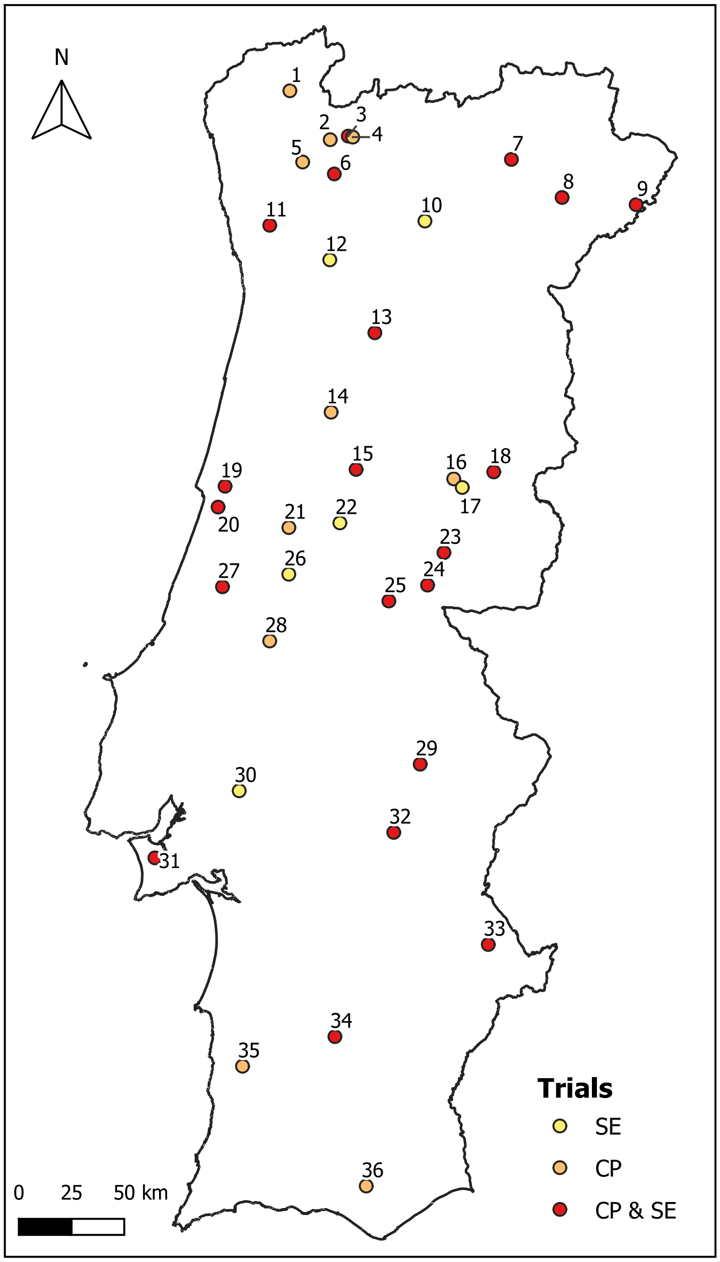

Figure S 4.1 - Location (centroids) of the 36 transmission (150-400 kV) power line projects in mainland Portugal subject to bird mortality monitoring programmes from which Carcass Persistence (CP) and/or Searcher Efficiency (SE) data was retrieved. See Table S 4.1 for details about each transmission project.

Table S 4.1 - List of transmission (150-400 kV) power line projects in mainland Portugal subject to bird mortality monitoring programmes from which Carcass Persistence (CP) and/or Searcher Efficiency (SE) data was retrieved. It is also shown the period covered by the field trials and the references to the corresponding bird monitoring reports.

(*) Raw data provided by the environmental consultancy team that carried out the CP and/or SE trials.

ID	Project Name	Trials	Year	Reference
1	Linha de ligação do Parque Eólico do Alto Minho I – Pedralva, a 150 kV	CP	2010	1
2	Ramal de Transporte de Energia da Linha Caniçada-Riba d'Ave 1 para o Posto de Corte de Venda Nova 2 (L1617), a 150 kV	CP	2005-2006	2 (*)
3	Linha Vieira do Minho - Pedralva 2, a 400 kV	CP & SE	2017-2018	3 (*)
4	Linhas a 400 kV entre os reforços de potência de Salamonde II e Venda Nova III e o Posto de Corte de Vieira do Minho	CP	2016-2017	4 (*)
5	Ramal de Transporte de Energia da Linha Vila Nova-Riba D'Ave para a Subestação de Oleiros, a 150 kV	CP	2005-2006	5
6	Linha de Alta Tensão de Interligação do Parque Eólico das Terras Altas de Fafe à Subestação de Riba D'Ave, a 150 kV	CP & SE	2006-2007	6
7	Linha Macedo de Cavaleiros-Valpaços a 220 (400) kV	CP & SE	2012-2013	7
8	Ramal da Linha Mogadouro-Valeira para a Subestação de Olmos (Macedo de Cavaleiros), a 220 kV	CP & SE	2009	8 (*)
9	Linhas integradas no projeto de Modificação da Rede Nacional de Transporte (RNT) na região do "Douro Internacional"	CP & SE	2011-2012	9 (*)
10	Subestação de Vila Pouca de Aguiar 220 kV / 60 kV e Linha Vila Pouca de Aguiar-Valdigem a 220 kV	SE	2008-2009	10
11	Linhas Recarei – Vila Nova de Famalicão e Vermoim – Vila Nova de Famalicão, a 400 kV	CP & SE	2017-2018	11 (*)
12	Linha Valdigem-Vermoim (VGVM) 4/5, troço entre a Subestação de Valdigem e o actual apoio 158 da LVGVM, a 220kV	SE	2010	12 (*)
13	Linha Bodiosa-Valdigem, 400 kV	CP & SE	2006-2008	13 - 14
14	Linha Bodiosa-Paraimo, a 400 kV	CP	2006-2007	15 - 18
15	Linha de Ligação entre o Parque Eólico de Pampilhosa da Serra e a Linha Vila Chã-Pereiros 2 (220 kV)	CP & SE	2006-2007	19
16	Linha Castelo Branco – Ferro 1/2, a 220 kV, e Ramal da LCBFE 1/2, a 220 kV, para a Subestação da Fatela	CP	2006-2007	20 - 23
17	Linha Castelo Branco – Ferro 1/2, a 220kV, e Ramal da Linha CBFE 1/2, a 220kV, para a Subestação da Fatela (Cegonha negra)	SE	2010	24 (*)
18	Linha Penamacor-Ferro, a 220 kV	CP & SE	2007-2008	25
19	Ramal da Linha Lares-Lavos 1, a 400 kV, para a subestação de Paraimo	CP & SE	2012-2013	26
20	Linha Lares-Lavos, a 400 kV	CP & SE	2011	27
21	Ramal de Transporte de Energia da Linha Pereiros-Zêzere (L2151), a 220 kV	CP	2005	28 (*)
22	Linha Penela-Tábua, a 220 kV	SE	2011-2013	29
23	Linha do Parque Eólico da Gardunha para a Subestação de Castelo Branco, a 150 kV	CP & SE	2007-2008	30
24	Linha Falagueira – Castelo Branco 1/2 a 150 kV, Troço Ródão-Castelo Branco	CP & SE	2006-2007	31
25	Linha de ligação do Parque Eólico do Pinhal Interior à Subestação da Falagueira (150 kV)	CP & SE	2006-2007	32
26	Linha Pereiros-Zêzere, a 220 kV e abertura da Linha Pereiros-Zêzere para a subestação de Penela (Linhas Pereiros-Penela e Penela-Zêzere)	SE	2007-2008	33
27	Linha Batalha-Lavos, a 400 kV	CP & SE	2011	34
28	Linha Batalha-Pego, a 400 kV	CP	2007	35 - 38
29	Linha Falagueira-Estremoz, a 400 kV	CP & SE	2010-2012	39
30	Ramal da Linha Palmela-Sines 3, a 400 kV, para Fanhões	SE	2013-2014	40

ID	Project Name	Trials	Year	Reference
31	Linhas elétricas aéreas, a 150kV, de ligação à subestação de Fernão Ferro e abertura da linha Palmela – Ribatejo, a 400kV, para a subestação de Fernão Ferro	CP & SE	2013	41 (*)
32	Linha de Estremoz-Divor, a 400 kV	CP & SE	2017-2018	42 (*)
33	Linha de Transporte de Energia Alqueva-Brovales, a 400 kV	CP & SE	2005-2007	43 - 47 (*)
34	Linha de Muito Alta Tensão Ferreira do Alentejo-Ourique	CP & SE	2005-2006	48 (*)
35	Linha Sines-Portimão 3, a 400 kV	CP	2007-2008	49 - 52
36	Linha Tunes-Estói, a 150 kV	CP	2006-2007	53 - 55

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4.8.2. Bird carcasses and dummies used in the compiled field trials

Table S 4.2 - Examples of bird specimens used in carcass persistence and searcher efficiency trials to surrogate small-, medium- and large-sized carcasses.

Carcass size	**Bird species**	**Illustrative photos**
Small (< 200 g)	<u>Reared specimens</u>: ~7-day-old domestic chicken (*Gallus gallus*) – Photo 1 Common quail (*Coturnix coturnix*) – Photo 2 Parakeet (*Melopsittacus undulatus*) <u>Wild specimens</u>: Woodlark (*Lullula arborea*) Eurasian blackcap (*Sylvia atricapilla*) Common chaffinch (*Fringilla coelebs*)	 
Medium (200 - 1000 g)	<u>Reared specimens</u>: ~4-week-old domestic chicken (*Gallus gallus*) – Photo 3 Red-legged partridges (*Alectoris rufa*) – Photo 4 Common pigeon (*Columba livia*) – Photo 5 <u>Wild specimens</u>: Common kestrel (*Falco tinnunculus*) Cattle Egret (*Bubulcus ibis*)	  

Carcass size	Bird species	Illustrative photos
Large (> 1000 g)	<u>Reared specimens</u>: Domestic chicken (*Gallus gallus*) – Photo 6 Common pheasant (*Phasianus colchicus*) Domestic duck (*Cairina moschata*) <u>Wild specimens</u>: White stork (*Ciconia ciconia*) – Photo 7 Northern Goshawk (*Accipiter gentilis*)	 

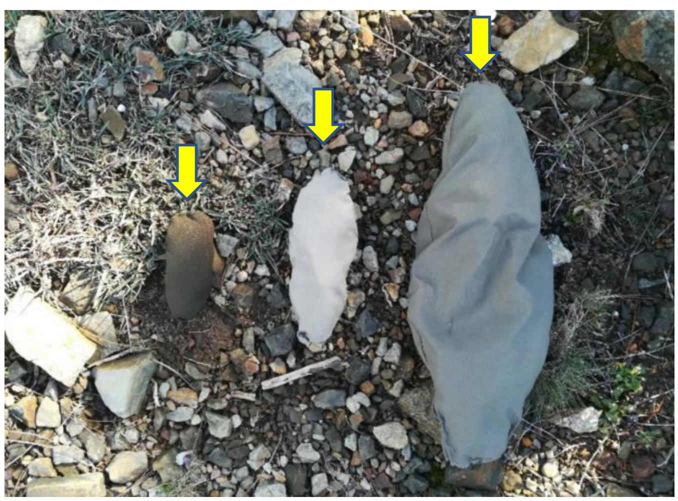

Figure S 4.2 - Examples of dummies used in the searcher efficiency trials to surrogate small-, medium- and large-sized bird carcasses (12 cm, 18.5 and 38 cm long, respectively).

Photo source: Moreira, M.S. (2018). *Methodological and Ecological Insights on Wind Farm Environmental Impact Assessment*. Master's thesis in Ecology and Environment. Faculty of Sciences of the University of Porto.

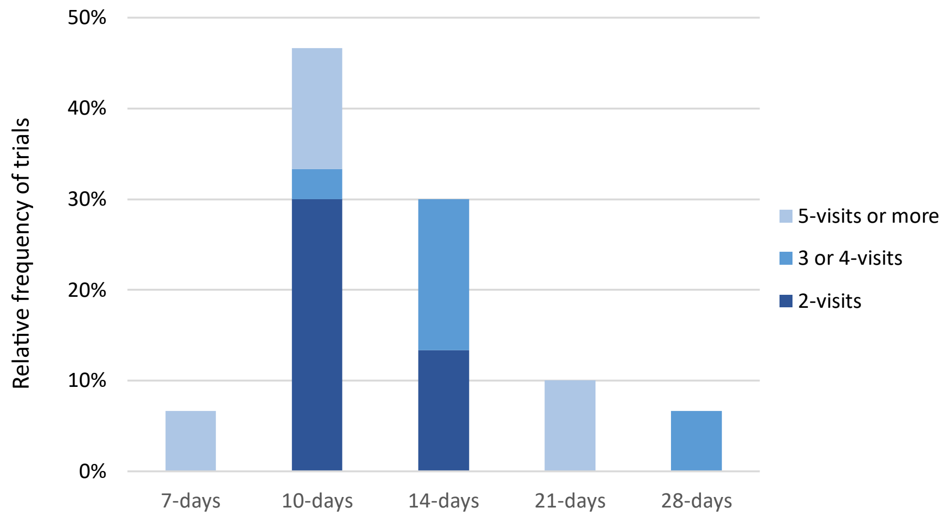

Figure S 4.3 - Relative frequency (%) of carcass persistence trials [n=30] with different combinations of trial duration and number of follow-up visits to evaluate the presence of detectable bird carcass remains.

4.8.3. Additional statistical modeling results

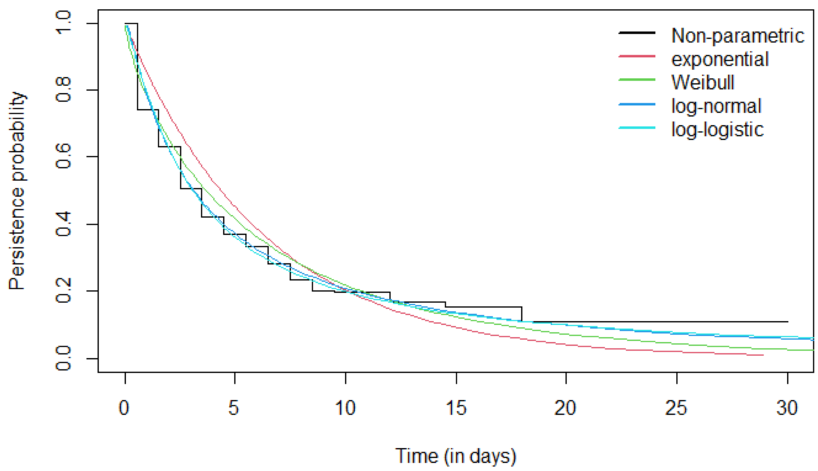

Figure S 4.4 - Kaplan-Meier curve of carcass persistence probability, compared to parametric AFT models (exponential, Weibull, log-normal and log-logistic distributions).

Table S 4.3 - Selection of best fitting parametric distribution (based on the lowest Akaike Information Criterion, AIC) for the accelerated failure time model for carcass persistence times. K – number of parameters; Δ_{AIC} – difference in AIC relative to the highest ranked model.

Distribution	**K**	**AIC**	Δ_{AIC}
log-normal	2	9243.66	0.00
log-logistic	2	9304.87	61.21
Weibull	2	9565.27	321.61
exponential	1	9788.88	545.22

Table S 4.4 - Summary of the frailty Accelerated Failure Time model (log-normal distribution family) for carcass persistence times.

Reference levels: 'Spring' for Season, 'Small' for Carcass size and 'Agroforestry' for Habitat.

Variables	**Coefficient ± se**	**Chi-square**	**p-value**
Intercept	1.376 ± 0.224	37.59	< 0.001
Season			
Summer	-0.023 ± 0.175	0.02	0.90
Fall	-0.774 ± 0.169	20.89	< 0.001
Winter	-0.663 ± 0.179	13.64	< 0.001
Carcass Size			
Medium	0.135 ± 0.108	1.57	0.21
Large	0.438 ± 0.158	7.69	< 0.001
Habitat			
Annual.crops	0.179 ± 0.147	1.47	0.23
Permanent.crops	0.003 ± 0.191	0.00	0.99
Forests	-0.032 ± 0.171	0.03	0.85
Scrublands	-0.222 ± 0.175	1.62	0.20
Season x Carcass size			
Summer x Medium	-0.082 ± 0.15	0.29	0.59
Fall x Medium	0.105 ± 0.158	0.45	0.50
Winter x Medium	0.228 ± 0.15	2.32	0.13
Summer x Large	0.015 ± 0.212	0.00	0.94
Fall x Large	0.823 ± 0.207	15.77	< 0.001
Winter x Large	0.001 ± 0.205	0.00	0.99
Season x Habitat			
Summer x Annual.crops	-0.344 ± 0.217	2.51	0.11
Fall x Annual.crops	0.241 ± 0.213	1.28	0.26
Winter x Annual.crops	0.425 ± 0.218	3.80	0.05
Summer x Permanent.crops	-0.132 ± 0.262	0.25	0.61
Fall x Permanent.crops	0.448 ± 0.268	2.79	0.10
Winter x Permanent.crops.	0.735 ± 0.266	7.67	< 0.001
Summer x Forests	-0.181 ± 0.210	0.75	0.39
Fall x Forests	0.808 ± 0.207	15.18	< 0.001
Winter x Forests	0.782 ± 0.213	13.51	< 0.001
Summer x Scrublands	-0.191 ± 0.221	0.75	0.39
Fall x Scrublands	0.812 ± 0.220	13.58	< 0.001
Winter x Scrublands	0.836 ± 0.222	14.21	< 0.001

Variance of random effect = 0.845

Table S 4.5 - Summary of the best mixed-effects logistic regression model to predict object detection probability for human observers.

Reference levels: ‘Carcass’ for Object type, ‘Small’ for Object size and ‘Low’ for Visibility.

Variables	**Coefficient ± se**	**Z**	**p-value**
Intercept	-1.594 ± 0.335	-4.761	< 0.001
Object type			
Dummy	-0.361 ± 0.479	-0.752	0.452
Object size			
Medium	0.610 ± 0.146	4.174	< 0.001
Large	1.140 ± 0.151	7.534	< 0.001
Visibility			
Intermediate	1.226 ± 0.177	6.942	< 0.001
High	1.906 ± 0.190	10.012	< 0.001
Object type x Visibility			
Dummy x Intermediate	-0.599 ± 0.183	-3.269	0.001
Dummy x High	-0.026 ± 0.206	-0.125	0.900
Object size x Visibility			
Medium x Intermediate	0.256 ± 0.188	1.365	0.172
Large x Intermediate	0.307 ± 0.195	1.574	0.115
Medium x High	0.276 ± 0.197	1.400	0.161
Large x High	0.641 ± 0.209	3.068	0.002

Variance of random effect = 1.154

Table S 4.6 - Summary of the best mixed-effects logistic regression model to predict carcass detection probability for dog-handler teams *versus* humans in ‘intermediate’ visibility areas.

Reference levels: ‘Human’ for Observer type and ‘Small’ for Carcass size.

Variables	**Coefficient ± se**	**Z**	**p-value**
Intercept	-0.244 ± 0.292	-0.835	0.404
Observer type			
Dog-handler team	1.418 ± 0.708	2.002	0.045
Carcass size			
Medium	0.657 ± 0.167	3.935	< 0.001
Large	1.007 ± 0.194	5.200	< 0.001

Variance of random effect = 0.824

Chapter 5

Response of vertebrate scavengers to power line and road rights-of-way and its implications for bird fatality estimates

Joana Bernardino, Regina Bispo, Ricardo C. Martins, and Francisco Moreira

5. Response of vertebrate scavengers to power line and road rights-of-way and its implications for bird fatality estimates

Abstract

Linear infrastructures, such as power lines and roads, are an important source of bird mortality. However, little is known on the potential effect of these infrastructures on local scavenger guilds, their foraging activity and the resulting bird carcass removal patterns. This is an important source of bias in studies aiming to quantify bird fatalities due to linear infrastructures. We used camera-traps to record scavenger identity and persistence patterns of bird carcasses placed close to linear infrastructure and nearby controls in two Mediterranean agricultural regions. We found that linear infrastructure influence on scavenger identity varied depending on the region. Contrary to expectations, linear infrastructure presence had either none or a positive effect on carcass persistence, meaning that carcasses placed within power line or road rights-of-way were not removed faster than the ones placed in controls. We conclude that linear infrastructure effect on vertebrate scavenging patterns is likely to be region-specific, and that reliable correction factors for carcass removal-bias in bird fatality estimates require site-specific experiments to characterize local scavenging processes.

Keywords

Linear infrastructures, carcass removal trials, scavenger efficiency, agricultural landscape, camera-trapping.

5.1. Introduction

Linear infrastructures (LI), such as power lines and roads, are ubiquitous elements of most natural landscapes (Dulac 2013). Despite their importance for human prosperity and quality of life, LI are responsible for a wide range of impacts on wildlife species and their habitats (Morelli *et al*. 2014; D'Amico *et al.* 2018), which need to be quantified to inform effective mitigation actions (Laurance *et al.* 2015; Ascensão *et al.* 2019).

One of the most common and harmful LI impacts is bird mortality caused by collisions with vehicles and power line wires (Loss *et al.* 2014b; Bernardino *et al*. 2018). The quantification of the number of birds killed by these infrastructures relies on well-designed monitoring protocols which typically comprise regular carcass searches. Due to resource and time limitations, these searches are often conducted on a weekly, monthly or even less frequent basis (Barrientos *et al.* 2011; Collinson *et al.* 2014). Several studies provide, however, evidence of a significant removal of small-bird carcasses in the first hours or days after fatality events, both in power lines (e.g., Ponce *et al.* 2010; Borner *et al.* 2017) and roads (e.g., Santos *et al.* 2011; Guinard *et al.* 2012), hence a large proportion of carcasses (or its remains) have low persistence rates and are missed by searchers. To correct for this bias, field experiments have to estimate the proportion of bird carcasses removed by scavengers or any other event (e.g., traffic, decomposition), to obtain accurate avian fatality estimates (Huso *et al.* 2016a; Barrientos *et al.* 2018).

Carcass persistence rates are typically evaluated through field experiments where a known number of bird carcasses is distributed along LI rights-of-way and regularly monitored until no detectable remains are left. Nonetheless, to avoid the so-called scavenger swamping - i.e., abnormal carcass removal by scavengers, due to a saturation of the study area with carcasses (Smallwood 2007) - it is recommended that carcasses are placed at least 100-500m distanced apart (e.g., Schutgens *et al.* 2014; Costantini *et al.* 2017). This requirement greatly restricts the number of carcasses to be placed simultaneously within the LI right-of-way, thus technicians have often questioned the possibility of distributing carcasses in nearby areas (with similar habitats) to achieve the optimal sample size. These alternative sites may not, nonetheless, recreate entirely the conditions of LI rights-of-way, with unknown consequences for the accuracy of the scavenging–bias correction factor derived.

Comprehensive understanding of the scavenging process and its overall effect on carcass persistence is, therefore, crucial for an accurate assessment of LI-related bird mortality levels and for setting adequate monitoring programmes (Smallwood *et al.* 2010; Loss *et al.* 2012). Carcass size (Flint *et al.* 2010; Ponce *et al.* 2010; Farfán *et al.* 2017), season or weather conditions (Guinard *et al.* 2012; Paula *et al.* 2015; Shaw *et al.* 2015), biogeographic context and microhabitat (Stevens *et al.* 2011; Costantini *et al*. 2017; Borner *et al.* 2017) are among the most commonly mentioned factors that influence carcass persistence. Complex interactions between these factors have been shown to modulate vertebrate scavenger communities and their scavenging efficiency (Rosene and Lay 1963; Turner *et al.* 2017; Riding and Loss 2018). The latter depends on (i) the amount of time a carcass takes to be detected by a scavenger; (ii) the way the carcass is consumed by the scavenger (i.e., whether it is completely removed, or more likely to be consumed *in situ*, often leaving detectable remains behind); and, ultimately, (iii) the amount of time these carcass remains (e.g., feather spots) persist in the field, until they are no longer detectable by searchers.

There is, however, limited understanding of how the presence of the LI itself shapes the composition of the local scavenger guilds, their scavenging efficiency and its cascading effects on carcass persistence (but see Lambertucci *et al.* 2009; Hill *et al.* 2018; Donázar *et al.* 2018). Local scavenger guilds and their foraging behaviour are greatly influenced by environmental factors, such as landscape features, weather conditions and carrion availability (e.g., DeVault *et al.* 2003; Huijbers *et al.* 2015; Olson *et al.* 2016; Smith *et al.* 2017). Because of the latter, there is growing belief that scavenging rates within power line and road rights-of-way are higher compared to the surroundings. This claim is mostly driven by the idea that generalist species soon associate the power line or road rights-of-way with a readily available source of food (Slater 2002; Dean *et al.* 2006; Joseph *et al.* 2017). Raptors and corvids often use power lines (including the ones that often run parallel to roads) as perching sites, which may increase their ability to detect and use carrion (Knight and Kawashima 1993; Meunier *et al.* 2000). Likewise, medium-sized carnivores often use anthropogenic linear features, like power line clearings and road verges, for foraging and/or travel (Frey and Conover 2006; Andersen *et al.* 2017; Raiter *et al.* 2018).

Previous studies showed that some opportunistic vertebrate species actively search for carrion or prey within LI rights-of-way, particularly along roads (e.g., Dean *et al.* 2006; Lambertucci *et al.* 2009; Silva *et al.* 2019). However, it has not been properly investigated whether the vertebrate scavenger guilds and their feeding behaviour change under LI influence (compared to control areas), and whether these potential differences in scavenger identity and activity indeed lead to lower persistence of LI-related bird carcasses. In fact, it can also be hypothesized that predation rates may be reduced within LI rights-of-way as vertebrate scavengers may avoid these areas because of potential disturbance (by vehicle traffic in the case of roads) and exclusion effects (Bautista *et al.* 2004; Benítez-López *et al.* 2010; Tyler *et al.* 2014; Donázar *et al.* 2018).

Here, we investigate the effect of two types of LI, namely transmission power lines and roads, on vertebrate scavenging patterns in two Mediterranean agricultural landscapes, by comparing scavenger identity and carcass persistence under LI influence with nearby control areas. Moreover, we examine if the observed patterns are explained by differences in scavenger efficiency, namely if scavenger identity determined (i) carcass detection (i.e., elapsed time until the first scavenging event); (ii) the likelihood of detectable remains being present after the scavenging event; and, ultimately, (iii) carcass persistence (i.e., elapsed time until the carcass or its remains are no longer detectable).

5.2. Methods

5.2.1. Study areas

The study was conducted in two agricultural landscapes in Central/Southern Portugal, with different management regimes and distanced ca. 90 km apart (Figure 5.1).

The first study area (V. F. Xira) is located within a relatively intensive agricultural area, surrounding the Tagus Estuary. Land use is dominated by irrigated rice fields, summer horticultural and cereal crops (mainly tomatoes, melons and maize) and livestock pastures. This study area also comprises a dense network of artificial water channels and non-asphalted roads, a main National road and several transmission and distribution power lines.

The second study area (Évora) is located in a far less intensive farmland. It is dominated by an agro-silvo-pastoral system formed by open Cork oak (*Quercus suber*) and Holm oak (*Q. rotundifolia*) woodlands with natural or cultivated pastures in the undercover (so-called Montados), interspersed with permanent pastures and dry cereal crop-fallow lands, often used for extensive grazing practices. This study area has a lower density network of roads and power lines, compared to the ones of V. F. Xira region.

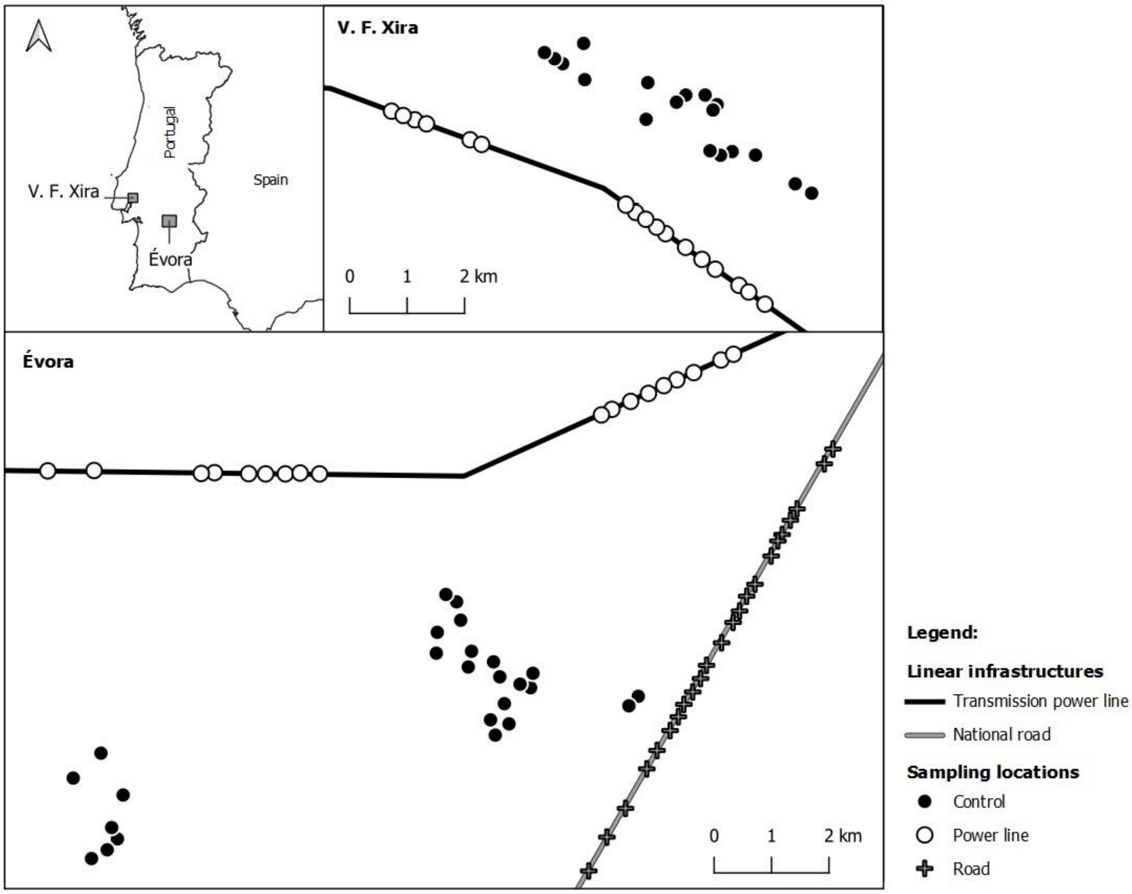

Figure 5.1 - Sampling locations of carcass persistence experiments conducted in V. F. Xira and Évora regions, during the winter periods of 2017 and 2018, respectively. Sampling locations separated less than 200 m apart were never used simultaneously.

5.2.2. Experimental set-up

To control for seasonal variations on carrion removal, we implemented carcass persistence experiments during the 2017 and 2018 winter periods (from January to mid-April) at V. F. Xira and Évora regions, respectively. During the experiments, the average daily temperature was 14.1ºC [7.1-23.6] in V. F. Xira and 10.9ºC [3.5-19.9] in Évora; the monthly average precipitation was, respectively, 66.1 mm [4.7-97.8] and 94.9 mm [48.5-172.5] (IPMA 2017, 2018).

In both regions, the experiments were conducted along a PL right-of-away (PL treatment) and in a nearby reference (control) area. In Évora region, the experiment further included the right-of-way of a two-lane paved road (Road treatment), with relative low-traffic volume (ca. 3700 vehicles per day and ca. 500 vehicles per night, on average (E.P. 2005)) . Power lines included in both experiments were transmission lines (>110 kV), supported by metal-lattice towers with two parallel shield wires on top, but distinct arrangement of conductors and total height (V. F. Xira: 400 kV double circuit, with 6 conductors arranged in three levels, tower height = 55-60 m; Évora: 150 kV single-circuit; with 3 conductors arranged in a single level, tower height = 30-35 m). Control locations were located at least 500 m from paved roads and transmission power lines and 200 m from distribution (≤60 kV) power lines.

We placed 250 free-ranged quail (*Coturnix coturnix*) carcasses (50 carcasses per region and treatment level) purchased from a local breeder. All carcasses were kept frozen from the moment they died until the day of placement and always handled using gloves to avoid traces of human scent. PL carcasses were placed below the power line wires to simulate natural collisions; whereas, road carcasses were placed on the road verge (but ≤5 m from road surface limits) to avoid carcass depletion by passing vehicles. Each carcasses was monitored with motion activated infrared cameras (Cuddeback Long Range IR 1224 or ACORN LTL-3310A). Cameras were set up to take time-lapse photos every hour and three sequential photos when triggered by motion, with a forced timeout delay of 1 min between trigger events. Each carcass was monitored up to a maximum of 21 days, or until it was removed by scavengers or decay to the point that we could not detect them (i.e., when we could not locate body parts containing flesh or bone, or ≥10 disarticulated feathers; Smallwood *et al.* 2010). Every camera was visited once a week to confirm carcass presence (or any detectable remains), replace camera batteries, and swap memory cards (to prevent data loss due to camera theft). Whenever a carcass was removed, the retrieved camera was relocated to a new sampling location and a new carcass placed. The same sampling location was not reused unless more than 7 days had passed since the complete removal of the previous carcass.

Carcass locations, within each treatment and control area, were selected in order to guarantee that carcasses were distanced apart at least 200 m, to avoid a potential saturation of the area with carrion (Stevens *et al.* 2011; Costantini *et al.* 2017), and distributed evenly among land uses (V. F. Xira: livestock pastures, horticultural crops and cereal crops; Évora: montado and fallow fields). The proportion of carcasses placed in each land use was not exactly the same across treatment and control areas (Supplementary material, Table S 5.1). To exclude the possibility of confounding effect caused by land use (e.g., one land use being more abundant in controls than in PL or Road treatments), potential differences in land uses among treatments were assessed through a Pearson's Chi-square test, with p-values determined by Monte Carlo simulations (2000 replicates). We found no evidence of significant differences in land uses among treatments (V. F. Xira: $\chi^2 = 4.38$, p = 0.122; Évora: $\chi^2 = 0.213$, p = 0.941). Since the experiments were performed during winter periods, all carcass locations were characterized by short-grass vegetation, typically with a large amount of bare soil. The undercover gradually became denser throughout the season in all land uses, but never to the point where carcass visibility from the air was significantly compromised. Forest cover was absent in all land uses except in Montado (Évora region), where the tree density was also relatively low.

5.2.3. Data analysis

We examined all motion-activated and time-lapse photos to determine, for each carcass: (1) the elapsed time until a scavenging event; (2) the vertebrate species responsible for the scavenging event; (3) the presence/absence of detectable carcass remains after the scavenging event, and (4) the elapsed time until the carcass or its remains were no longer detectable. We considered the scavenging events to be independent if more than 30 min had elapsed between consecutive photos of the same scavenger species at the same location. Camera/carcass weekly checks were used to confirm presence/absence of detectable carcass remains (after a scavenging event) and/or time elapsed until remains were no longer detectable, whenever that information could not be extracted from the time-lapse photos. For the analyses, we clustered scavenging species into four main groups: “Raptors”, “Corvids”, “Carnivores” and “Domestic animals”. Although we observed the presence and activity of invertebrate scavengers and rodents (on 5 occasions), these groups were excluded from the analyses since cameras (due to limitations in the sensors) did not capture these events consistently.

All statistical analyses were conducted in R v. 3.6.1 (R Core Team 2019). The proportion of scavenging events carried out by each scavenger group, in LI treatments and control areas, was compared using the Pearson's Chi-square test, with p-values determined by Monte Carlo simulations (2000 replicates) (using the function $Boot$ from R-package car).

To investigate differences in carcass detection (i.e., elapsed time until the first scavenging event) and carcass persistence (i.e., elapsed time until the carcass or its remains were no longer detectable), we used survival analyses (using the R-package $survival$), which can handle interval- and right-censored time-to-event data (Therneau 2019). Recorded detection and persistence times were frequently either interval-censored, due to camera trap failure to record the exact scavenging time, or right-censored, because some carcasses persisted until the end of the experiments. We fitted accelerated failure time (AFT) models using the parametric distribution among the ones most commonly used in carcass persistence models - namely, exponential, Weibull, log-logistic and log-normal (Bispo *et al.* 2013b; Dalthorp *et al.* 2018) - that best described carcass detection/persistence times, based on Akaike Information Criterion (see Supplementary material, sub-section 5.7.2). To assess LI effect on carcass persistence, we fitted separate AFT models for the V. F. Xira and Évora regions, both including 'Treatment' (Control, Power line, Road) as an explanatory variable. To investigate differences in scavenger efficiency, we modelled the two response variables (carcass detection and carcass persistence) as function of the explanatory variable 'Scavenger_group' (Raptors, Corvids, Carnivores, Domestic animals). Both AFT models also included 'Treatment_ID' (with categories V. F. Xira/Control, V. F. Xira/Power line, Évora/Control, Évora/Power line and Évora/Road) as a frailty term (equivalent to the inclusion of a random effect; Gutierrez 2002), to account for non-independence between carcasses within the same region and treatment level. To test the overall significance of the explanatory variables, we compared full models against the corresponding null models using a likelihood ratio test (see Supplementary material, sub-section 5.7.3). The accuracy of the parameters obtained for each final model was evaluated based on 2000 boot-resamples of the original dataset (using the function $Boot$ from R-package car). To visualize the results, carcass persistence curves and restricted mean detection/persistence times (± standard error, s.e.) were estimated non-parametrically using the Kaplan-Meier estimator (Kaplan and Meier 1958).

To determine whether the presence/absence of detectable carcass remains after the first scavenging event was significantly different from chance level (probability of 0.5), we performed exact binominal tests, separately for each scavenger group (using the function $\mathrm{binom.test}$ from R-package $stats$).

5.3. Results

In total, we recorded 256 independent scavenging events (Table 5.1). At least 14 species of vertebrate scavengers exploited the monitored quail carcasses (8 species in V. F. Xira, and 11 species in Évora), with Red fox (*Vulpes vulpes*) being the most common scavenger in both regions. The identity of the scavenger was unknown for 77 scavenging events (30.1%), mostly due to camera failure (e.g., humidity and condensation on the lens). From a total of 250 carcasses monitored, only six (12.0%) were never scavenged by vertebrate species during the 21-day experiments. On average, carcasses took 4.60 ± 0.36 days to completely disappear, i.e., to reach to the point at which no carcass parts remained to be detected.

Table 5.1 - Number (and percentage) of independent scavenging events detected by vertebrate species for each treatment during the carcass persistence experiments conducted in V. F. Xira and Évora regions (winter periods of 2016/17 and 2017/18, respectively). Treatment: CO – Control; PL – Power line; RO – Road.

Scavenger group / species	V. F. Xira		Évora			Total
	CO	PL	CO	PL	RO	
Raptors	**21 (42%)**	**4 (8%)**	**2 (4%)**	**1 (2%)**	**2 (4%)**	**30 (11.7%)**
Buteo buteo	3 (6%)	2 (4%)	-	1 (2%)	1 (2%)	7 (2.7%)
Circus aeruginosus	16 (32%)	2 (4%)	-	-	-	18 (7.0%)
Circus cyaneus	1 (2%)	-	-	-	-	1 (0.4%)
Falco tinnunculus	1 (2%)	-	-	-	-	1 (0.4%)
Milvus milvus	-	-	2 (4%)	-	1 (2%)	3 (1.2%)
Corvids	**3 (6%)**	**11 (22%)**	**6 (12%)**	**6 (12%)**	**3 (6%)**	**29 (11.3%)**
Corvus corax	-	-	1 (2%)	1 (2%)		2 (0.8%)
Corvus corone	3 (6%)	11 (22%)	2 (4%)	1 (2%)	1 (2%)	18 (7.0%)
Pica pica	-	-	3 (6%)	4 (8%)	2 (4%)	9 (3.5%)
Carnivores	**9 (18%)**	**27 (55%)**	**34 (65%)**	**21 (40%)**	**19 (36%)**	**110 (43.0%)**
Genetta genetta	-	-	3 (6%)	5 (10%)	1 (2%)	9 (3.5%)
Herpestes ichneumon	-	2 (4%)	-	5 (10%)	-	7 (2.7%)
Martes foina		-	6 (12%)	-	4 (8%)	10 (3.9%)
Vulpes vulpes	9 (18%)	25 (51%)	25 (48%)	11 (21%)	14 (26%)	84 (32.8%)
Domestic animals	**1 (2%)**	**-**	**-**	**1 (2%)**	**8 (15%)**	**10 (3.9%)**
Canis lupus familiaris	-	-	-	1 (2%)	-	1 (0.4%)
Felis catus	1 (2%)	-	-	-	8 (15%)	9 (3.5%)
Unknown	**16 (32%)**	**7 (14%)**	**10 (19%)**	**23 (44%)**	**21 (40%)**	**77 (30.1%)**
Total	**50 (100%)**	**49 (100%)**	**52 (100%)**	**52 (100%)**	**53 (100%)**	**256 (100%)**

5.3.1. LI effect on scavenger identity and carcass persistence

The identity of the scavenger species that used the carcasses varied among LI treatments within the same region (Figure 5.2 A). In V. F. Xira, the proportion of scavenging events carried out by each scavenger group varied noticeably between control and PL locations (χ^2 = 24.9, df = 2, p

<0.001). Within PL right-of-way, cameras captured the carcasses being mostly scavenged by Carnivores (64.3%), followed by Corvids (26.2%) and Raptors (9.5%); whereas, in control locations, the majority of the carcasses were scavenged by Raptors (61.8%), followed by Carnivores (26.5%) and Corvids (8.8%). In contrast, the proportion of scavenging events carried out by each scavenger group did not differ significantly between control and PL locations in Évora (χ^2 = 3.28, df = 3, p = 0.39), with most of the scavenging being carried out by Carnivores (72.4 - 81.0%), followed by Corvids (14.3 - 20.7%) and Raptors (3.4 - 4.8%). Nonetheless, the proportion of scavenging events carried out by each scavenger group differed significantly between control and Road locations (χ^2 = 10.72, df = 3, p<0.006), where Domestic animals were responsible for 25.0% of the scavenging events, with a consequent decrease in the proportion of carcasses scavenged by Carnivores (59.4%) and Corvids (9.4%).

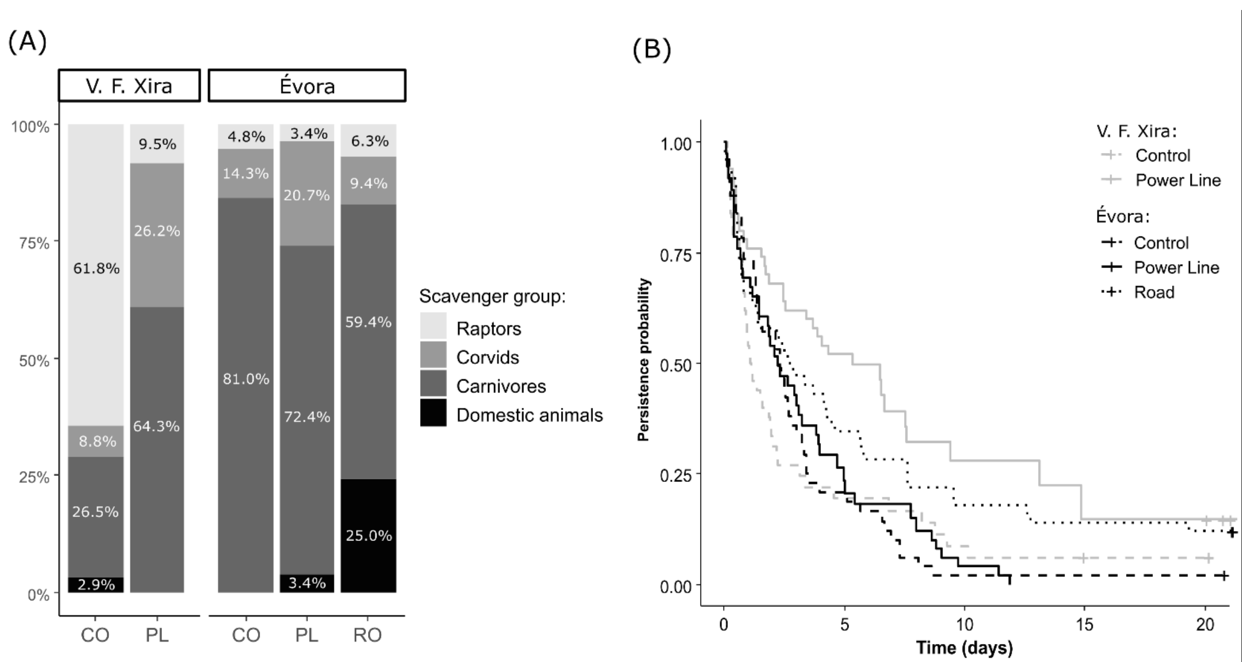

Figure 5.2 - Linear infrastructure effect on (A) the proportion of scavenging events carried out by each scavenger group and (B) the carcass persistence probability, in V. F. Xira and Évora regions. CO – Control; PL – Power line treatment; RO – Road treatment.

Carcass persistence (i.e., elapsed time until the carcass or its remains were no longer detectable) was also significantly affected by LI treatment (V. F. Xira: χ^2 = 10.6, df = 1, p= 0.0011; Évora: χ^2 = 10.4, df = 2, p= 0.0056), but differently depending on the region (Table 5.2; Figure 5.2 B). In V. F. Xira, PL presence was associated with higher carcass persistence (mean time: 7.32±0.96 days), when compared to control locations (mean time: 3.32±0.71 days) (Figure 5.2 B). This pattern was not observed in Évora, where carcass persistence was not significantly affected by PL presence (mean time: 3.37±0.46 days), compared to control locations (mean time: 3.07±0.47 days). On the other hand, carcasses placed on road verges (Évora) tended to persist longer (mean time: 5.60±0.93 days), than the ones placed below the PL or at controls.

Table 5.2 - Parameters and bootstrap results of best accelerated failure time models to predict (A) carcass persistence as function of power line or road treatment in V. F. Xira and Évora regions (models A1 and A2, respectively), and (B) carcass detection and carcass persistence as function of scavenger group (model B1 and B2, respectively).

Best Accelerated Failure Time (AFT) models selected based on the lowest Akaike Information Criteria (AIC) statistic (see Supplementary material). In AFT models, the coefficients are logarithms of ratios of survival times, so higher (positive) coefficients mean longer times to carcass detection or overall persistence. Reference levels: 'Control' for models (A); 'Raptors' for models (B).

			Coefficient		**p-value**	
Model	**Response Variable**	**Explanatory variable**	**Original**	**Bootstrap Median [95% CI]**	**Original**	**Bootstrap Median [95% CI]**
A1	Carcass persistence	Treatment - V. F. Xira				
		intercept	0.33	0.31 [-0.04 – 0.79]		
		Power line	1.07	1.08 [041 – 1.67]	<0.001	<0.001 [<0.001- 0.31]
A2	Carcass persistence	Treatment - Évora				
		intercept	1.07	1.07 [0.78 – 1.47]		
		Power line	0.04	0.05 [-0.42 – 0.44]	0.853	0.507 [0.527 – 0.999]
		Road	0.72	0.72 [0.14 – 1.28]	0.004	0.003 [<0.001 – 0.634]

Table 5.2 (continued).

Model	Response Variable	Explanatory variable	Coefficient Original	Coefficient Bootstrap Median [95% CI]	p-value Original	p-value Bootstrap Median [95% CI]
B1	Carcass detection	Scavenger group				
		intercept	0.49	0.51 [0.13 - 0.88]		
		Corvids	0.35	0.24 [-0.17 - 1.26]	0.213	0.298 [<0.001 - 0.884]
		Carnivores	0.75	0.71 [-0.33 - 1.19]	<0.001	0.002 [<0.001 - 0.158]
		Domestic animals	1.01	0.92 [0.16 - 2.05]	0.011	0.028 [<0.001 - 0.518]
B2	Carcass persistence	Scavenger group				
		intercept	1.37	1.38 [0.81 - 1.94]		
		Corvids	0.04	0.02 [-0.71 – 0.80]	0.889	0.439 [0.705 - 0.999]
		Carnivores	0.05	0.04 [-0.53 – 0.67]	0.847	0.479 [0.527 - 0.998]
		Domestic animals	1.25	1.24 [0.27 - 2.70]	0.014	0.019 [<0.001 - 0.719]

5.3.2. Scavenger efficiency

Carcass detection (i.e., elapsed time until the first scavenging event) varied significantly among scavenger groups (χ^2 = 18.4, df = 3, p<0.001; Table 5.2). In general, avian scavengers tend to detect the carcasses sooner (mean time: 1.93 ±0.39 days) than mammalian ones (mean time: 3.59±0.34 days) (Figure 5.3 A).

After the first scavenging event, most of the sampling locations (77.0%) were left without any evidence of the carcass. However, the presence of detectable carcass remains depended on the scavenger group (Figure 5.3 B). Detectable remains (hereafter denoted as DR) were significantly less likely to be present if the carcass was scavenged by Raptors ($P(DR)$ = 0.25, 95% CI: 0.11-0.45; Exact binomial test: p = 0.012) or Carnivores ($P(DR)$ = 0.08, 95% CI: 0.04-0.15; Exact binomial test: p <0.001). For Corvids, the likelihood of leaving carcass remains after the scavenging event was not different from random ($P(DR)$ = 0.53, 95% CI: 0.33-0.73; Exact binomial test: p = 0.845). Domestic animals showed a higher probability of leaving carcass remains ($P(DR)$ = 0.67, 95% CI: 0.30-0.92), although it was not significantly different from chance level (0.50) (Exact binomial test: p = 0.508).

Overall, carcass persistence (i.e., elapsed time until the carcass or its remains were no longer detectable) also varied among scavengers' groups (χ^2 = 48.3, df = 3, p<0.001), although with a different pattern from the observed for carcass detection (Table 5.2). Compared to the first model, there were no longer significant differences between carcasses first scavenged by birds (Raptor or Corvids) and Carnivores (mean time: 3.98±0.36 days), but carcasses scavenged by Domestic animals (cats and dogs) still tended to persist significantly longer (mean time: 9.51±2.69 days) (Figure 5.3 A).

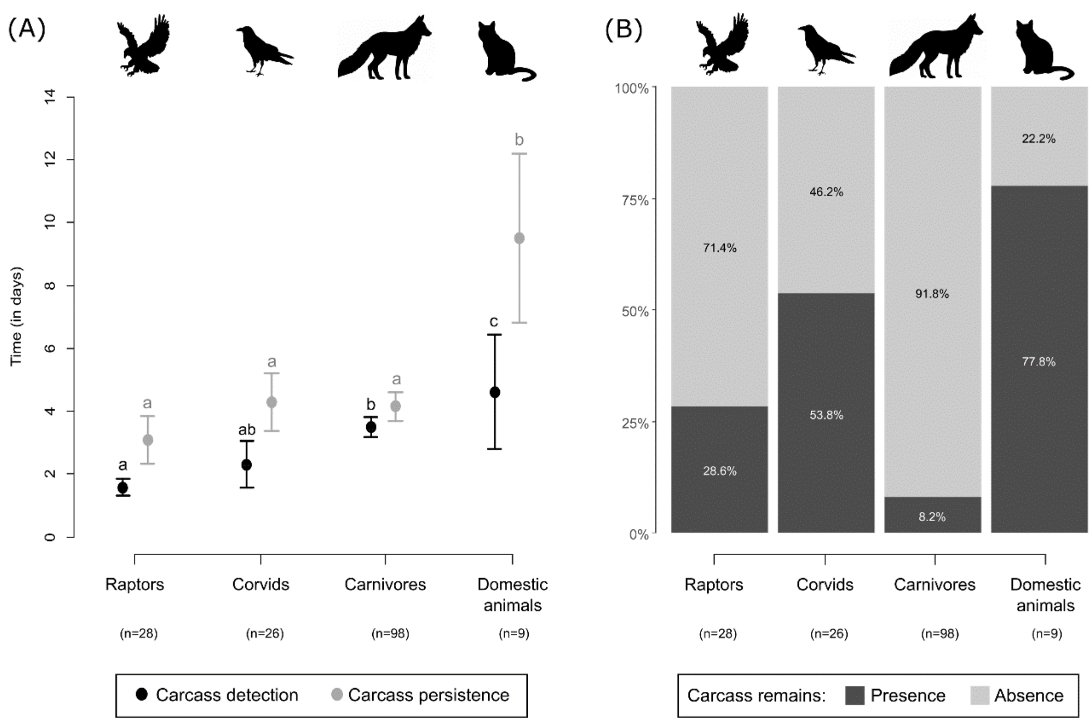

Figure 5.3 - Scavenger identity effect on (A) the mean (± standard error) carcass detection and persistence time; and (B) proportion of cases with presence vs. absence of detectable carcass remains after the first scavenging event.

Whiskers topped by different letters indicate significant differences ($p < 0.05$) between scavenger groups in carcass detection (black letters) and carcass persistence (grey letters). Number of scavenging events for each scavenger group is contained in parentheses.

5.4. Discussion

We found that carcasses were detected and removed by scavengers at high rates in both our study regions. This pattern of rapid scavenging has previously been observed in road verges and power lines that bisect agricultural landscapes (e.g., Ponce *et al.* 2010; Guinard *et al.* 2012; Borner *et al.* 2017), as well as for other anthropogenic sources of bird mortality, like wind farms, fences and pesticides (e.g., Linz *et al.* 1997; Stevens *et al.* 2011; Farfán *et al.* 2017).

5.4.1. LI effect on scavenger identity and carcass persistence

Several studies showed that both avian and mammal scavengers actively forage within LI rights-of-way due an increased likelihood of finding carrion (e.g., Dean *et al.* 2006; Lambertucci *et al.* 2009; Silva *et al.* 2019). Yet, few have investigated whether carcass persistence rates are reduced indeed, particularly in the case of power lines. In our study, the presence of the PL had either none or a positive effect on carcass persistence. In Évora region, there were no significant differences between the PL treatment and control areas, with carnivores being the most common scavengers in both cases. Hill *et al.* (2018), which performed a similar carcass persistence experiment during winter but in forested habitats, also observed almost no differences in scavenger species identity, as well as in the proportion of carcasses scavenged within power line clearings, compared to control areas. A possible explanation, hypothesized by Borner *et al.* (2017), is that scavenger behaviour may be less predictable under power lines because mortality due to collision with wires may be less frequent than mortality on roads.

In V. F. Xira region, however, a completely different scavenging pattern was observed, with the proportion of scavenging events carried out by each scavenger group being significantly different between control and PL locations. Western marsh harriers (*Circus aeruginosus*), abundant in this study region (Lourenço 2009), removed a large proportion of carcasses placed in the control area, at very high rates (see next sub-section, Scavenger efficiency), likely leaving few carcasses for carnivores or other scavengers. In turn, scavenging within the PL right-of-way was mostly carried out by carnivores, and at slower rates, most probably due to the reduced number of scavenging events (n=2) by marsh harriers. Unlike other sympatric raptors (e.g., buzzards), that often use PL and other structures as hunting perches, marsh harriers forage primarily through cruising flights (Simmons 2000), which may explain why the species did not take advantage of PL right-of-way. A similar response to PL presence was noted by DeGregorio *et al.* (2014), that investigated how different landscape features influenced the risk of avian nest predation. These authors observed that, although raptors and crows occurred in high densities near power lines (compared to control areas), raptors were more likely to prey on nests away from power lines.

Because roads are seen as a readily available source of carrion (Slater 2002; Dean *et al.* 2006; Joseph *et al.* 2017), we expected carcass removal rates to be more pronounced within road rights-of-way (even after controlling for carcass removal caused by traffic or other environmental factors). This common assumption was, however, contradicted by the carcass removal patterns observed in Évora region, with carcasses placed on road verges taking more time to be removed compared to carcasses in control locations. This same assumption has also been partially refuted by Lambertucci *et al.* (2009), which investigated the foraging space use of an assemblage of diurnal scavenging raptors in relation to distance from roads in northwest Patagonia. In general, carcasses near roads were detected and removed by diurnal scavenging raptors much faster, but some raptor species (condors and buzzard-eagles) preferred to feed further away from roads, even though they flew all over the area. Hill *et al.* (2018) also found that the scavenger community overall did not show a substantial response to roads and that the proportion of carcasses removed, as well as scavenger arrival time, were similar to controls. In our case, the higher persistence rates near roads were associated to a higher proportion of scavenging events carried out by domestic animals, which tended to remove the carcasses more inefficiently (see next Sub-section, Scavenger efficiency).

5.4.2. Scavenger efficiency

Small- and medium-sized carcasses, like the ones tested in this study (quails), are often used by a diverse assemblage of facultative scavengers, i.e., vertebrate predators that opportunistically scavenge on fresh carrion when available (DeVault *et al.* 2003; Beasley *et al.* 2015). Indeed, in our study, most scavenging events were carried out by meso-predators, with red foxes being responsible for almost half of the scavenging events recorded (V. F. Xira: 44.7%; Évora: 48.5%). Although the overall proportion of carcasses consumed by raptors and corvids was smaller (16.8% and 16.2%, respectively), both groups tend to detect the carrion sooner (lower times to first scavenging event) than other groups, probability because avian predators travel long distances while foraging and use their visual perception to find carrion, which is particularity effective in open habitats (DeVault *et al.* 2003; Peisley *et al.* 2017). Conversely, mammal scavengers rely mostly on their olfactory perception to locate carrion and use the decomposition odour as their dominant stimulus, which takes longer to become marked in winter periods (DeVault and Rhodes 2002; Turner *et al.* 2017).

Several studies found a positive relationship between carcass size and persistence rates, as result of the inability of some scavengers to deal with large carcasses and because small carcasses can be exploited by a greater number of species (e.g., Flint *et al.* 2010; Smallwood *et al.* 2010; Farfán *et al.* 2017; Riding and Loss 2018). In our study, carcasses were relatively small and weighted only 100 gr, therefore they could easily be removed by medium-sized scavengers. The way carrion was consumed differed, however, among scavenger groups. Carnivores and raptors tend to remove the carcass completely, while corvids and domestic animals (cats and dogs) had equal or higher probability of leaving carcass parts or feather piles behind, as a result of consuming the carcass *in situ*. Previous studies support the idea that meso-carnivores and diurnal raptors tend to remove carrion more efficiently, while ravens and magpies forage in groups and prefer to take small pieces of the carcass, leaving feather piles or other carcass remains scattered around the site (Hiraldo *et al.* 1991; Peisley *et al.* 2017). Carcass persistence experiments conducted in urban environment by Hager *et al.* (2012) and Riding & Loss (2018) revealed, however, different scavenging behaviours. In both studies, raccoons, opossums and corvids were observed consuming small avian carcasses resulting from window-collisions mainly at the initial site, whereas cats and squirrels carried carcasses away. These contradicting results suggest that the feeding behaviour within a same scavenger group, particularly across medium-sized carnivores, may vary greatly depending on the species, season and landscape.

In our study, carnivores (mostly red foxes) consistently left no remains of the carcass after the predation event, but took longer to detect the carrion. Thus, the overall persistence time estimated for carcasses scavenged by carnivores was not significantly different from that estimated for carcasses scavenged by corvids (which find carcasses faster but are likely to leave carcass remains behind) or even by raptors (which also find carcasses quickly and leave almost no scavenging evidence). Still, and overall, carcasses scavenged by carnivores and corvids showed higher persistence times (mean time: 4.29±0.38 days) compared to raptors (3.08±0.75 days), which explains the higher persistence probability observed within the PL right-of-way in V. F. Xira region. In this study region, these two groups together were responsible for the majority (90.5%) of the scavenging events in the PL right-of-way, while, in the control area, carcasses were predominantly scavenged by raptors (61.8%). Domestic animals, on the other hand, tend to detect the carcass later and, moreover, leave detectable remains behind, which explains the higher carcass persistence rate observed at the road right-of-way in Évora region (where dogs were responsible for a relative high proportion of the scavenging events, compared to PL treatment and controls).

Our experiments were carried out during winter, but seasonal changes in scavenging efficiency are likely to occur (e.g., Prosser *et al.* 2008; Costantini *et al*. 2017; Borner *et al.* 2017). For example, carnivores' ability to locate carrion is expected to increase with higher temperatures during spring and summer, when olfactory cues are more marked due to decomposers' activity (DeVault and Rhodes 2002; Turner *et al.* 2017). This can potentially lead to an overall decrease of carcass persistence, particularly in areas where carcasses were mostly consumed by mammals. Moreover, competition for carcasses between avian scavengers, mammalian meso-predators, rodents and invertebrates is expected to increase in warmer months (DeVault *et al.* 2011; Olson *et al.* 2016).

5.4.3. Implications for bird fatality estimates

Our research provides new insights on the importance of vertebrate scavenging as a source of bias in bird fatality surveys in LI rights-of-way. Similarly to studies conducted in temperate regions, small-bird carcasses were removed at high rates by vertebrate scavengers, often without leaving a trace of evidence. However, carcass persistence can still vary greatly across regions. For instance, carcass persistence within PL right-of-way was considerably higher in V. F. Xira (mean time: 7.32±0.96 days), compared to Évora (mean time: 3.37±0.46 days). According to the recently developed "Generalized Estimator" (GenEst) software (Dalthorp *et al.* 2018), in a scenario of weekly carcass searches, the estimated probability of a small carcass persisting until the day of the search is 0.58 in V. F. Xira, but decreases to 0.43 in Évora. This means that, one would have to multiply the number of bird carcasses found by a factor of 1.7 in V. F. Xira and 2.3 in Évora, to obtain the corresponding bird fatality estimates adjusted for scavenging bias. This shows the extent to which bird fatality estimates are affected by the magnitude of scavenging-bias correction factor obtained for each individual LI project, and reinforces the need for site-specific experiments that characterize the local scavenging rates.

Our results, combined with previous literature, also show that broad generalizations about power line and road effect on scavenging patterns and their cascading effects on carcass persistence may not be appropriate. LI effect on carcass persistence is likely once again to be region-specific and driven by the identity of the local scavenger species, as well as by their inherent ability to find and efficiently remove (or not) carrion from LI rights-of-way. In our study, for instance, the differences in carcass persistence observed between the PL and control areas in V. F. Xira (located near an important wetland) are most probably explained by the high abundance of marsh harriers in the region and their species-specific response to PL right-of-way. Nevertheless, further research on scavenging ecology under LI influence, may help identify the most prevalent carcass persistence patterns across the different types of LI and land uses.

In our study, and contradicting common assumptions, we found no evidence that the presence of a LI increases carcass removal rates due to scavenging by opportunistic vertebrate species. In both agricultural landscapes, LI effect (if present) was positive for carcass persistence, which means that carcasses placed, for instance, next to roads were not removed faster than the ones placed in controls. This unexpected result suggests that bias in small- to medium-sized bird mortality estimates resulting from scavengers' activity at roads may be negligible at times, particularly when compared to carcass removal rates driven by high vehicle-traffic (Ratton *et al.* 2014; Santos *et al.* 2016a).

Finally, our findings may also contribute for a better planning and design of future carcass persistence experiments in bird-fatality monitoring programmes, particularly the ones conducted in power lines. To comply with a pre-established trial sample size, technicians may feel tempted to saturate the power line right-of-way with carcasses - which may induce scavenger swamping (Linz *et al*. 1991; Smallwood *et al.* 2010) - or, alternatively, to place additional carcasses in nearby locations. Our results show that placing trial carcasses outside the LI right-of-way, even in locations with relatively similar habitat features, may lead to biased persistence rates. For instance, in one of our study regions (V. F. Xira), the use of carcass removal data from the control area to adjust the observed bird casualties within the PL right-of-way (assuming, e.g., weekly carcass searches) would have resulted in >2-fold higher bird fatality estimates. Thus, the implementation of carcass persistence experiments outside the PL right-of-way should be, as much as possible, avoided. The appropriate sample size for estimating carcass persistence should be assured through careful planning of the experiments and by placing carcasses, if necessary, spaced out in time, so scavenger swamping can be avoided (Huso *et al.* 2016a).

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5.7. Supplementary material

5.7.1. Land use among linear infrastructure treatments and controls

Table S 5.1 - Number (and percentage) of carcasses placed by land use across treatment and control areas in V. F. Xira and Évora regions.

Region	Land use	Control	Power line	Road
V. F. Xira	Livestock pastures	19 (38%)	29 (58%)	-
	Horticultural crops	13 (26%)	7 (14%)	-
	Cereal crops	18 (36%)	14 (28%)	-
	TOTAL	50 (100%)	50 (100%)	-
Évora	Montado	24 (48%)	24 (48%)	26 (52%)
	Fallow fields	26 (52%)	26 (52%)	24 (48%)
	TOTAL	50 (100%)	50 (100%)	50 (100%)

5.7.2. Selection of best parametric distribution for each accelerated failure time model

Table S 5.2 - Selection of best parametric distribution (using Akaike Information Criterion, AIC) for the accelerated failure time model to assess 'LI treatment' effect on carcass persistence in V. F. Xira region.

Distribution	K	AIC	Δ_{AIC}	AIC weight
Log-normal	3	414.70	0.00	0.58
Log logistic	3	415.38	0.68	0.41
Weibull	3	424.29	9.59	0.00
Exponential	2	441.48	26.77	0.00

K – number of parameters; Δ_{AIC} – difference in AIC relative to the highest ranked model.

Table S 5.3 - Selection of best parametric distribution (using Akaike Information Criterion, AIC) for the accelerated failure time model to assess LI treatment effect on carcass persistence in Évora region.

Distribution	**K**	**AIC**	**ΔAIC**	**AIC weight**
Weibull	4	688.15	0.00	0.62
Log-normal	4	690.40	2.25	0.20
Log-logistic	4	691.19	3.04	0.14
Exponential	3	693.76	5.61	0.04

K – number of parameters; Δ_{AIC} – difference in AIC relative to the highest ranked model.

Table S 5.4 - Selection of best parametric distribution (using Akaike Information Criterion, AIC) for the accelerated failure time model to assess 'Scavenger group' effect on carcass detection.

Distribution	**K**	**AIC**	Δ_{AIC}	**AIC weight**
Exponential	4	674.09	0.00	0.71
Weibull	5	675.89	1.80	0.29
Log-normal	5	688.11	14.01	0.00
Log-logistic	5	690.48	16.38	0.00

K – number of parameters; Δ_{AIC} – difference in AIC relative to the highest ranked model.

Table S 5.5 - Selection of best parametric distribution (using Akaike Information Criterion, AIC) for the accelerated failure time model to assess 'Scavenger group' effect on carcass persistence.

Distribution	**K**	**AIC**	Δ_{AIC}	**AIC weight**
Log-normal	5	715.53	0.00	0.56
Weibull	5	717.02	1.48	0.27
Log-logistic	5	717.95	2.42	0.17
Exponential	4	724.11	8.57	0.01

K – number of parameters; Δ_{AIC} – difference in AIC relative to the highest ranked model.

5.7.3. Results of the Likelihood ratio tests to compare full vs. null accelerated failure time models

Table S 5.6 - Results of the Likelihood ratio tests to compare the accelerated failure time models for 'LI treatment' effect on carcass persistence in V. F. Xira and Évora region, against the corresponding null models.

Model	**Deviance**	**df**	**p-value**
V. F. Xira	10.60397	1	0.0011
Évora	10.35518	2	0.0056

Table S 5.7 - Results of the Likelihood ratio tests to compare the accelerated failure time models for Scavenger group' effect on carcass detection and carcass persistence, against the corresponding null models.

Model	**Deviance**	**df**	**p-value**
Carcass detection	14.97233	3	0.0018
Carcass persistence	16.52639	3	0.0009

Chapter 6

General discussion

6. General discussion

The overall aim of this thesis is to deepen the knowledge about bird collisions with power lines and the existing mitigation measures, as well as contribute to the methodological improvement of the impact and mitigation monitoring programmes. Over the last decades extensive work has been carried out on the topic, both in R&D and post-EIA monitoring context. However, this body of evidence has hardly ever been integrated and/or systematically reviewed, something that I sought to overcome with this thesis.

Synthesising results across studies or analysing combined data from multiple projects is an important but often overlooked opportunity to zoom out from individual study findings and identify broad patterns or effects (Stewart 2010; Gurevitch *et al.* 2018). It is also an opportunity to evaluate the methodological strengths and limitations of the existing studies, in order to identify opportunities for improvement (e.g., Rytwinski *et al.* 2016; Conkling *et al.* 2020). Systematic literature reviews and meta-analysis are, therefore, powerful tools to summarise existing evidence and inform the decision-making, impact monitoring and mitigation of T&D power lines, which is the ultimate goal of the present thesis.

6.1. Overview of main findings

6.1.1. Drivers of bird collisions with power lines

In Chapter 2, we performed a systematic literature review on the driving factors of bird collisions with power lines, so EIA practitioners may better predict and address this impact in future T&D developments. We have shown that species-specific physiology, morphology, and ecology are often identified as key contributing factors to bird collision risk (51.3% of all studies compiled; Chapter 2, Figure 2.2). For instance, bustards (Otididae) are medium- to large-sized birds with relatively short wings and tails, which confer them low flight manoeuvrability (Rayner 1988; Janss 2000). Additionally, bustards' vision is characterised by small binocular fields and extensive blind areas in the frontal hemisphere (both above and below the bill), which can make them "fail to see" obstacles when flying in open airspace (Martin and Shaw 2010; Martin 2011). Thus, these biological traits have for long been identified as the main reasons why bustards are particularly prone to collisions with overhead wires, namely power and telephone lines, railway wires and fences (e.g., Alonso and Alonso 1999; Anderson 2002; Shaw *et al.* 2010a; Garcia-del-Rey and Rodriguez-Lorenzo 2011; Vadász and Lóránt 2014; Ashbrook *et al.* 2016).

However, a recent work conducted by Marques *et al.* (2021) showed how habitat and infrastructure features may also play an important role in bustard collision risk. The study concluded that collisions of Little Bustard (*Tetrax tetrax*) and Great Bustard (*Otis tarda*) were far more likely in power line sections that bisected open farmlands (>20% and >50% of open area for little and great bustard, respectively), and/or in power lines with taller pylons and higher number of vertical wire levels. Shaw *et al.* (2018) also found that the Ludwig's Bustard (*Neotis ludwigii*) collision hotspots on transmission lines were mainly explained by season (collisions more likely in winter) and rainfall (less likely in drier areas), and on distribution lines by season (again more likely during winter) and proximity to roads (more likely far away from roads). Hence, and based on the systematic review performed in Chapter 2, we concluded that species-specific collision risk factors frequently do not act alone but in complex interactions with site-specific and infrastructure-specific factors (Figure 6.1).

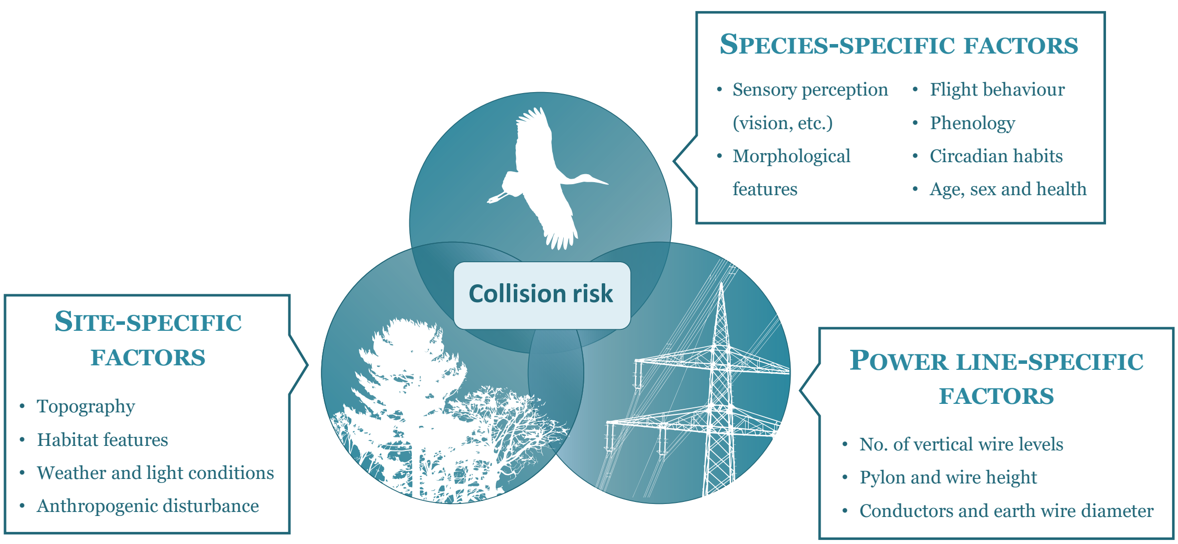

Figure 6.1 - Main driving factors of bird collision risk with power lines.

Site-specific factors that affect bird collision rates include topography, habitat features (e.g., vegetation, prey abundance), weather and light conditions (e.g., Faanes 1987; Savereno *et al.* 1996; Shimada 2001; Mojica *et al.* 2009; Demerdzhiev 2014). According to the systematic review, this group of collision risk factors was the second most studied over the last decades (34.0% of all studies compiled; Chapter 2, Figure 2.2). By contrast, infrastructure-specific factors are still poorly understood, with only 11.0% of the total number of studies evaluating (or merely mentioning) their potential contribution to bird collision risk. This was a rather important and surprising finding, as understanding the relative importance of the different power line features to bird collision risk is critical for a better prediction and mitigation of this impact in future T&D projects. The low number of studies addressing the topic is partially explained by the fact that the individual contribution of each power line feature (e.g., voltage, pylon height, cable diameter and arrangement, number of vertical wire levels) is hard to evaluate. For example, in most cases the number of vertical wire levels cannot be dissociated from other power line features, such as pylon and wires height. Thus, finding two power lines that bisect similar habitats and only differ, for instance, in the number of vertical wire levels (i.e., pylon height and spacing, cable diameter and arrangement are exactly the same) may be very difficult. Despite the technical challenges, further studies focusing on infrastructure-specific factors are of utmost importance, with power lines running parallel or retrofitting projects of existing power lines being a good opportunity to test such effects on bird collision rates (using *Control-Impact* and *Before-After* designs, respectively).

The predicted expansion of T&D grids worldwide, particularly in developing countries, raises several conservation concerns. Nonetheless, due to the increasing awareness about power line impacts on bird communities (e.g., Birdlife International 2015; Collar *et al.* 2017; Mahood *et al.* 2018), these new T&D developments may also be an opportunity for further (and surely needed) research in regions of the world other than Europe, North America and South Africa. According to the systematic review, studies outside these three main regions are uncommon (<15.0% of all studies compiled; Chapter 2, Figure 2.3). The expected expansion of T&D lines to different biomes (tropical forests, deserts, etc.) will, therefore, raise new questions and challenges for researchers and EIA practitioners, in terms of overall impact assessment but also potential new species-specific and site-specific bird collision drivers.

6.1.2. Mitigation measures and their effectiveness

The literature review in Chapter 2 revealed that, over the last decades, a wide range of mitigation measures have been proposed to reduce bird collisions with power lines. We were able to assemble them into five main categories: (1) underground cabling; (2) power line routing; (3) power line configuration; (4) wire-marking; and (5) habitat management. Although underground cabling is the only solution that completely prevents bird collisions, wire-marking is currently the mitigation measure most widely used because it is considered to be a generally effective measure, with relatively low implementation costs (APLIC 2012; Lobermeier *et al.* 2015; Moreira *et al.* 2018).

Indeed, the meta-analysis performed in Chapter 3 confirmed that the installation of wire-markers is associated with an overall decrease in bird collision rates. On average, wire-marking has reduced bird collisions with power lines by half (50.4%; 95% confidence interval: 40.4 - 58.8%). The meta-analysis also revealed, for the first time, some general effectiveness patterns, namely that wire-marking tends to be more effective in wetlands and flappers (devices with moving parts) generally perform better than static devices. Nonetheless, the estimated overall wire-marking effectiveness was considerably lower than the one previously estimated by Barrientos *et al.* (2011) (78%; 95% confidence interval: 55 - 94%). The inclusion of a high number of wire-marking experiments in our analysis (n = 66), compiled both from peer-reviewed articles and grey literature, also uncovered the presence of high heterogeneity in wire-marking effects across studies. This indicates that, similarly to bird collision risk, mitigation effectiveness is highly variable and dependent on target species (i.e., their vision, flight behaviour, circadian habits, etc.), site characteristics and, of course, wire-marking design.

These findings are relevant for applied researchers, T&D developers and EIA practitioners for three main reasons. First, they unravel the need to continue carrying out field experiments to address still unexplored or less understood aspects of wire-marking effectiveness, for example “what is the most cost-effective wire-marking scheme (spacing between markers, etc.)?”, or “what is the best performing device for each target species or group?”. Second, they underline the importance of keeping investing in the development and testing of alternative (but promising) approaches to increase wire visibility for birds, such as wire marking with self-illuminated devices (using LED lights) or near-ultraviolet light (e.g., Dwyer *et al.* 2019) to mitigate nocturnal bird collisions. Third, and perhaps the most important, the results of Chapters 2 and 3 highlight the fact that bird collisions must be tackled in multiple fronts, due to the complexity of ecological and technical issues involved in mitigation effectiveness. An effective mitigation will be difficult to achieve with a single solution (e.g., wire-marking), and will most likely require the combination of two or more measures, adapted to the specificities of each T&D infrastructure, study site and bird species potentially affected.

The literature review in Chapter 2 revealed, however, several important knowledge gaps in terms of the effectiveness of almost all mitigation measures besides wire-marking. Few studies have truly assessed the effect of alternative power line routes and/or configurations on bird collision rates (Beaulaurier 1981; Ward and Anderson 1992; Bevanger and Brøseth 2001; Infante et al. 2005; Marques et al. 2021) and, to my best knowledge, none have tested the effectiveness of habitat management measures (but see Heijnis (1980) and Janss *et al.* (1999) regarding the use of raptor silhouettes or decoys). These are notable research evidence gaps since all these measures are frequently included in best practice guidelines (e.g., Haas *et al.* 2005; APLIC 2012; Prinsen *et al.* 2012; EC 2018). A reduction in bird collision rates through habitat management may be challenging to achieve and even to test, as manipulating bird movements to significantly reduce power line crossings (and consequently collision risk) would require habitat modification on a large scale. In contrast, mitigation through enhanced power line routing and design is relatively feasible and expected to be very effective. Nonetheless, the extent to which these measures mitigate bird collisions with power lines has not been clearly established and, once again, is likely to be species- and site-specific. T&D grid extension and infrastructure upgrading may, however, offer a great opportunity for developers and researchers to test the effects of such measures on bird collision rates, like, for instance, when an existing power line is replaced by another one with a different route, or replaced by a power line within the same right-of-way but with a different pylon design.

6.1.3. Carcass persistence and searcher efficiency biases

In Chapter 2, based on the literature review and knowledge gaps that were identified, we presented a comprehensive list of research topics which still needed to be developed to better understand and address bird collisions with power lines. Among those was the "*development of methods to accurately estimate bird fatality (based on carcass searches) and related correction factors…*". Carcass removal (e.g., by scavengers) and imperfect detection by observers are very important sources of bias in wildlife fatality assessments (Bernardino *et al.* 2013; Barrientos *et al.* 2018; Huso 2019). Nonetheless, these two biases and associated correction factors – carcass persistence (CP) and searcher efficiency (SE) rates - are relatively understudied in the context of power lines, when compared to the volume of research dedicated to this topic in other infrastructures, such as wind farms (e.g., Bernardino *et al.* 2011; Villegas-Patraca *et al.* 2012; Smallwood 2013; Peters *et al.* 2014; Huso and Dalthorp 2014; Hallingstad *et al.* 2018; Domínguez del Valle *et al.* 2020), roads (e.g., Santos *et al*. 2011; Guinard *et al.* 2012; Teixeira *et al.* 2013;

Ratton *et al.* 2014; Skórka 2016; Schwartz *et al.* 2018) and windows (e.g., Hager *et al.* 2012; Kummer *et al.* 2016; Bracey *et al.* 2016; Riding and Loss 2018; Clarke *et al.* 2020). This means that CP and SE biases at power lines have been mainly assessed within the framework of post-EIA monitoring and, consequently, the results are not subjected to a peer-review process and often not publicly available (see discussion in Chapter 6.2).

In this context, in Chapter 4, we explored key ecological and methodological factors driving CP and SE within the rights-of-ways of 36 transmission lines in mainland Portugal. We found that bird carcasses or their remains had a median persistence time of 3.5 days (95% CI: 0.6 – 7.5 days). Larger bird carcasses tend to persist more time in the field, as found in previous studies (e.g., Ponce *et al.* 2010; Costantini *et al.* 2017; Farfán *et al.* 2017). However, differences between CP times of small, medium and large carcasses were significantly less marked during spring and early summer, probably because competition for carrion (by vertebrate scavengers, invertebrates and microbes) tends to increase during these seasons (DeVault *et al.* 2004; Henrich *et al.* 2017; Turner *et al.* 2017) and carcasses, regardless of their size, are easier to detect in warmer months by scavengers that rely mainly on olfactory cues (Ruzicka and Conover 2012; Paula *et al.* 2015; Henrich *et al.* 2017). We also found that CP times were influenced by habitat type, but these effects were again dependent on season. In general, carcass removal rates were slower in areas dominated by scrublands and forests during colder/rainy months. Regarding SE by humans, detection probabilities sharply increased with increasing carcass size and habitat visibility, but differences between medium and large carcasses tend to be more subtle in intermediate and high visibility areas. This is probably due to large and medium-sized carcasses becoming considerably easier to find as vegetation height and ground cover decrease, in opposition to small carcasses that continue to have relatively low detection probabilities (Smallwood 2007, 2013). Unsurprisingly, human observers were always outperformed by dog-handler teams, particularly when looking for small bird carcasses (Reyes *et al.* 2016; Smallwood *et al.* 2020; Domínguez del Valle *et al.* 2020).

Despite these broad patterns, CP and SE rates varied greatly across studies, even between transmission projects located in a same region and/or bisecting similar habitats. Geographic heterogeneity was also confirmed by the results of the CP experiments conducted in Vila Franca de Xira (VFX) and Évora (Chapter 5), both agricultural areas located in central/southern Portugal. Bird carcasses or their remains took, on average, 7.32 days to completely disappear within the right-of-way of VFX power line, while in Évora they took almost half that time (on average, 3.37

days). Thus, the results from Chapter 4 and 5 showed that if spatio-temporal variation in CP and SE correction factors is ignored or incorrectly accounted for, the derived bird fatality estimates are likely to be biased and may lead to erroneous inferences or management decisions at project level (Huso 2011; Korner-Nievergelt *et al.* 2011; Reyes *et al.* 2016). Moreover, impact assessments based on uncorrected bird fatality data (i.e., raw fatality counts not adjusted for CP and SE biases) from different regions or time frames lack comparability and undermine the assessment of cumulative impacts (Loss *et al.* 2012; Huso 2019).

The CP trials performed using camera-trapping methods (Chapter 5) had, nonetheless, the additional objective of providing new evidence on the importance of vertebrate scavenging as a source of bias in bird fatality surveys. Specifically, we aimed to assess if the power line itself influenced scavenger identity and led to increased bird carcass removal rates (compared to the surrounding areas), as previous studies had suggested that generalist scavengers benefit from linear infrastructure presence (e.g., birds use it as hunting perches; carnivores use the rights-of-way to travel) and actively search for preys or carrion along rights-of-way (e.g., Knight and Kawashima 1993; Meunier *et al.* 2000; Lambertucci *et al*. 2009; Morelli *et al.* 2014). Thus, the CP trials conducted in VFX and Évora regions (during the 2017 and 2018 winter periods, respectively) involved the placement of small bird carcasses (quails, *Coturnix coturnix*) beneath a transmission line and in a nearby control area, that were then monitored up to 21-days using motion activated infrared cameras. In the second year (Évora region), we took advantage of an additional research opportunity and associated funding resources to extend the field experiment to a third area – a two-lane paved road. Roads are an important anthropogenic source of direct bird mortality (Erritzoe *et al.* 2003; Santos *et al.* 2016b), so we expected the potential "attraction" effect of carrion on generalist scavengers to be even more marked at the roadside than within the transmission line right-of-way.

The results of our CP field experiments showed that linear infrastructure influence on scavenger identity varied depending, once again, on the region. But, contrary to our expectations, infrastructure presence had either none or a positive effect on carcass persistence times, meaning that carcasses placed within power line or road rights-of-way were not removed faster than the ones placed in controls. A similar result had been achieved by Hill *et al.* (2018), which performed a similar CP experiment during winter but in forested habitats. We conclude that generalisations about the effect of power line presence (Chapter 5) or any other environmental factors, like habitat, season, etc. (Chapter 4), on scavenging patterns and their cascading effects on CP rates are not appropriate. Bird carcass removal is likely to be region-specific and driven by the behaviour and identity of local scavengers (Figure 6.2), thus reliable correction factors for carcass removal-bias in bird fatality estimates require site-specific CP trials.

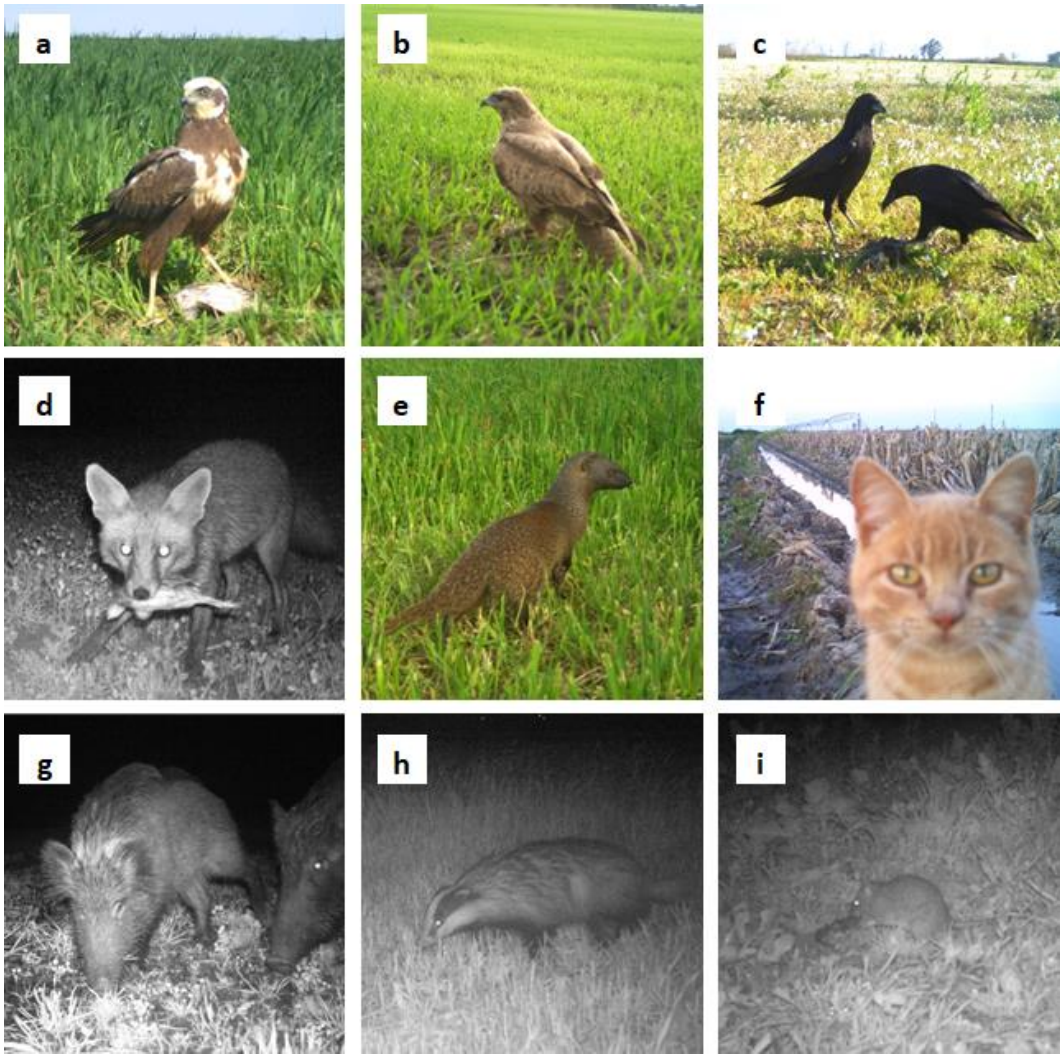

Figure 6.2 - Vertebrate scavengers removing bird carcasses within the right-of-way of a transmission power line and control area in Lezíria Grande de Vila Franca de Xira (Portugal).

(a) Western Marsh-harrier (*Circus aeruginosus*); (b) Eurasian Buzzard (*Buteo buteo*); (c) Carrion Crow (*Corvus corone*); (d) Red Fox (*Vulpes vulpes*); (e) Egyptian Mongoose (*Herpestes ichneumon*); (f) Domestic cat (*Felis catus*); (g) Wild Boar (*Sus scrofa*); (h) Eurasian Badger (*Meles meles*); (i) Rat (*Rattus* sp.).

6.1.4. Advances in bird fatality and mitigation monitoring

Study design and systematic data collection are key elements in the monitoring of anthropogenic impacts, as well as of the success of mitigation actions (Likens and Lindenmayer 2010; Christie et al. 2019). Poorly designed monitoring programmes typically produce inaccurate estimates of mitigation effectiveness or achieve inconclusive results, as evaluating *treatment* effects requires statistical power and control of potential confounding factors (Rytwinski *et al.* 2015; Sinclair and DeGeorge 2016; Christie *et al.* 2019).

Before-After Control-Impact (BACI) designs are considered the most robust method to evaluate environmental impacts (or mitigation effects) and, as with any experiment, they become more powerful when more replicates are used (Smokorowski and Randall 2017; Christie *et al.* 2019). As regards the evaluation of wire-marking effectiveness, the adoption of a BACI design implies the monitoring of bird fatalities along marked and unmarked power line sections (impact and control groups, respectively) both before and after the installation of the wire-markers. However, only 27.3% of the experiments included in our meta-analysis (Chapter 3) used a BACI design. The remaining wire-marking experiments used Control-Impact (CI) designs (39.4%) or Before-After (BA) designs (33.3%). This may be because BACI designs typically require greater sampling effort, but it may also be due to:

- **'Precautionary principle'** - In EIA context, a favourable decision for T&D development is usually conditional to the installation of wire-markers immediately at the power line construction phase. This makes it impossible to collect bird mortality data before the wire-marking treatment and leaves only the possibility of adopting a CI design.
- **Retrofitting projects** - Post-construction monitoring sometimes reveals unexpected high bird collision rates that demand the implementation of additional mitigation measures, namely installation of wire-markers, in a latter phase of the T&D development. In these cases, wire-marking effectiveness is typically evaluated using a BA design.

Sub-optimal experiments (i.e., using CI or BA designs) create an additional challenge, which is to disentangle the effect of the mitigation treatment from natural environmental changes (Colman *et al.* 2017; Christie *et al.* 2019). Natural changes in estimated bird fatality rates (i.e., not related to wire-marking treatment) may be caused by potential spatio-temporal differences in bird activity and/or fatality survey biases (CP and SE rates) between the marked and unmarked power line sections (in CI experiments), or between the periods before and after the wire-marking treatment (in BA experiments). If ignored or incorrectly accounted for, these natural variations may lead to inaccurate, or at least limited, estimates of wire-marking effectiveness. Indeed, in our meta-analysis (Chapter 3), 6 of the 7 wire-marking experiments that achieved implausible negative effects (i.e., wire-marking increased the bird collision rates) used CI designs.

Thus, in Chapter 3 (Table 3.1), we presented several recommendations to address the limitations of CI and BA designs in wire-marking experiments. In addition to bird fatality searches, the field work should include: (1) surveys to assess bird activity/movements and then calculate bird collision risk (mortality rate / bird-crossing rate); and (2) field trials to account for survey bias related to carcass persistence and detection. Based on a careful evaluation of the compiled studies for the meta-analysis, additional recommendations valid for all study designs (BACI, BA and CI) are also presented, mostly related to the (1) selection of the power line sections to include in the experiments; (2) required survey effort to guarantee reliable conclusions; and (3) control of confounding factors (e.g., avoid combinations of different devices and/or wire-making intensities in a same experiment).

Regarding the assessment of bias sources in bird fatality surveys, the CP and SE data compiled from the 36 transmission lines (Chapter 4) and the results of the CP field experiments in VFX and Évora region (Chapter 5) reinforce the importance of carefully planning and designing the field experiments to achieve reliable bias corrections factors and, consequently, accurate bird fatality estimates. For instance, several EIA practitioners often question if, to increase sample size but minimise potential *scavenger swamping* (Smallwood 2007; Smallwood *et al.* 2010), CP trials may also include areas with similar habitats but outside the power line right-of-way. In VFX region (Chapter 5), CP times of the placed bird carcasses were much higher beneath the power line (compared to the control). Thus, the use of CP data from a nearby site (the "control" area) to adjust the bird fatality counts at the VFX power line would have biased the bird fatality estimates by more than 2-fold (assuming weekly carcass searches). In sum, researchers and EIA practitioners seeking to estimate CP and SE bias corrections at a particular site should be cautious in using bias correction values from nearby or similar sites (Linz *et al.* 1997; Stevens *et al.* 2011; Borner *et al.* 2017; Huso 2019). Since many site-specific factors contribute to variability in CP and SE rates, field experiments to assess the corresponding bias correction values should be conducted ideally along the power line sections where bird carcass searches regularly take place. This is particularly important in CP trials because carcass removal is often determined by fine-scale spatial variations in scavenger activity (Flint *et al.* 2010; Borner *et al.* 2017; Clarke *et al.* 2020).

Regarding the variables that should be included in the experimental design (Chapter 4), we found that 'carcass size' and surrounding 'habitat' significantly affect CP rates, but such effect is also mediated by seasonality. This means that the three main variables ('carcass size', 'season' and/or 'habitat') typically included in the design of the field experiments (in the context of post-EIA monitoring) indeed influence CP times at power lines in Portugal. Barrientos *et al.* (2018), that assessed the CP rates (only after 24h) of wildlife fatalities resulting from different anthropogenic activities or infrastructures, also found that they are significantly influenced by 'carcass size', but only slightly influenced by 'habitat' and not significantly influenced by 'season'. However, the detection of season and habitat effects may have been hampered by the heterogeneity of studies included in their analysis, in terms of geographic regions (United States, Canada, Iberian Peninsula, South Africa, etc.), carcass taxon (birds, mammals, amphibians) and human activities / infrastructures (wind farms, roads, power lines, pesticides). In temperate regions, seasonality plays an important role in scavengers' activity and weather conditions, both determining factors in carcass removal rates (e.g., DeVault *et al.* 2004; Ruzicka and Conover 2012; Henrich *et al.* 2017; Turner *et al.* 2017). Thus, and also in accordance with the existing best practice guidelines for wind farms and solar facilities (e.g., Strickland *et al.* 2011; Atienza *et al.* 2014; Huso *et al.* 2016b), 'season' is an important factor to be taken into consideration in the design of CP trials in temperate regions. Conversely, season itself seems not to be a determining factor in SE rates, unless it entails drastic changes in vegetation density and height. We found that carcass detection by searcher is mainly affected by 'visibility' (conferred by the habitat features, topography, etc.) and by 'carcass size'. The latter is particularly critical for human observers, and undoubtedly needs to be taken into account in the design of SE trials. It is also important to use bird carcasses or surrogates (the so-called dummies) that fairly mimic the wild bird species (in their size, colour, etc.) exposed to collision in each specific T&D project.

Chapters 4 and 5 have the ultimate goal of improving the design of CP and SE field trials. However, it is also noteworthy the use of survival data analysis, in both these chapters, to study CP bias and its drivers. Survival analysis techniques were first developed for medical studies but quickly expanded to other disciplines including ecological studies (Pyke and Thompson 1986). Some examples include the study of survival times for animals or plants, plant germination timing, and how long a carcass remains in the field until its removal by scavengers, decomposition, etc.

(e.g., Pollock *et al.* 1989; Nur *et al.* 2004; Giménez-Benavides *et al.* 2005; Smith *et al.* 2017). Regarding the latter, survival analysis has long been used in studies assessing the persistence of wildlife fatalities caused by pesticides (e.g., Balcomb 1986; Linz *et al.* 1991; Kostecke *et al.* 2001), more recently in studies aiming to monitor wildlife fatalities caused by infrastructures like wind farms and roads (e.g., Santos *et al.* 2011; Bispo *et al.* 2013a; Urquhart *et al.* 2015), but rarely used before in studies at power lines (Costantini *et al.* 2017; Borner *et al.* 2017). Survival analysis techniques are, nevertheless, extremely useful because CP data is typically censored time-to-event data, i.e., the exact carcass removal time is unknown. It is only known to have occurred between two consecutive follow-up visits (interval-censored data) or, for the carcasses that persisted until the end of the CP trial, to have occurred after the last follow-up visit (right-censored data).

Thus, in Chapters 4 and 5, we used the non-parametric Kaplan-Meier method to estimate the survival curves (i.e., CP probabilities) and mean CP times (Kaplan and Meier 1958); and the parametric approach – Accelerated Failure Time (AFT) models (Wei 1992) – to investigate the effect of the different ecological and methodological factors on CP times and their two-way interactions. In particular, and because our CP data was clustered into groups (i.e., the datasets included bird carcasses from a same region or project), we used frailty AFT models which allow to introduce random effects (called frailty terms) into models for survival data (Gutierrez 2002). Survival data analysis may be challenging for EIA practitioners with no statistical background. But, in recent years, user-friendly software has been developed – e.g., “GenEst - A Generalized Estimator for mortality" (Simonis *et al*. 2018) – to help EIA practitioners produce accurate wildlife fatality estimates (based on carcass counts) and, among several other tools, analyse their CP datasets using survival analysis techniques. Although first developed for wind and solar facilities, GenEst software may also be adopted in T&D projects to analyse CP data from now on and help EIA practitioners improve the quality of the derived bias corrections for bird fatality estimates.

6.2. Implications for the “Adaptive management” cycle

This thesis was primarily motivated by the recognition that we need more than “good science” to improve the prediction, mitigation and monitoring of bird collisions with power lines. In other words, the vast scientific research conducted on the topic over the last decades needs to be assembled and reviewed in order to effectively inform EIA and monitoring practices in future T&D projects, as well as identify remaining knowledge gaps. Additionally, a large amount of data has been collected over the years under the framework of post-EIA monitoring studies worldwide, but rarely used outside the scope of each individual project. This is mainly explained by (1) poor data standardisation and reporting, which hampers the integration of data or results from different studies; and (2) limited dissemination and access to study findings or data, as studies are rarely published in peer-reviewed journals, being mostly available in grey literature often not readily accessible to researchers or EIA practitioners. Hence, with this thesis, I aimed to overcome some of these barriers and contribute to the “Adaptive Management” process throughout double-loop learning, i.e., the use of findings beyond a single infrastructure project (Figure 1.2).

In Chapter 3, we were able to compile field experiments from Europe (68.2%), North America (16.7%), Africa (12.1%) and South America (3.0%) that assess wire-marking effectiveness in reducing bird collisions. A large proportion of the experiments compiled (n=49, 76%) was only available in grey literature, which turned out to be critical for the meta-analytic results. If only peer-reviewed studies had been included in our meta-analysis (n=12), the estimated wire-marking effectiveness would be higher (56.4% reduction in bird collision rates) than the one estimated based on grey literature (48.7%). This means that, if we had not made the effort to retrieve as many unpublished studies as possible, the estimated effect sizes would be biased, and our study conclusions would be weaker. Publication bias towards studies showing (strong) positive wire-marking effectiveness was expected, as studies with negative or non-significant results are poorly disseminated and often difficult to publish in peer-reviewed journals (Barto and Rillig 2012; Parker *et al.* 2016). However, this was not the only barrier we faced in our meta-analysis. Another one was poor reporting of methods (e.g., study design, sampling effort) and results (e.g., summary statistics and associated variances), which limited the data extraction and, ultimately, led to the exclusion of some studies from the meta-analysis. Thus, in Chapter 3 (Table 3.1), we provide recommendations for future wire-marking studies on how to improve the reporting of the experiments and results achieved, regardless of statistical significance and (positive or negative) direction of the effect observed. With that, we sought to maximise the individual power of primary studies, i.e., to improve study comprehension, facilitate their inclusion in future meta-analysis and, through that, promote double-loop learning within the “Adaptive Management” framework.

Data standardisation and sharing have been repeatedly discussed in the context of infrastructure impacts on wildlife (e.g., Shilling *et al.* 2015; Kettel *et al.* 2019; Conkling *et al.* 2020). Power lines are no exception, and several European T&D developers acknowledge that transparency and data sharing among stakeholders (academia, environmental consultants, NGOs, etc.) would help better understand power line impacts and plan mitigation and monitoring actions (Kettel *et al.* 2019). There are already some examples of data gathering and standardisation on a national level, although the existing centralised databases include mostly data on wildlife fatalities and, occasionally, on bird presence/abundance. Thus, to my best knowledge, data on CP and SE biases are not centralised and/or available for wider use in any country. In Chapter 4, we were able to compile, standardise and analyse CP and SE data from 36 transmission projects in Portugal. Extracting the data from the post-EIA monitoring reports was a difficult and time-consuming task because they were only available in PDF format, CP and SE data was often scattered by several progress reports and presented in a non-standardised way. For several transmission projects, raw data was impossible to extract from the reports (only summary statistics were available) and the inclusion of their results in our analysis was only possible because environmental teams that carried out the CP and SE trials kindly provided us with the raw data. Thus, the creation of national database systems to gather and standardise data from individual T&D projects on bird abundance/presence, bird fatalities and associated survey biases would be extremely useful. This would be an important step to improve transparency and collaborations among stakeholders, and make the most of the large amount of data collected on the context of post-EIA monitoring programmes.

Having easy access to unpublished studies and data would likely promote more scientific research like the one carried out in this thesis (Chapters 2, 3 and 4), which is subject to peer-review and now publicly available. However, if we want decisions on future T&D projects to be evidence-based, it is important to actively promote the transfer of this new knowledge to T&D developers, environmental consultants, NGOs and other stakeholders. So, in parallel with the present work, I took part in the scientific team that developed the recent Portuguese Guidelines for monitoring the impacts of transmission power lines on birds and effectiveness of the mitigation measures (CIBIO 2020). The findings of the present thesis were incorporated into three main sections: 1) design of CP and SE field trials and estimation of derived bias corrections; 2) design of experiments to assess wire-marking effectiveness; and 3) recommendations for reporting of study results and implementation of adaptive management measures. Another example of proactive knowledge transfer is the dissemination of study findings through online knowledge platforms that gather and/or share evidence on the topic. Some examples are the website "Conservation evidence – Providing Evidence to Improve Practice" (which reviews the effectiveness of e.g. several bird conservation actions at power lines) and the website "TRANSPORT-ECOLOGY.info" (which shares research, best practices and case studies on quantification and mitigation of ecological impacts at linear infrastructures). The results of Chapter 2 were shared in the latter website, through an outreach article entitled "What we know (and don't know) about bird collisions with power lines and how to mitigate them".

6.3. Final remarks and opportunities for future research

This thesis provides an overview and evaluation of the factors influencing bird collisions with T&D power lines and the existing mitigation measures. Bird collision events are often explained by complex interactions between two or more collision risk factors; thus, there is unlikely to be a single, universal solution to mitigate this impact. Successful management of bird collisions in future T&D developments will most likely require a combination of multiple mitigation measures tailored to the specificities of each site and project features. We have shown (Chapter 2), however, that there is little evidence of the effectiveness of several mitigation measures often included in international best practice guidelines (e.g., reducing the number of vertical wire levels; clustering new power lines with other existing linear infrastructures; habitat management to reduce bird exposure to power lines). Even wire-marking – the mitigation measure more widely implemented and studied so far – still needs to be further developed and tested (Chapter 2 and 3), since its effectiveness is driven by a wide range of factors (e.g., target bird species, device type, marking intensity, background contrast) that remain relatively understudied.

Thus, Table 6.1 (an improved version of Table 2.1 presented in Chapter 2) outlines suggestions for future research to address the knowledge gaps identified in three broad areas: (1) bird perception and behavioural response to power line infrastructure; (2) assessment of individual- and population-level impacts; and (3) development and testing of mitigation measures. Future research will certainly be boosted by recent (and still ongoing) technological advances for studying species, environments and their interactions (Allan *et al.* 2018). Recent advances in bird tracking technologies (three-dimensional tracking, accelerometers, etc.) - that combine location with behavioural data of individuals (Bouten *et al.* 2012; Brown *et al.* 2013) - will be important to deepen the understanding of bird collision drivers and to assess individual behavioural responses to different power line features and mitigation measures. Radar technology may be particularly useful in monitoring bird abundance and movements at large spatial scales and, for instance, to compare the collision risk of alternative power line routes, or to assess the effectiveness of wire-making and habitat management measures (e.g., Aschwanden *et al.* 2018; Pavón-Jordán *et al.* 2020). Short- and medium-range detection technologies, such as thermal imaging, video and vibration sensors, may be used to monitor bird behaviour nearby the power line but, most importantly, to quantify collisions with wires and bird crippling (Murphy *et al.* 2016b; Largey *et al.* 2021). All these technologies entail the collection of a large volume of data that will also benefit from current advances in data management and analysis, such as machine-learning techniques and Bayesian hierarchical models (Rosa *et al.* 2016; Yoshihashi *et al.* 2017; Farley *et al.* 2018). Genetic and stable isotope data may also play an important role in future research, namely in the identification of bird species that collide with power lines and assessment of population-level consequences (e.g., Bech *et al.* 2012; Ruegg *et al.* 2020; Katzner *et al.* 2020).

Nevertheless, and despite the ground-breaking developments and cost reductions achieved in recent years, I foresee that these technologies will be mostly used in R&D projects or, within EIA framework, only in T&D developments that are expected to affect very sensitive areas or bird species. Thus, it will be important to continue improving the bird fatality survey methods traditionally used in post-EIA monitoring programmes. Chapters 4 and 5 explored the ecological and methodological drivers of CP and SE biases and provide recommendations for the design of future field trials. Further research is, however, needed to determine the optimal sample size (no. of carcasses placed per combination of factors tested), so that bird sacrifice can be minimised without compromising the accuracy of the derived bias corrections. Moreover, in CP trials, the placement of a high number of bird carcasses at the same time is often not recommended because it presumably leads to an abnormal carcass removal by scavengers (so-called 'scavenger swamping'; Smallwood 2007). However, the few studies that investigated such potential effect and its implications for CP times achieved contradictory results (Prosser *et al.* 2008; Smallwood *et al.* 2010; Ponce *et al.* 2010) and, therefore, it is also a topic that still requires investigation. In the case of SE trials for human observers, further research is needed to better understand the costs and benefits of using dummies (instead of 'real' bird carcasses), namely the effect that their different shapes and colours have, once again, on the reliability of the derived SE bias corrections.

Finally, this thesis took advantage of the rare opportunity of having full access to the archives of the Portuguese transmission system operator (REN – Rede Eléctrica Nacional, S.A.), namely to numerous post-EIA monitoring reports from which results of wire-marking experiments (Chapter 3) and raw data from CP and SE trials (Chapter 4) were retrieved. Future research on bird-power line interactions will benefit from similar collaborations between academia and T&D energy sector. For instance, the development, testing and implementation of new technologies to monitor and mitigate bird collisions will require full cooperation from T&D developers. In turn, researchers should try to understand and address the challenges faced by the T&D energy sector, to enhance knowledge transfer and to help T&D developers continuously improve their practices. In short, the establishment of win-win relationships between academia, T&D developers and other stakeholders (environmental authorities, NGOs, consultants, etc.) is of utmost importance for the development of future research on the topic, and also for faster and better use of scientific knowledge in project planning, impact mitigation and monitoring at future T&D developments.

Table 6.1 - Suggestions of future research based on the knowledge gaps identified in terms of bird perceptions and behavioural responses, bird mortality assessment and mitigation measures.

Knowledge gaps / Research questions	**Potential research topics**
Bird behaviour and perceptions	
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.
Assess visual and perceptual aspects	• Experimental approaches to assess 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-imaging cameras and radar.
Bird mortality assessment	
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.

Knowledge gaps / Research questions	**Potential research topics**
	• 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).
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.
Improve detection of collisions and methods for fatality estimation	• Technological development and testing of remote bird activity and collision monitoring devices, including thermal-imaging systems, small unmanned aircraft, bird strike indicators, and radar. • Development of methods to accurately estimate bird fatality (based on carcass searches) and related bias corrections, with particular focus on crippling bias. • Assess trade-offs between accuracy of the bias corrections and number of ecological factors (and factor levels) tested and sample size in carcass persistence and searcher efficiency trials.
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).
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.
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.

Knowledge gaps / Research questions	Potential research topics
	• 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 (except in retrofitting projects), characterisation of crossing rates is important to evaluate differences.

6.4. References

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