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REVIEW

Effects of wind farms on raptors: A systematic review of the current knowledge and the potential solutions to mitigate negative impacts

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Abstract

Wind farms are a clean and efficient source of renewable energy. However, they cause negative impacts on raptors. Here, we present a review of the existing scientific literature on the effects of wind farms on raptors' ecology with a particular interest in the potential solutions. After collecting 216 studies, we found a consensus in the literature that raptors exhibit avoidance behaviors, and that the abundance of raptors decreases after wind farm installation, although it might recover over time. The position of wind farms on mountaintop ridges poses a particular danger to large soaring raptors, as they rely on orographic uplift to gain altitude. Adult mortality significantly affects population dynamics, particularly in endangered species, but young inexperienced individuals show a higher collision risk. The combination of different methods including field monitoring, GPS telemetry and systematic search for carcasses is an adequate approach to further investigate the problem and solutions. Shutdowns on demand, the installation of deterrents, turbine micro-sitting and the repowering of wind farms have been suggested as potential solutions, although results are contradictory and case-specific. Furthermore, it is essential to report the potential occurrence of conflicts of interest in scientific papers, as they can influence the interpretation of the results. Finally, from a future perspective, it is crucial to assess the effectiveness of solutions to mitigate the negative effects of wind farms to promote raptor conservation. This becomes increasingly relevant in the context of renewable energy development and increasing energy demand worldwide.

Introduction

The development of renewable energies has constituted a significant paradigm shift in addressing the escalating global energy demand. Renewable energies offer an alternative solution to fossil fuel energy sources and their polluting emissions, which are increasingly contributing to climate change (Sawin *et al.*, 2018). Electric power generation through wind energy stands out as the technology that has experienced the most substantial global expansion in recent decades, owing to its capacity for efficient and cost-effective energy production without emissions (Kumar *et al.*, 2016). For this reason, it is perceived as a favorable environmental alternative (Allison *et al.*, 2017). However, there is a growing concern regarding the negative impacts that wind farms can generate on both biodiversity and the landscape (e.g. Kunz *et al.*, 2007; Smallwood & Thelander, 2008; Bailey *et al.*, 2010; Schuster, Bulling, & Koeppel, 2015). Among these impacts, wildlife mortality due to collision with turbine blades, habitat fragmentation, habitat degradation and habitat loss, as well as mortality resulting from collisions and electrocutions with associated electrical transmission infrastructures in the form of power lines (Drewitt & Langston, 2006) are prominent. The species most directly affected by wind farms are birds and bats, primarily due to their high vulnerability to collisions (Osborn *et al.*, 2000). Specifically, there is broad consensus in the scientific literature that soaring birds, and particularly raptors, are the most vulnerable avian group to wind farm collisions (e.g. Hunt, 2002; Barrios & Rodriguez, 2004; Drewitt & Langston, 2006; Madders & Whitfield, 2006; de Lucas *et al.*, 2008; Lanzone *et al.*, 2012). This vulnerability stems from the fact that even small mortality rates can have severe effects on long-lived species that typically exhibit low rates of reproduction and slow development, as is often the case with raptors (Linder *et al*., 2022).

The vulnerability of raptors can vary depending on morphology, home range behavior, flight type and habitat use within their living environments (Dohm *et al*., 2019). Additionally, the degree of vulnerability also depends on the type of technology used in wind farm construction, the arrangement of wind turbines, rotor height and blade size (Sterže & Pogacnik, 2008; McClure *et al*., 2021b). The habitat type in which wind farms are situated, the prevailing weather conditions and the local topography are also significant factors to consider when assessing the risk of raptor collisions (Watson *et al*., 2018). Although there is an extensive body of literature on the actual and potential impacts of wind farms on raptors, the disparity in methodologies and technologies employed for analyzing animal behavior in relation to wind turbines results in substantial variation in study outcomes, both within and among geographical regions (Sheppard *et al*., 2015; Chabot & Slater, 2018). New remote tracking technologies, notably GPS/GSM tracking, play a pivotal role in the assessment of impacts (Kikuchi *et al*., 2019). However, there is substantial variation among device types and data processing methods (López-López, 2016). Therefore, despite the growing concern over the potential combined impacts of all the previously mentioned factors on raptors, there is a lack of consensus studies that synthesize the primary findings regarding the effects wind farms can have on birds in general, and raptors in particular. This is because most results from published works tend to be context-dependent, influenced by the specific spatial and temporal conditions in which they were conducted (Katzner *et al*., 2019). This is primarily due to the variability in behavioral responses among species, the types of environments studied, the technology used for tracking in each country and the specific biogeographic region in which wind farms are located (Watson *et al*., 2018; Dohm *et al*., 2019; Battisti *et al*., 2020).

Amidst the backdrop of the rapidly increasing global energy demand and the ongoing energy transition, it is crucial to comprehend the effects of wind farms on the most vulnerable species (Fernandez-Bellon *et al*., 2019). Since raptors constitute a diverse group of species and many of them are conservation flagship species, their protection can benefit numerous other species, serving as umbrella species (Bose *et al*., 2020). The pursuit of global solutions and, above all, the verification of the effectiveness of these solutions are fundamental in reducing and reversing the impact caused by wind farms on wildlife (Donazar *et al*., 2016). For this reason, it is essential to gather as much as possible information, consolidate consensus findings and investigate discrepancies in results when searching for and implementing solutions (Martinez *et al*., 2010). This approach allows for progress in taking measures that truly provide efficient solutions.

In this review, we have compiled and analyzed the published literature on the impacts of wind farms on raptors worldwide. Unlike previous works (e.g. Kikuchi, 2008; Watson *et al*., 2018; Fernandez-Bellon *et al*., 2019; Conkling *et al*., 2021), we have not only summarized the effects of wind farm construction on birds but have also collected, integrated and analyzed the solutions proposed by various authors and their long-term effectiveness. To accomplish this, we have organized available information based on the taxonomic order of the studied raptors, size, flight type, diet, the impacts they experience, their effects, observed behavior and the methods employed to obtain information. This study synthesizes all available information to date, consolidates consensus findings from the literature and highlights discrepancies among different studies to emphasize areas that should continue to be investigated. Additionally, this study underscores the importance of seeking solutions and verifying their effectiveness to mitigate impacts on the most vulnerable species and promote their conservation on a global scale.

Materials and methods

To gather the available literature on the impact of wind farms on raptors, we conducted a search in the Google Scholar and Scopus databases, spanning records up to June 2024. The parameters used for the search were as follows:

Title OR Abstract OR Keywords = (‘Wind farm’ OR ‘Wind-farm’ OR ‘Windfarm’ OR ‘Wind turbine’ OR ‘Wind-turbine’ OR ‘Wind farms’ OR ‘Wind power’ OR ‘Wind-power’ OR ‘windmill’) AND (‘Raptor’ OR ‘Raptors’ OR ‘Rapt*’ OR ‘Soaring bird’ OR ‘Soaring-bird’ OR ‘Soaring birds’ OR ‘Bird of prey’ OR ‘Eagle’ OR ‘Vulture’ OR ‘Kite’ OR ‘Harrier’ OR ‘Condor’ OR ‘Falcon’ OR ‘Owl’).

This comprehensive search employed the primary terms used to investigate the effects of wind farm installation on raptors (Table 1). It is important to note that the search was limited exclusively to scientific articles published in English and in journals included in the Science Citation Index (SCI). Works published as ‘gray literature’ such as technical reports, environmental impact studies, reports and assessments for public administrations and environmental authorities, undergraduate or master’s theses, as well as presentations at specific national and international conferences on the subject, were not included in this review due to the lack of a peer review scrutiny.

For the analysis of information, we incorporated the type of methodology used for data acquisition (Table 2). Additionally, we classified the raptors by taxonomic order, size, diet, and flight type.

For each article, we recorded the study period (i.e. start and end dates) as well as the publication year to assess changes in publications over time. Additionally, we added information about the country and continent where each article was conducted to evaluate the possible existence of geographic biases in the publications. Lastly, we noted whether the published studies had declared conflicts of interest, or if they had not.

For the data analysis, we used the R software (version 4.3.3) and R-Studio (version 2023.12.1 + 402). Each of the parameters was divided into categories (Tables 1 and 2). Subsequently, we conducted a systematic comparison by

Table 1 Variables included in this work to categorize the effects of the installation of wind farms on raptors

Term or variable	Definition
Type of wind farm	Classification of wind farms based on the following categories 1 *Onshore* (wind farms located on land) 2 *Offshore* (wind farms located at sea)
Study characteristics	Classification of articles based on whether they studied a single species (*monospecific*) or multiple species (*multispecific*)
Topic	Classification of articles based on the information they aimed to obtain, subcategorized as 1 *Predictions*: Articles that used predictive models to study future scenarios for raptors due to the presence of wind farms 2 *Risk Zones*: Articles whose primary purpose was to study areas with a high risk of collision for raptors 3 *Mortality Detection*: Articles primarily focused on studying raptors that died as a result of collisions with wind farms 4 *Consequences*: Actions related to wind farms that generate a range of impacts on raptors, without specifying their duration over time 5 *Long-term Consequences*: Actions related to wind farms that have prolonged impacts on raptors, specifically extending beyond a period of 6.5 years (being this the lowest value employed by the analyzed papers) 6 *Solutions*: Articles that studied potential solutions to reduce the impact of wind farms 7 *Efficacy of Solutions*: Articles that sought to determine the effectiveness of implemented solutions
Adverse effects	Negative impacts on raptors in the literature, categorized in this present study as 1 *Behavior*: Alterations in a species' behavior as a consequence of the presence of a wind farm. Subcategorized in this study as avoidance (alteration of flight path or altitude to avoid potential collisions with wind turbines), or non-avoidance. Following May *et al.* (2015) classification, we studied avoidance at different scales: macro-avoidance (territory abandonment or avoidance of specific areas [i.e. disuse]), meso-avoidance (avoidance of specific turbines) and micro-avoidance (last-minute changes in flight directions and altitudes) 2 *Mortality*: Number of raptors that die as a result of collisions with wind farms. Subcategorized as: increase, decrease (articles considering the application of solutions that aid in reducing collisions), local extinction (articles considering an increase in mortality that could lead to species extinction in the long term), risk zones (articles documenting raptor mortality within zones determined as high risk under specific conditions) and no effects (articles not reporting mortality) 3 *Home Range*: Areas used by raptors for their daily activities. Subcategorized as: increase, decrease, risk zones (articles that analyzed home ranges within what they considered collision risk zones) and no effects 4 *Population Trend*: Viability of a population over time, considering the number of individuals, reproduction rate, emigration/immigration rate and annual mortality rate. Subcategorized as: increase (articles reporting positive population trends), decrease (articles reporting negative population trends) and no effects 5 *Abundance*: Difference in the total number of birds counted before and after the installation of wind farms. Subcategorized as: increase (articles reporting an increase in the number of observed birds within a wind farm after installation), decrease (articles reporting a decrease in the number of birds after wind farm installation), risk zones (studies on raptor abundance within what they considered collision risk zones) and no effects (articles not reporting changes in the local abundance of species)
Size	*Large raptor*: Wingspan >2 m *Medium-sized raptor*: Wingspan between 1 and 2 m *Small raptor*: Wingspan <1 m
Diet	Classification of the dietary type of each raptor based on the most common food source. Studies involving the examination of more than one raptor have been categorized as 'More than one' 1 Strict scavengers 2 Strict predators 3 Opportunistic predators that occasionally scavenge
Flight type	Categorization of articles based on the flight type of the studied species considering that these are the flights they predominantly undertake (Ferguson-Lees & Christie, 2001), acknowledging that they are not exclusive and may employ other types of flights under specific circumstances, categorized as: 1 *Flapping*: Flight involving the rapid motion of wings for propulsion 2 *Soaring*: Flight primarily relies on thermal and orographic wind currents for movement without the need for wing flapping 3 *Flapping and Soaring*: A combination of both flapping and soaring flight types

Table 2 Classification of methodologies used for the analysis of the effects of wind farms on raptors

Method	Description	References
Database literature	Processing of information obtained from pre-existing databases or scientific papers before the onset of the study	For example, Smallwood (2013); Loss, Will, & Marra (2015); Hunt & Watson (2016); Allison *et al.* (2017); Law and Fuller (2018)
Local monitoring	Establishment of fixed observation points and/or linear transects designed for the purpose of quantifying the number of birds traversing wind energy facilities	For example, Hilgerloh, Michalik, and Raddatz (2011); Dohm *et al.* (2019); McClure *et al.* (2021a); Cervantes, Martins, and Simmons (2022)
Wind farm revision	Searching for raptor carcasses in the vicinity of wind turbines to estimate mortality resulting from collisions	For example, Smallwood, Rugge, & Morrison (2009); Smallwood *et al.* (2010); Huso *et al.* (2015); DeVault *et al.* (2017); Katzner *et al.* (2017)
Cameras	Placement of visible light and infrared video cameras on the rotors of wind turbines to collect information about birds that engage in flights near the installations	Murai *et al.* (2015); Therkildsen *et al.* (2021); McClure *et al.* (2021c); Linder *et al.* (2022)
GPS/GSM	Electronic devices powered by internal batteries or small solar panels, which facilitate the determination of the bird's location. These devices employ various data transmission methods, including utilization of the mobile phone network, the Argos system, or local data retrieval in the field through the deployment of a reception base station	For example, Miller (2012); Rushworth and Krueger (2014); Reid *et al.* (2015); Sur *et al.* (2018)
Radio-tracking	Very High Frequency (VHF) radio devices that enable the determination of individual locations through *in situ* triangulation	For example, Hunt *et al.* (1999); Hunt (2002); Kolar (2013); Kolar and Bechard (2016)
Radar	A method enabling the acquisition of information regarding birds passing in close proximity to wind farms through the identification of signals based on radar pulses	Baisner *et al.* (2010); Villegas-Patraca, Cabrera-Cruz, & Herrera-Alsina (2014); Cabrera-Cruz and Villegas-Patraca (2016); Skov *et al.* (2016)
Visual marks or tags	Individual identification technique that enables the determination of the origin of raptors through the placement of distinctive elements (typically on the tarsus or wings). This method also allows the inference of population size using capture, mark and recapture methods, among others. Mark-recapture studies were used to estimate survival rates of wind farm exposure	For example, Martinez-Abrain *et al.* (2012); Sanz-Aguilar, De Pablo, and Antonio Donazar (2015)
Combination of methodologies	Utilization of multiple of the aforementioned methodologies within a single study	For example, Schaub (2012); Bay *et al.* (2016); Dohm *et al.* (2020); Santos, Marques, and May (2020); Duriez *et al.* (2022)

calculating the number of articles per category and the percentage they represented of the total for that category. To represent the geographic distribution of the data obtained, we used QGIS version 3.16.

Results

After data filtering, we obtained a total of 216 scientific articles specifically addressing the impact of wind farms on raptors. The majority of the articles focused on species from the Order Accipitriformes (*n* = 123) and were conducted in onshore wind farms (*n* = 202). Raptors with a combination of wing flapping and soaring flight were the most studied (*n* = 162). Studies that simultaneously included raptor species of all sizes were the most abundant (i.e. multi-species studies) (*n* = 68). The most commonly employed method for data collection was local monitoring (*n* = 72). The most frequently observed adverse effects and consequences were the study of risk zones within raptor foraging areas (*n* = 62) and increased mortality (*n* = 48), respectively. Interestingly, there is a scarcity of articles specifically addressing the impact of wind farms on Strigiformes with mono-specific studies (*n* = 6) (e.g. Smallwood *et al.*, 2007; López-Peinado *et al.*, 2020).

Main topics of interest: Geographical and temporal distribution

Most of the articles were published in Europe (49.5%) and America (33.3%) specifically in North America and Southwestern Europe with the United States and Spain having the highest number of publications, at 68 and 34 respectively (Fig. 1). While in Europe, Asia and Oceania (37.4%, 37.5%, 50.0% respectively), the articles primarily focused on studying the consequences of wind farms, in America and Africa, they mostly centered on studying risk zones for raptors (26.0% and 36.4%, respectively). In articles where the study area included more than one continent, the consequences of wind farms on raptors were predominantly analyzed (58.3%) (Fig. 2).

The number of articles analyzing the overall impact of wind farms on raptors has increased over time. Specifically, the study of the specific effects of wind farms on raptors has

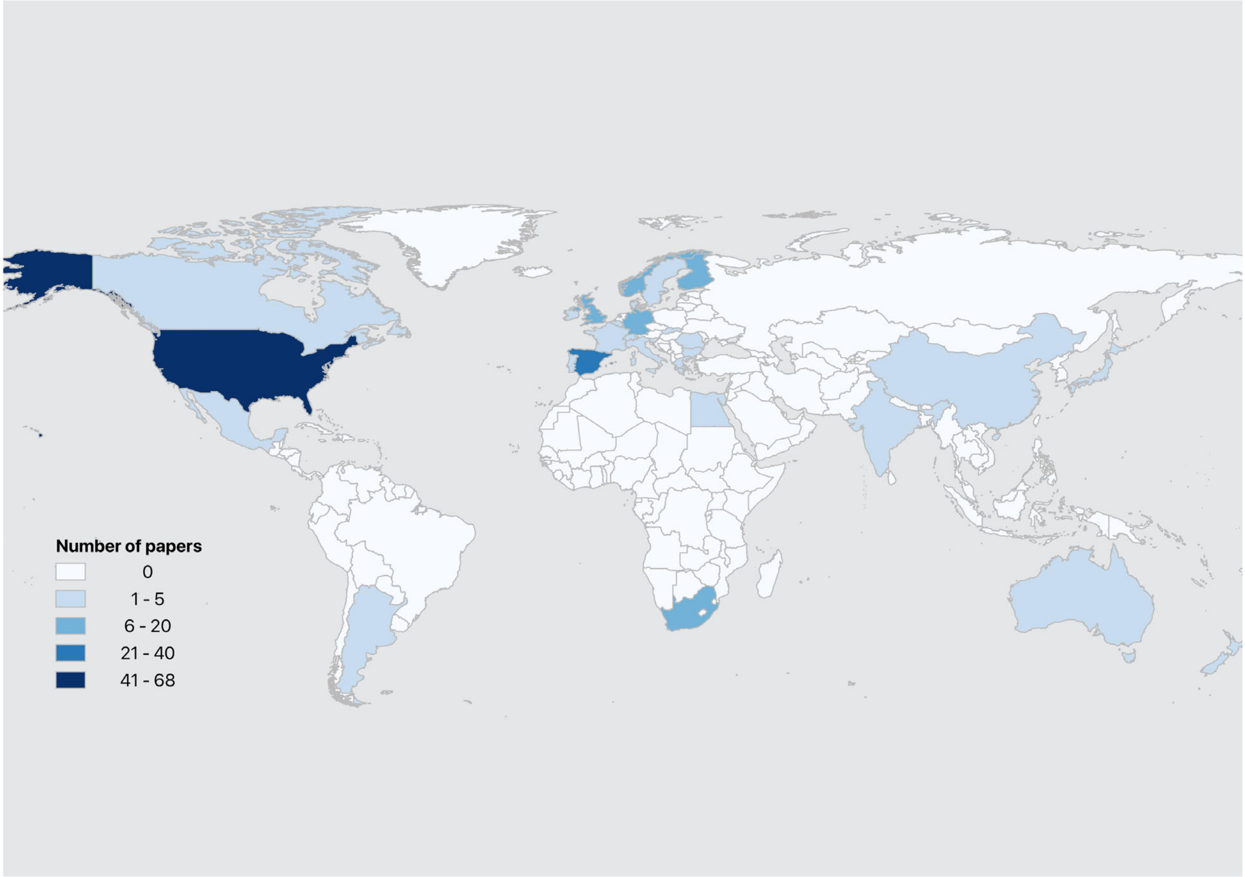

Figure 1 Geographic distribution of research papers that investigated the effects of wind farms on raptors across the world.

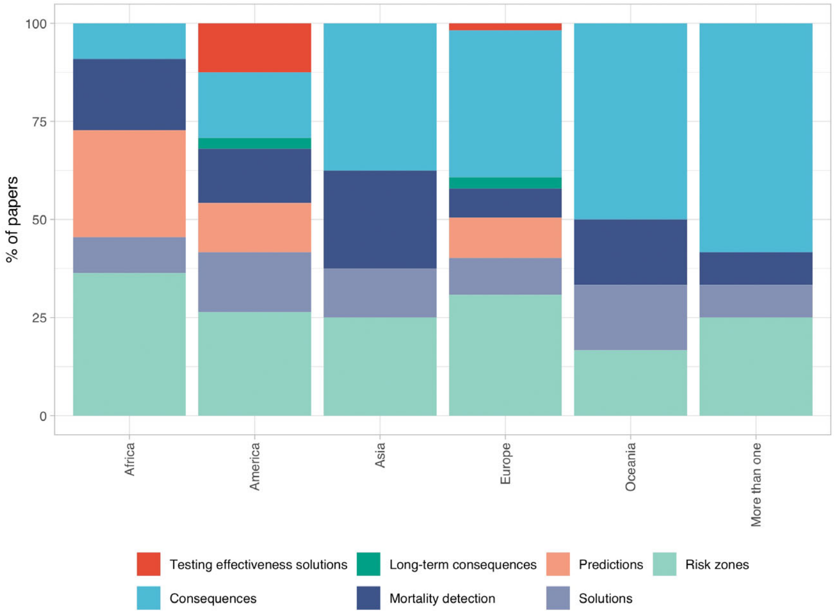

Figure 2 Percentage of research papers that investigated the effects of wind farms on raptors across the world, by topic and continent (see text for details).

generated greater interest over the years (from 0.9% of articles in 2004 to 9.7% in 2022). There has also been an increased interest in studying collision risk zones around wind turbines (from 1.6% in 2002 to 6.5% in 2022). Although virtually all aspects of scientific paper production have increased tremendously over the past years (Evans, 2013), this increase is likely facilitated by the expansion of built wind turbines and thus potential study areas facilitating such studies.

Methods used for data collection

Articles employing local monitoring as a data collection method increased over time. Despite being the most widely used technology, the method that has experienced the most substantial growth from 2010 onwards has been the use of GPS/GSM transmitters (from 2.3% in 2012 to 20.5% in 2022). To the best of our knowledge, radio-tracking was the first methodology used for the specific case of our study (Hunt *et al.*, 1999), but in the latest decade, it has fallen out of use due to the rise of GPS/GSM transmitters. UV light was used in a single article to observe if raptors avoided wind farms (Hunt, McClure, & Allison, 2015).

The use of cameras for raptor detection and subsequent image processing for identification is a new methodology. Although it has been proposed for other porpoises such as techniques for counting and estimating bird-wind turbine collisions (Desholm *et al.*, 2006), it was employed for studying the impact of wind turbines on raptors in 2015 (Murai *et al.*, 2015) and has continued to be implemented in the last decade (13 articles in 9 years). The two least employed methods have been reading raptor visual marks or tags and radar, with only two (i.e. Martinez-Abrain *et al.*, 2012; Sanz-Aguilar *et al.*, 2015) and four articles (i.e. Baisner *et al.*, 2010; Villegas-Patraca *et al.*, 2014; Cabrera-Cruz & Villegas-Patraca, 2016; Skov *et al.*, 2016), respectively. The combination of multiple techniques has increased in the last two decades (from 5.3% in 2004 to 15.8% in 2022).

Regarding the type of wind farms, the majority of articles focused on the impact of onshore wind farms (93.5%), while offshore wind farms accounted for a minimal percentage of the total (3.7%). Those articles that considered both types of farms were a minority (2.8%). Most data collection methods were employed in onshore wind farms. However, it is worth noting that in the case of radar, most of the articles were conducted in offshore wind farms (75.0%).

Adverse effects on raptors

Raptor mortality was the most studied adverse effect over time (30.6%), followed by changes in home range area (30.1%) and changes in behavior (25.4%). However, variations in abundance (8.3%) and alterations in population trends (5.6%) have been studied since the late 1990s to the present but to a lesser extent.

All considered adverse effects in this review were studied in onshore wind farms. However, in Offshore areas, all negative effects were reported except for changes in population trends, although to a lesser extent than in the case of Onshore areas. In articles that simultaneously studied the effects in onshore and offshore wind farms, alterations in behavior (50.0%) and home range (50.0%) were considered.

All adverse effects have been studied for species of the order Accipitriformes. For Strigiformes, changes in behavior, abundance (16.7% each), home range and mortality (33.3% each) were studied. In the case of Falconiformes, the effect

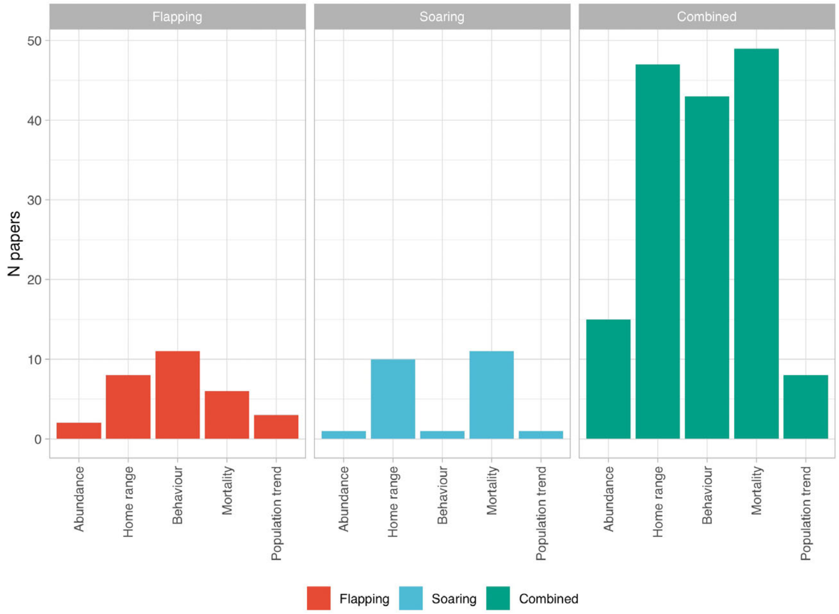

Figure 3 Number of research papers in relation to the adverse effects investigated categorized by raptor flight type.

on mortality and home range (40.0% each) and variations in population trends (20.0%) were studied. All effects were studied in studies that considered more than one order.

Regarding the study of flight types in relation to different effects, the majority of papers report the effects of raptors with flapping and soaring flight types together (75.1%). For species with flapping flight, articles primarily focused on analyzing changes in raptor behavior (36.7%). In papers that exclusively studied soaring raptors, the effects on mortality were predominantly examined (45.8%) (Fig. 3).

Consequences of adverse effects

From the analysis of adverse effects and their consequences, the following results were obtained:

Abundance

In 72,2% (*n* = 13) of the articles that studied bird abundance before and after the installation of wind farms, a decrease in the number of birds after installation was observed. The declines in abundance were studied in both strict scavenger species (7,7%) and strict predator species (23,1%), as well as opportunistic species alike (38,5%). In multi-species studies, declines in abundance were also reported (30,8%). All these articles were published in Europe, America and in those articles in which more than one continent was considered and reported a decrease in population sizes of *Aquila chrysaetos, Circus cyaneus, Neophron percnopterus, Milvus milvus, Circus aeruginosus, Accipiter nisus, Accipiter gentilis, Pernis apivorus, Buteo buteo, Buteo lagopus, Pandion haliaetus, Falco tinnunculus, Falco columbarius, Falco subbute, Circaetus gallicus* and *Gyps fulvus* (e.g. Watson & Whitfield, 2002; Campedelli *et al*., 2014; Olea & Mateo-Tomas, 2014). In 11,1% of the articles (*n* = 2), an increase in abundances was reported. After 8 years since the installation of wind farms, increases in the abundances of populations of *Cathartes aura, Buteo jamaicensis, Accipiter sp*, have been reported using local monitoring in the United States (Dohm *et al*., 2019). In Europe, an increase in abundances has also been reported using local monitoring after 6.5 years of wind farm installation for *Aquila fasciata, Aquila chrysaetos, Circaetus gallicus, Gyps fulvus* and *Bubo* (Farfan *et al*., 2017). The diet of the abovementioned species ranges from strict scavengers to strict predators and opportunistic feeders. Two articles were classified as 'no negative effect' because they proposed solutions to mitigate the impacts of wind farms (11,1%) (Schindler *et al*., 2015; Law & Fuller, 2018). The remaining 5,6% corresponds to a single article in which bird abundance was analyzed before and after the installation of the wind farm within what the authors considered a collision risk zone (Telleria, 2009). However, in a previous review, it was reported that some of the results provided by articles studying raptor abundances before and after wind farm installations were not adequately conducted (e.g. incomplete studies, lack of standardization, or absence of detection probability estimates). This underscores the importance of conducting comprehensive studies that observe long-term variations in abundances (Conkling *et al*., 2021).

Home range

In the vast majority of articles that studied space use (95.4%, *n* = 62), collision risk zones were defined (i.e. spaces within the home range area that could imply a collision risk for raptors). An increase in home range area was observed in *Nisaetus nipalensis* (Asia) during various phases of wind farm construction (Nishibayashi, Kitamura, & Yoshizaki, 2022). There was one article that studied the effectiveness of solutions concerning the study of home range area and how wind farms' presence affected it. This article was categorized as having 'no negative impact' (Sur *et al*., 2018). Reductions in home range were observed in *Bubo bubo* (Husby & Pearson, 2022) due to the proximity of wind farms to nesting sites (41% reduction in the territories of individuals whose nests were located in closer proximity to the wind farms). In addition, a decrease was observed also in the home range areas of *Haliaeetus albicilla* in nests located farther from wind farms, whereas the home range areas increased in nests situated closer (May *et al*., 2013).

Mortality, reproduction and population trends

Overall, 72.7% of the papers reported an increase in mortality (*n* = 48). In those studies where measures were implemented to reduce mortality, a decrease in mortality was observed (10.6%, *n* = 7). The decrease in mortality was studied by comparing the number of collisions before and after the implementation of the solution. Among the solutions implemented in the studies, notable interventions included on-demand stopping (tested for vultures in Europe [de Lucas *et al*., 2012a; Ferrer *et al*., 2022]), the removal of attractants such as food (tested in a species of *Falco* in Europe [Pescador, Gomez Ramirez, & Peris, 2019]), or the development of risk maps (tested in *Aquila verreauxii* in Africa [Murgatroyd, Bouten, & Amar, 2021]). Out of all the articles 7.6% (*n* = 5) predicted the long-term local extinction of the studied species as a result of the presence of wind farms; 7.6% (*n* = 5) did not observe any negative effects; and in 1.5% (*n* = 1), mortality associated with collision risk zones was observed (i.e. an article that established collision risk zones and studied mortality within them). Interestingly, there was a paper whose primary focus was on the impact on reproduction, and it asserted that a decrease in birth rates occurred after the installation of wind farms (Balotari-Chiebao *et al*., 2016).

Finally, 75.0% (*n* = 9) of the articles reported a decrease in population trends and 8.3% (*n* = 1) did not observe negative effects on population trends. All articles that documented a decline in population trends did so for species characterized by a long lifespan: *Aquila chrysaetos* (Hunt *et al*., 1999), *Neophron percnopterus, Gyps fulvus* (Garcia-Ripolles & Lopez-Lopez, 2011) and *Haliaeetus albicilla* (Dahl, 2014). These observations were primarily conducted through field observations, although one of the articles employed radio-tracking methods (Hunt *et al*., 1999). The findings from these studies suggested that the decline in population primarily stemmed from adult mortality. With regard to those articles that reported

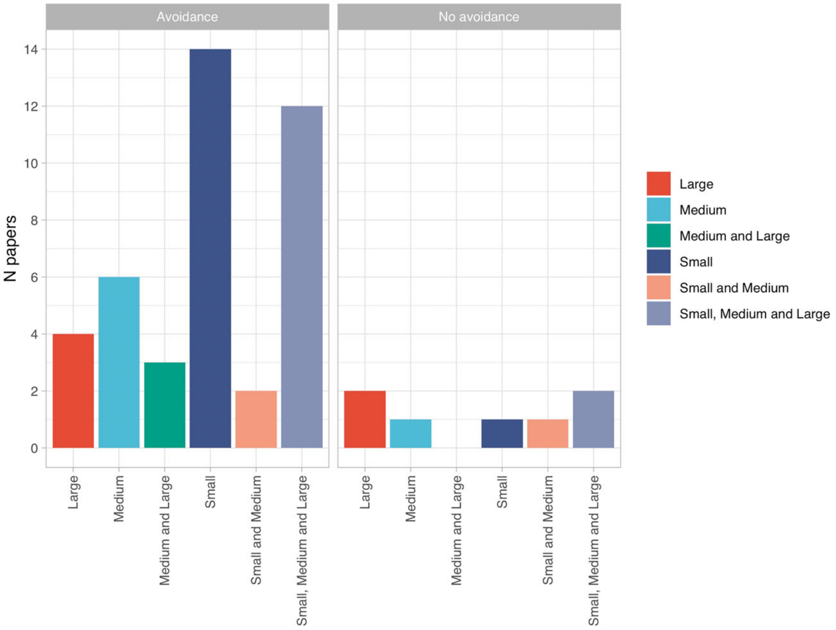

Figure 4 Number of papers reporting avoidance or lack of avoidance behavior in relation to raptors' size.

an increase in population trends (16.7%), they correspond to two studies in which long-term research was conducted following the installation of wind farms, observing recoveries in population trends over time (Farfan *et al*., 2017; Farfán *et al*., 2023).

Behavior

In 74.6% of the articles reporting changes in raptor behavior as a consequence of the presence of wind farms, avoidance behavior was observed. However, in 12.7% of the studies, avoidance behaviors were not observed and in 12.7%, no negative effects were observed. From the articles that reported avoidance as a consequence of wind farm presence, 9.8% reported increases in flight heights. There was a higher number of articles in which avoidance behaviors were reported (n = 41) compared to those in which they were not observed (n = 7). Furthermore, 34.1% of the articles documented avoidance behaviors in small raptors, 29.4% in small, medium and large raptors studied together, 9.7% in large raptors, 14.6% in medium-sized raptors, 7.3% in medium and large-size raptors and 4.9% in small and medium-sized raptors studied together (Fig. 4). Of the articles reporting avoidance behaviors, 56.1% were limited to the order Accipitriformes, 41.4% observed it in those where more than one order was analyzed and 2.4% in the order Strigiformes. Avoidance was neither detected nor absent in raptors of the order Falconiformes in the papers analyzed in this study. Of the articles that reported avoidance behavior, 75.7% were in species with flight types that combine soaring with flapping flight, 24.4% observed it in flapping raptors. None of the articles studied recorded the absence or presence of avoidance in soaring raptors.

Furthermore, adhering to various types of avoidance (May, 2015) it was determined that 9 papers reported macro-avoidance, 12 meso-avoidance and 20 micro-avoidance. Among the papers that examined macro-avoidance, 22.2% was observed in opportunistic raptors, 22.2% in strict predators and the remaining 55.6% were studied in multispecific papers (diet not analyzed). In the case of meso-avoidance, 16.7% was observed in opportunistic raptors, 33.3% in strict predators and the remaining 50.0% was studied in multispecific papers (diet not analyzed). In the case of micro-avoidance, 35.0% was observed in opportunistic raptors, 25.0% in strict predators and the remaining 40.0% was studied in multispecific papers (diet not analyzed).

Solutions

In addition to the search for solutions, it is crucial to be acquainted with tools that facilitate the identification or effectiveness assessment of these solutions. We have compiled those used in the literature reviewed (Table 3).

Following the hierarchy employed by Allison *et al*. (2017), we have classified various solutions and useful applications for solution implementation based on: (i) avoidance of the situation causing a negative impact and (ii) minimization of the generated impact.

There are various solutions for the avoidance or minimization of the impact of wind farms on raptors (Table 4).

Discussion

Raptors are one of the groups of birds most vulnerable to the presence of wind farms (Desholm, 2009; Wulff, Butler, & Ballard, 2016; May *et al*., 2021; Balotari-Chiebao, Valkama, &

Table 3 Applications that can serve as a guide for the implementation of solutions to avoid negative effects of wind farms on raptors

Mitigation hierarchy	Proposed application	Description	Applications	References
Avoid	Habitat suitability models	Models that examine the best and worst areas for wind farm installation based on raptor habitat use	1 Modifying the planning of wind farm installation 2 Reducing the number of turbines in it	For example, Murgatroyd *et al.* (2021); Ng *et al.* (2022)
Minimize	BACI studies	Studies in which a Before and After Control Impact (BACI) approach is employed. In these studies, information is compared before and after the installation of the wind farm and between control and experimental sites	1 To gain a comprehensive understanding of raptor habitat utilization and behavioral changes occurring after the installation of wind farms 2 To assess the effectiveness of models predicting the impact of wind farms and to calibrate them	Garvin *et al.* (2011); Dahl *et al.* (2012); Campedelli *et al.* (2014); May *et al.* (2020); Conkling *et al.* (2021); Therkildsen *et al.* (2021)

Table 4 Proposed solutions in the literature that could be applied to avoid negative effects of wind farms on raptors

Mitigation hierarchy	Proposed solution	Description	Applications	References
Avoid	Turbine micro-siting	Alteration of turbine distribution based on the risk predicted by habitat suitability models	1 Removal of turbines on the most frequently used mountain ridges by soaring raptors 2 Avoidance of nesting areas 3 Avoidance of areas that are heavily used or where more food is available	Allison *et al.* (2017); Pescador *et al.* (2019)
Minimize	Repowering	Reduction in the number of wind turbines and an increase in the rotor height of those that are retained	Reduction in collision risk due to the taller rotors of the new wind turbines. At least for species that fly at low height (e.g. harriers). (High cost)	Hunt and Hunt (2006); Smallwood & Karas (2009); Schaub (2012)
Minimize	Shut down on demand of specific turbines	Allows for the shutdown of those wind turbines over which a raptor is predicted to fly at a collision-risk altitude	Allows for the reduction of mortality among the most vulnerable raptors with only a minimal decrease in energy production (only a 0.07% reduction). Its effectiveness has been demonstrated	Smallwood *et al.* (2009); de Lucas, Ferrer, and Janss (2012b); Ferrer *et al.* (2022)
Minimize	Elimination of attractants	Removal of elements that may attract raptors to wind farms	1 Removal of food sources 2 Reduction of perches near the wind farm 3 Removal of carcasses near the wind farm	Allison *et al.* (2017); Pescador *et al.* (2019)
Minimize	Installation of repellents to reduce collision probability	Placement of devices in the middle to deter raptors	1 Painting the wind turbine blades to make them more visible. Contradictory results among studies 2 Installation of UV lights to create visual disturbances. This measure has not been effective for the studied species 3 Generation of annoying sounds. The installation of these elements has not been shown to reduce collisions	Barrientos *et al.* (2011); May *et al.* (2013); Hunt *et al.* (2015); Allison *et al.* (2017)
Minimize	Nest removal	Removal of unoccupied nests by raptors before the breeding season begins or the disabling of areas where new nests could be established	Preventing raptors from nesting within wind farm facilities. There is controversy regarding its effectiveness and ethical considerations associated with such measures	Hunt and Watson (2016); Allison *et al.* (2017)

Byholm, 2021), although the degree of impact and vulnerability can vary depending on species (Smallwood *et al*., 2009; Hernandez-Pliego *et al*., 2015; Schuster *et al*., 2015; Dohm *et al*., 2019), habitats (Barrios & Rodriguez, 2004; Schuster *et al*., 2015; Watson *et al*., 2018) and the different technologies used by each wind farm (Hunt, 2002; Kikuchi, 2008; Sterže & Pogacnik, 2008; Schuster *et al*., 2015). Despite the variability in reported results in the scientific literature, there are common patterns in how birds interact with wind turbines. This allows for the determination of general aspects of knowledge acquired over time about the impact of wind farms on raptors and the establishment of some minimum consensuses (Watson *et al*., 2018).

Geographical and temporal variation

The study of mortality caused by wind farms has been extensively investigated over time. Variations in behavior and raptor foraging areas have also been widely studied. As these are the most visible impacts that can be observed following the installation of wind farms, these aspects have been extensively reported in the scientific literature.

Because onshore wind farms are predominant worldwide, they have been studied more over time (e.g. Hunt *et al*., 1999; de Lucas *et al*., 2008; Monti *et al*., 2023). However, the number of studies focusing on the impacts of offshore wind farms on raptors is much smaller. This could be attributed to the fact that the majority of raptors do not frequent marine areas, thus fewer efforts are invested in understanding the impacts of offshore windfarms. Furthermore, there are logistical difficulties of research the impacts of windfarms at sea (Schuster *et al*., 2015).

Among all the groups of raptors studied, the papers focusing on Accipitriformes have predominated over time (e.g. Murgatroyd *et al*., 2021). This may be because it is the largest group of raptors and likely includes more vulnerable species (Thaxter *et al*., 2017). The concern about understanding the effects and consequences of wind farms on Accipitriformes has led to a larger number of articles, and this number has remained relatively constant over time. The number of species studied in each research varied widely depending on the type of information desired and the methodology used to obtain that information (Dohm *et al*., 2019). Thus, single-species and multi-species studies have been published extensively over time.

The continents where the most research has been published over time are America and Europe. This could be because these are two continents with a large expansion of these infrastructures (Allison *et al*., 2017; Farfan *et al*., 2017) and congregate the countries with high economic income per capita. Therefore, they devote efforts to studying the impacts of wind farms on the most vulnerable species. The absence of articles from many Eastern countries such as Russia or China, and Southern nations, predominantly across the African continent, suggests a potential loss of scientific information, probably due to publications in non-English-languages (Konno *et al*., 2020; Amano *et al*., 2021). Although there are few articles published in Africa, there has been an increase in the number of articles on the continent in recent years (Reid *et al*., 2015; Cervantes *et al*., 2022). This may be driven by the increasing number of these infrastructures on the continent (McClure *et al*., 2021c), despite existing economic disparities worldwide.

There is variation in the number of publications across different continents, but the information reported in some of them is comparable because the concern about the impact of wind farms on raptors is shared worldwide. Despite the considerable variation in habitats, species and technologies used, much of the published information can be grouped and shared to simplify and facilitate future research. Furthermore, many of the findings contributed by researchers can be applied to different species inhabiting various parts of the world, thereby reducing the preparation and work time for future investigations.

Methods of data acquisition

The prevalence of local monitoring in most articles can be attributed to its cost-effectiveness, allowing for the collection of data on the number of birds crossing a wind farm, their altitude and flight direction. However, this methodology heavily relies on the observation skills and perception of field personnel, making it inherently variable (Madders & Whitfield, 2006; Douglas *et al*., 2012). Additionally, with larger wind farms, the detection of species through visual observations becomes more complex (Sur *et al*., 2018). Local monitoring is also a technique that varies depending on the field effort. Studies have shown that its efficiency improves in surveys where researchers spend the entire day in the field conducting observations (Chabot & Slater, 2018). Despite being the most commonly used methodology, there may be a vast array of different questions and different techniques to address them. Therefore, standardizing protocols can be a difficult task, making result comparisons challenging.

On the other hand, the use of GPS/GSM provides a viable alternative for detecting birds that pass close to wind farms, as it reduces the subjectivity associated with sampling effort and the experience of personnel (Kikuchi *et al*., 2019). Furthermore, it can facilitate early hazard detection (Watson *et al*., 2018). However, GPS/GSM data collection requires large sample sizes to draw conclusive information, which may not always be feasible for some species (López-López, 2016). The papers examined in this study that utilized GPS/GSM for data collection were able to analyze variations in behavior (e.g., changes in altitude, flight directions, or avoidance behavior) with a drastically reduced margin of error (e.g. Katzner *et al*., 2012; Sheppard *et al*., 2015; Mojica, Watts, & Turrin, 2016). Numerous applications exist, such as selectively stopping wind turbines when a GPS-equipped raptor enters a wind farm's area (Sheppard *et al*., 2015), early collision prevention (Watson *et al*., 2018), or even calibration of other methods to ensure they are being conducted correctly (Sur *et al*., 2018). Radio-tracking is a similar methodology to GPS/GSM but is less precise as it requires triangulation of bird positions, necessitates fieldwork to locate marked raptors, and also relies on large sample sizes (López-López, 2016). For these reasons, coupled with the availability of increasingly lightweight, smaller and cheaper transmitters, it is a technology that is practically obsolete, at least for raptors (though not for other animal groups like bats) (Gottwald *et al*., 2019). There is currently a new network, the Motus Wildlife Tracking System, that employs automated radio telemetry. This system is designed to study the movements of small flying animals, such as small birds. This new tool utilizes a single frequency at receiver stations across a wide geographic scale (Crewe *et al*., 2017; Griffin *et al*., 2020). Furthermore, it enables continuous and simultaneous tracking by multiple researchers. The development and implementation of this new technology can provide extensive information regarding the impact of wind farms on smaller raptors across a large spatial scale, allowing for the simultaneous study of various species.

For the calculation of bird mortality, carcass searches are the most commonly used methodology (e.g. Smallwood & Thelander, 2008; Smallwood & Karas, 2009). However, to obtain an accurate estimate of mortality, it is necessary to study the carcass disappearance rate (i.e. to estimate birds that have died but were not found due to scavenger activity) (Wilson, Hulka, & Bennun, 2022). In this methodology, there is also a lot of variation depending on the effort of the researcher and the type of carcass used (Smallwood, 2013; DeVault *et al*., 2017). Raptors are the carcasses that persist the longest, so some studies suggest that using other birds as carcasses to calculate the disappearance rate may alter the actual mortality rate (Smallwood *et al*., 2010; Hallingstad *et al*., 2018; Wilson *et al*., 2022). Furthermore, the absence of carcasses does not correlate with the absence of collisions, so some authors developed equations that allow estimating the number of collided birds based on the probability that these birds are within the study area (Huso *et al*., 2015).

Radar, due to its high economic cost and logistical difficulties, is the least used methodology. This technology is based on the use of electromagnetic waves to determine the type of raptor, its position and its speed (Schekler *et al*., 2023), which enables observations of birds that are not easily visible to the naked eye (e.g., migratory movements or nighttime bird displacements). However, deep learning methods are required to distinguish between the different elements it detects and eliminate radar echoes that limit species differentiation (Schekler *et al*., 2023). In some cases, direct field observations are also needed to calibrate the information obtained (Panuccio, Ghafouri, & Nourani, 2018).

The use of cameras triggered by the passage of birds near wind turbines allows for the determination of the number of birds crossing, and in some cases, the distinction between species and ages (Murai *et al*., 2015). Software based on artificial intelligence is employed to discern between the species present in the images (McClure *et al*., 2021c). However, the range of photography is not very extensive, so it may not capture all species passing near wind turbines. Additionally, these identification programs have certain associated errors, requiring machine learning supervision (McClure, Martinson, & Allison, 2018).

The use of visual marks or tags for the calculation of survival estimates in raptors has the drawback that it requires reading the marks to confirm the presence of an individual in a specific location, depending strictly on the researcher's effort and detection ability. While other methodologies can provide information such as speed, flight direction, or altitude, reading bands only allow the study of the presence or absence of an individual in a specific location without additional information about its origin (Strandberg, Klaassen, & Thorup, 2009).

The combination of methodologies for conducting studies that can be comparable and replicable in other research is crucial for obtaining results that can help reduce the impacts of these infrastructures on raptors (Smallwood, 2013).

Establishing global consensus on potential negative effects and their causes allows for a detailed examination of possible solutions to be implemented. Moreover, and most importantly, thanks to all the studies conducted to date, we can proceed to develop effective measures to reduce negative impacts and promote the conservation of raptors.

Lack of consensus on behavior and population dynamics

Given the abundance of studies aiming to ascertain the impacts of wind farms on raptors worldwide, there are various aspects for which sufficient consensus is still lacking.

With regard to annual variations, there is variation in the number of collisions depending on the season due to changes in the behavior and abundance of raptors at different times of the year (Barrios & Rodriguez, 2004; Carrete *et al*., 2012). Peaks in mortality have been reported during months of migratory activity (Barrios & Rodriguez, 2004; Smallwood *et al*., 2007). However, there is a lack of consensus on whether migratory raptors are the most affected (Kikuchi, 2008) or if it is the local ones (Katzner *et al*., 2012; Schuster *et al*., 2015).

Yet, there is also a lack of consensus as to whether raptors are differentially affected by gender and age factors. Some studies have concluded that there are more young individuals in the vicinity of wind farms (Dahl, 2014), and they exhibit lower avoidance behaviors (Watson *et al*., 2018). We have only found one article that addresses the difference between males and females concerning the risk of collision (Heuck *et al*., 2020). In this article, it is mentioned that no differences were found between the age of individuals of *Haliaeetus albicilla*, but there were differences between sexes. Males were more prone to collisions than females. Perhaps this can be explained by the effort exerted by males during the breeding season in the search for food.

Different studies argue that the reduction in the abundance of raptors in a specific area due to the presence of wind farms is temporary (Farfan *et al*., 2017; Dohm *et al*., 2019) and can recover over time. These abundances were observed following the long-term study of wind farms before and after their installation (8 and 6.5 years, respectively). While the first one has been debated due to the methodologies employed (Santos *et al*., 2020), the results suggest the recovery of some species in the study area. The diet of the studied species is highly varied and does not seem to be the likely cause of their recovery. Nonetheless, there is no consensus on this matter, as only two articles assert a recovery of abundance, and one of them has been widely criticized. It would be interesting to conduct further studies on this topic to analyze whether raptors can indeed acclimate and recover their abundance after extended periods of time.

Although not all studies report avoidance behavior, most confirm that raptors are capable of detecting the presence of a wind turbine and try to avoid it, regardless of the species or its size (Villegas-Patraca *et al.*, 2014; Cabrera-Cruz & Villegas-Patraca, 2016). However, it should be noted that certain species, such as vultures, are less likely to detect wind turbines due to their predominantly downward vision in search of carcasses, making them more vulnerable to collision (Martin, Portugal, & Murn, 2012). Avoidances have been observed in studies involving direct field observations as well as those using GPS/GSM technology. In the latter, precise changes in flight altitudes were observed following the detection of wind farms, which indicates the presence of avoidance behaviors (Johnston, Bradley, & Otter, 2014; Linder *et al.*, 2022). Moreover, changes in flight direction (Johnston *et al.*, 2014), displacement to other habitats (Marques *et al.*, 2020), or even shifts in nest locations (Dahl *et al.*, 2012) have also been reported. Among the various types of avoidance (macro-avoidance, meso-avoidance and micro-avoidance), there does not seem to be a relationship with the diet. This may also be attributed to the fact that the majority of articles were multispecies, and the diet could not be analyzed individually for each species covered in them.

Recognizing areas of non-consensus is crucial for advancing research on the effects of wind farms on raptors in a scientifically formal context. It underscores the dynamic and complex nature of ecological interactions, emphasizing the need for comprehensive investigations that consider various factors. By acknowledging gaps in consensus, researchers can identify specific aspects requiring further exploration, directing attention to critical areas where knowledge is limited.

Consensus on behavior and population dynamics

Soaring raptors make use of orographic lift in the absence of ascending thermal currents (e.g., in winter and during twilight hours) to ascend during their flights. Therefore, some of the most dangerous wind farms are those with turbines located on mountain ridges (Barrios & Rodriguez, 2004; Katzner *et al.*, 2012; Miller *et al.*, 2014; Schuster *et al.*, 2015; Singh *et al.*, 2016; Peron *et al.*, 2017; Poessel *et al.*, 2018a). Additionally, soaring raptors, being large birds, have less maneuverability in flight and tend to follow routes that minimize energy expenditure. They follow prevailing wind currents, which are also utilized by wind farms to generate energy. In this regard, some studies demonstrate a direct relationship between the distribution of dominant wind currents and the distribution of mortality in *Gyps fulvus* in wind farms (de Lucas *et al.*, 2012b). Moreover, regardless of size and flight type, in situations with adverse weather conditions (i.e. strong winds or low visibility), raptors engage in more high-risk flights (i.e. flight at rotor height) (Johnston *et al.*, 2014).

Regarding home range, articles reporting an increase have observed it due to disturbance caused by different phases of wind farm construction. This disturbance has led to a displacement of the studied species towards areas farther from the wind farm (Nishibayashi *et al.*, 2022). In the case of decreases, they have been observed in two different species: *Bubo bubo* and *Haliaateus albicilla* (May *et al.*, 2013; Husby & Pearson, 2022). Both species decreased their foraging areas as they were forced to move to other locations, altering their movement patterns due to the disturbance from the presence of wind farms.

Wind farms cause habitat degradation and habitat loss for raptors due to flight disturbance (e.g., noise or reflections) and the barrier effect (Balotari-Chiebao *et al.*, 2021; Fernández-Bellon, 2020; Jacobsen, Jensen, & Blew, 2019). The barrier effect limits their access and, as a result, leads to avoidance behavior (Schuster *et al.*, 2015). Additionally, wind farms are often located in areas that are ideal for prey hunting. Consequently, hunting grounds become disabled and raptors must search for food elsewhere, resulting in a loss of habitats used by raptors for their vital functions (Watson *et al.*, 2018).

In papers that studied the effect of wind farms on the population dynamics of raptors, it was found that in species with low individual density (i.e. threatened species), even though the probability of collision is lower, wind farm impacts affect population growth. This is because even a slight increase in adult mortality can lead to local extinction of a species in the short term, especially in long-lived species (Jongejans *et al.*, 2020). Other studies report that despite the local mortality caused by wind farms, the persistence of some species depends on the balance between population mortality and the rate of immigration of new individuals (Hunt *et al.*, 1999; Martinez-Abrain *et al.*, 2012; Katzner *et al.*, 2016; Watson *et al.*, 2018). The articles examining population trends observed a decline attributable to wind farms (e.g. Hunt *et al.*, 1999).

The breeding performance of some raptors can be affected by the installation of wind farms. This is because nest site selection and reproductive success depend largely on the proximity of wind farms (Martinez *et al.*, 2010; Kolar, 2013; Balotari-Chiebao *et al.*, 2016). For example, some raptors avoid nesting within a 500 m radius of wind farms (Pearce-Higgins *et al.*, 2009), while in others, there are reports of a lack of breeding individuals in the vicinity of wind farms due to noise pollution, which could hinder prey detection, especially in nocturnal raptors (López-Peinado *et al.*, 2020).

There is a consensus that local raptor abundance does not correlate with higher mortality (e.g. Ferrer *et al.*, 2012; Hull *et al.*, 2013; Martin *et al.*, 2018). The study of abundances could be used as a method to determine where to install a wind farm (Carrete *et al.*, 2012) or to compare large-scale raptor groups and similar species, but not for calculating collision probability (Watson *et al.*, 2018). Furthermore, there is consensus regarding the use of sensitivity maps to identify high-risk zones for wind farm installation. Some of the studied factors include the following: the presence of raptors flying at risk height (Vignali *et al.*, 2022), wind resources in raptor frequented areas (Miller *et al.*, 2014; Balotari-Chiebao *et al.*, 2018), the abundance of raptors vulnerable to collisions, proximity to breeding or feeding grounds (Percival, 2005) and steep slopes (Singh *et al.*, 2016; Poessel *et al.*, 2018b).

Solutions and conflicts of interest

A set of consensus management measures can be formulated based on the information derived from research investigating the impacts of wind farm on raptors. These measures are essential for predicting and mitigating adverse effects effectively in the long term, irrespective of the local or geographical context. Habitat suitability models have been widely employed in the literature reviewed. These models facilitate the creation of areas that are safer for raptors and the identification of zones where installation should be avoided. By utilizing these models, solutions such as relocating specific turbines or siting wind farms in different locations than originally planned can be implemented. It is crucial to test these models to assess their accuracy in representing the reality of the studied species and to determine their true utility.

Before-After-Control-Impact (BACI) designs are valuable tools for evaluating the effectiveness of implemented solutions or identifying potential solutions to be implemented. Such tools can be essential for studying population trends of species and understanding how these trends vary as a result of the presence of wind farms (Dahl *et al.*, 2012; Conkling *et al.*, 2021).

There are various solutions for the avoidance or minimization of the impact of wind farms on raptors. Among the proposed solutions aimed at avoiding impacts, turbine micro-siting stands out. By utilizing sensitivity maps to identify high-risk zones, modifying the placement of the most hazardous wind turbines can contribute to reducing mortality for numerous vulnerable species (Bay *et al.*, 2016). Regarding solutions aimed at minimizing negative effects, repowering has been also implemented. Although it may be controversial, this solution allows for a reduction in the number of turbines and an increase in rotor height, thereby reducing the collision risk for species with lower flight patterns (Smallwood & Karas, 2009). However, it could still pose a risk to species with higher flight patterns. Emergency shutdowns, or stop-on-demand systems, are also noteworthy. These systems enable the wind farm to stop if a target species approaches. This approach can be implemented on a long-term basis, such as during specific seasons when the study species is in the vicinity of the wind farm. Additionally, it can be adaptive, involving manual or automatic observation of a specific species approaching particular wind turbines. This solution has been implemented and has proven to be effective (de Lucas *et al.*, 2012b). Another proposed and tested solution is the removal of attractants. The elimination of potential food sources or perches has proven effective in reducing the number of collisions (Allison *et al.*, 2017). However, this practice in the long term could lead to the displacement and abandonment of territories.

The installation of repellents has a very similar application to the previously discussed solution. Auditory and visual repellents have been installed on turbines in some wind farms to make these elements more noticeable. One of the main challenges with these elements is the diversity in the vision and hearing abilities of each species. Acoustic repellents could be effective, but since hearing ability varies widely among species (nocturnal raptors are much more sensitive to sounds than diurnal ones), they should be tailored to species at higher risk (May *et al.*, 2015). However, this also poses a disadvantage, as they may work for some species but not be effective for others. Visual repellents have also been implemented, such as painting turbine blades black (May *et al.*, 2020), but we have not found any articles demonstrating their effectiveness in raptors apart from the article proposing it as a solution.

The removal of nests is also a proposed solution to prevent the presence of raptors, especially young individuals, near wind farms (Hunt & Watson, 2016). However, while this practice may be effective, it can also lead to the abandonment of territories and the displacement of species.

The implementation of evaluation schemes to assess the management measures is crucial to determine whether they should be modified or retained (Allison *et al.*, 2017; May *et al.*, 2021).

Another important challenge to address is the existence of conflicts of interest. The disclosure of conflicts of interest aims to reveal whether a private company has an interest in publishing specific information that may favor its interests. Interestingly, none of the examined papers included in our review declared conflicts of interest. It is advisable to explain and specify the possibility of their existence, as the data could be misinterpreted or information could be masked (Boutron *et al.*, 2019). One potential solution for conducting studies supported by renewable energy industries could involve establishing a contract between the environmental consultants or researchers and the company, stipulating that the publication of results would always be honest, even if it might potentially harm the contracting company. This contract could be appended to further scientific papers to demonstrate a genuine absence of conflicts of interest.

Future perspectives

Thanks to the compilation and sharing of existing consensuses published in scientific articles, we can focus more efforts on aspects where sufficient knowledge is still lacking or where a consensus has not yet been reached. Some possible lines of future research could include:

1. Verification of the effectiveness of proposed solutions, including the effectiveness of deterrents for raptors, as well as corrective measures over the 30-year lifespan of wind turbines, and developing efficient compensatory measures tailored to the most vulnerable species in the study area.
2. Calibration of predictive models using Before and After Control Impact (BACI) techniques. Comparing conditions before and after wind farm installation and between control and experimental sites to correct possible model errors

could enhance and complement existing information. Furthermore, standardization of this approach is necessary for cross-taxon comparisons.
3. Development of techniques to determine the number of collisions occurring in offshore wind farms and gain a deeper understanding of the impacts these types of farms have on raptors.

Conclusions

Raptors are the bird group most vulnerable to the presence of wind farms in their habitat. As a consequence, numerous papers aim to clarify the most relevant impacts on raptors and how these impacts could be reduced. Given the existing knowledge and the results reported in the literature, it is evident that, despite variations among species, habitats and types of wind farms, there is enough information to reach the following consensus:

1. The reviewed articles report that wind farms have a negative impact on the population dynamics of raptors.
2. The combination of different methods for obtaining information provides the possibility of obtaining comprehensive and reliable data. An adequate combination could involve using GPS/GSM for obtaining precise locations of vulnerable species, along with direct field observations to estimate bird abundances, and carcass searches to determine mortality rates.
3. Most papers agree that raptor abundance decreases after the installation of wind farms. In some cases, over time, abundances might recover to levels similar to those before wind farm installation.
4. The potential risk areas for raptors around wind farms have been extensively studied. The home ranges decrease as wind farms are farther from their territories and increase when they are closer, according to the examined articles.
5. After the installation of wind farms, increases in mortality and declines in population trends have been reported. Furthermore, the mortality of adult individuals drastically affects population dynamics, especially in endangered species. Nevertheless, using local abundances to calculate mortality risk is not a reliable method, as there is no correlation between pre-wind farm installation abundance and collision risk.
6. There are more papers reporting avoidance behaviors of raptors in relation to wind farms than studies that do not report avoidance. However, there are various forms of avoidance that are explored in diverse ways. Hence, there still exist numerous knowledge gaps concerning this topic.
7. The presence of thermal updrafts and orographic uplift is crucial for large raptors to gain altitude during flight. Therefore, wind farms located on mountain ridges are more dangerous for these species than those located in flat areas. This negative effect is especially pronounced in adverse weather conditions.
8. Although none of the articles reported conflicts of interest, it would be essential to honestly declare the potential existence of conflicts, as the interpretation of results could interfere with the particular interests of an electric sector company.
9. Presenting solutions and, fundamentally, verifying their effectiveness is crucial to mitigate the negative effects of wind farms and promote raptor conservation. This is especially important in the context of the increasing installed capacity of new wind farms due to growing energy demand and the global decarbonization process in progress worldwide.

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Authors’ contributions

I.E.-D. and P.L.-L. conceived the idea. I.E.-D.: analyzed the data and wrote the first draft of the paper. P.L.-L.: provided the materials and revised the paper.

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Supporting information

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

Data S1. Supporting Information.