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Wind Farms' Impacts on Raptors: Predictors, Study Methods, and Mitigation Measures

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Abstract

In order to slow down climate change, scientists recommend reducing the use of pollutant energy sources and developing renewable energies to both cope with excessive CO_2 emissions and decrease the use of fossil fuels. Among renewable energy sources, wind power is one of the most widespread worldwide. It is considered to have a lower environmental impact by reducing environmental pollution and water consumption. However, wind farms show potential adverse effects on the surrounding wildlife through two main disturbances: collision and displacement. In this paper, we first summarize factors likely to influence birds, and especially birds of prey collision on rotor turbines and effective displacement. This can help to outline which factors can better predict disturbance risks according to landscape characteristics, the species using the territory, or the wind facility features. In the second part, we discuss the experimental design, as well as the models used to assess disturbances. These experiments and analyses are necessary to identify the main disturbance predictors and quantify their relative contribution, which is crucial to establishing appropriate information-based mitigation measures that we detail in the last section.

Keywords

Wind Farms, Bird Mortality, Mitigation Measures, Avoidance Behaviour

1. Introduction

For centuries, energy has been extracted from fossil fuels while polluting and depleting the environment [1]. With a worldwide population of over 7.5 billion people, the demand for resources—from food to energy—is growing extensively [2]. This massive demand is the general driver of global change that poses a direct threat to biodiversity and ecosystem services. Nowadays, climate change draws the most attention and consideration in debates or funding [3]. In order to slow down climate change, scientists recommend reducing the use of pollutant energy sources and developing renewable energies to both cope with excessive CO_2 emissions and decrease the use of fossil fuels.

Among renewable energy sources, wind power is one of the most widespread worldwide, both offshore and onshore [4] [5]. It is considered to have a lower environmental impact by reducing environmental pollution and water consumption [6]. However, wind farms show potential adverse effects on the surrounding wildlife through two main disturbances: collision and displacement. Collision with the blades occurs in the case of no displacement and is often considered to be the main direct issue. However, displacement is at least as important, if not more so, since it results in effective habitat loss. Disturbances may drive animals into less suitable habitats and affect foraging activity, potentially reducing their ability to survive and consequently their reproductive success [7]. Disturbances driving displacement can occur at each step of the wind farm establishment: at the beginning, due to construction and transformation of the landscape, and then, during the whole lifetime of the wind facility, because of turbine avoidance behaviours and the effect of increased human and noisy machine presence for maintenance [8]. This indirect disturbance has been overlooked compared to the collision phenomenon. Indeed, numerous studies have recorded direct mortalities of animals, especially birds and chiropterans, on operational turbine rotors. Wind farms are expected to kill hundreds of thousands of bat individuals per year solely in the USA [9]-[11]. Furthermore, bat fatality observations have also been noticed in other countries developing wind power infrastructure, such as Spain [12] or Germany [13]. Bats are long-lived species with low reproduction rates and are therefore vulnerable to cumulative fatalities, suggesting a detrimental and substantial effect of wind facilities on certain bat populations [14] [15]. In this sense, it has been argued [16] that population growth rates of hoary bats (*Lasiurus cinereus*) were insufficient to reach stability in populations with high levels of mortality caused by wind turbines. Those results have led to the implementation of mitigation measures.

While studies about wind farm impact on birds are much more frequent, the scientific community agrees that birds are less affected than bats. The first concerns about the killing potential of rotor blades arose in the Altamont Pass Wind Resource Area in California (USA), where hundreds of birds, mainly raptors, collided each year [17]. Expressing this number with the commonly used unit, *i.e.*, the average number of fatalities yearly per turbine, gives a lower general impression since this reaches no more than 0.02 to 0.15 collisions/turbine at this site. However, considering the size of the Altamont Pass Wind Resource Area (7000 turbines), the total impact should not be underestimated. Similar considerations emerge at Zeebrugge Harbour in Belgium, with high levels of gull and tern fatalities: 19.1 collisions/turbine/year measured across the whole site. Considering only the 14 sea-directed turbines on the breakwater, this figure increased to 27.6 collisions/turbine/year. These numbers are partly explained by the high correction factors of searching efficiency and carcass removal by scavengers [18].

This difference evidences the importance of wind farm location among the large range of other factors predicting collision. Indeed, depending on study designs, models and factors used, studied species or wind park sites, the number of bird fatalities varies greatly. Some studies have even argued that wind facilities insignificantly impact most species of birds [19] [20].

However, there is a consensus that raptors (*i.e.*, orders Falconiformes, Accipitriformes, and Strigiformes) may be more prone to colliding with blades than other birds [21] [22] because of their morphology, foraging behaviour, or flight behaviour [23] [24]. Birds of prey are also more prone to foraging near turbines or even perching on them [17] [25]. A similar scenario to the Altamont Pass Wind Resource Area occurred in Navarre (Spain), where a one-year study recorded 138 bird carcasses, of which 62% were Griffon vulture (*Gyps fulvus*) [26]. Like bats, raptors are long-lived species characterised by a low reproductive rate and delayed maturation, making them more sensitive to any individual removal. Hence, even a small increase in their mortality rate by a wind farm may have a potentially significant negative effect on population viability [27]. Additionally, some of the mitigation measures that have been found to be effective for raptors were also effective for birds in general [16]-[23].

These proven consequences on the avifauna result in the implementation of conservation policies and mitigation measures in wind facilities to avoid or minimize the impact of disturbances. Yet, because of the complex predictor interactions, no general formula of combined factors can be designed to be successfully applied to any site [28].

In this review, we first summarize factors likely to influence bird of prey collision on rotor turbines and effective displacement. This can help to outline which factors can better predict disturbance risks according to landscape characteristics, the species using the territory, or the wind facility features. In the second part, we discuss the experimental design as well as the models used to assess disturbances. These experiments and analyses are necessary to identify the main disturbance predictors and quantify their relative contribution, which is crucial to establishing appropriate information-based mitigation measures that we detail in the last section of this review.

2. Disturbances and Their Predictors

To gather the available literature on the impact of wind farms on raptors, we conducted a search in the Web of Science and Google Scholar for articles published or available online until the end of 2023. We used 186 studies published in scientific journals concerning bird collisions and avoidance of wind turbines. The information gathered in this review could be helpful for future studies and protocols on the topic, and it facilitates a database with valuable information on risk assessment of raptor collisions with wind farms. We used different keywords and combinations of terms, such as "Wind farm" or "Wind-farm" or "Windfarm" or "Wind turbine" or "Wind-turbine" and "Raptor" or "Raptors" or "Bird of prey", and then we also checked for subsequent references as well as authors' bibliographies.

This comprehensive search employed the primary terms used to investigate the effects of wind farm installation on raptors. 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). **Table 1** summarizes the eight collision predictors discussed.

Table 1. Collision predictors.

Predictor of collision
morphology
age
abundance
seasonality
perception
topography
weather
prey
turbine features
configuration

2.1. Collisions

Collisions happen when birds have not been displaced. As previously shown, numerous predictors supposed to influence raptor crashes have been disentangled. However, since they are intricately interconnected, distinguishing one main collision driver is challenging. For instance, if a species with a specific morphology adapted for a certain type of flight is regularly found to be a wind turbine victim, we may argue that any species with this morphology would be more prone to colliding. But even if some species with this specific morphology are more likely to ram blades, others are not. These inconsistent results among similar species could originate in behavioural dissimilarity not reflected in the morphology [29].

2.1.1. Morphology, Behaviour, and Age

Morphological characteristics with a higher risk of collision are related to body size. Long, broad wings with a high wing load, correlated with a larger size, are characteristic of soaring birds such as raptors. These morphological features are associated with low manoeuvrability in flight and weak-powered flight capacity [30]. Thus, soaring flights rely heavily on updrafts to compensate for their weak-powered flight and minimize energy expenditure, allowing long-distance travel. Two types of updrafts are used by soaring birds: thermal uplift and orographic uplift [31]. Thermal uplifts are formed by the heat released from a surface struck by solar radiation. These thermal currents are thus dependent on seasonal and latitudinal fluctuations of solar irradiation, physical landscape features, and meteorological factors.

Soaring birds usually gain elevation by circular movement in thermals and glide linearly to the next thermal toward the chosen direction. Orographic uplift is generated by the deviation of horizontal wind on large obstacles or sloping terrain [32]. These uplifts are commonly used either to glide up and down or to travel along an orographic uplift corridor like mountain slopes [33]. Hence, birds tend to use favorable corridors with high uplift potential, especially during long travels. Thus, the importance of the migration path depends on the uplift location [34]. However, areas with high elevation potential are also sought after for wind farm projects. Thus, migratory corridors and wind facilities are often overlapping, resulting in soaring bird collisions or displacement. In some seasons with fewer thermals, birds are forced to rely more on orographic uplift, exposing them to the turbines at the top of the mountain slopes [35]. In Tarifa (Spain), a study concluded that the lack of seasonal thermals contributed to 49 raptor collisions, including 30 Griffon vultures, because vultures were compelled to use slopes to lift, exposing them to turbines [25] [36]. The close link between wind characteristics, flying behaviour, and landscape features will be regularly addressed throughout this review as they are substantial indicators of disturbance.

Collision risk is also related to certain spatial patterns and flight behaviours. While raptors are hunting or foraging, they use specific flight behaviours that are more prone to driving them into the rotor blades. In addition, being heavily focused and fixated on their prey, raptors decrease their vigilance regarding their surroundings, such as turbine location [25]. The kiting behaviour of the red-tailed hawks (*Buteo jamaicensis*) and the hovering behaviour of the common kestrels (*Falco tinnunculus*) have been identified as main predictors of their high death rate [25] [37]. Kiting and hovering are sensitive to strong changing winds with gusts that abruptly modify the position of the bird. Flight elevation also has an impact, which will be further developed in a section in relation to turbine height.

Age class has been regularly advanced as a collision predictor in mortality studies. Being young is expected to be associated with being less experienced in flight and hazard identification. A study on white-tailed hawks (*Geranoaetus albicaudatus*) showed that subadults were crossing the wind farm area more often than adults, increasing the collision probability, though no significant differential collision rate was eventually detected [38]. Conversely, a Norwegian wind farm located in a white-tailed eagle (*Haliaeetus albicilla*) nesting area recorded higher adult mortality compared to other age classes [39]. Gregarious roosting and territorial fights are likely to be the explanation for this selective fatality.

2.1.2. Abundance and Seasonality

A common rationale for high mortality of a particular species or at a certain site is bird abundance. This claim arises from the idea that statistically, a higher density of birds leads to a higher chance of bird collision. In a yearlong study, the authors highlighted an increase in mortality when turbines were standing in highly populated areas [27]. The same argument was put forward as an explanation for the high mortality rate of burrowing owls (*Athene cunicularia*), American kestrels (*Falco sparverius*), red-tailed hawks, and golden eagles (*Aquila chrysaetos canadensis*) at the Altamont Pass Wind Resource Area [17] [40] [41]. However, contradictory results were obtained, showing a high death rate of griffon vultures with no increase in mortality during the peak season of abundance [36].

Whether it is during migration or the breeding period, seasons influence bird abundance and behavioural patterns. In addition to population size variation, seasonality is linked to behavioural changes. For example, the white-tailed eagle has a peak of activity during the breeding season in spring, which also coincides with a peak of eagle collisions [42].

2.1.3. Sensorial Perception

Raptors are known for their extraordinarily sharp visual acuity, which is twice as high as that of humans for some species. Sight is the primary sense providing information about the bird's environment and the presence of prey carcasses [43]. The configuration of the field of view varies between scavengers and pursuit-hunters but remains significant [21] and may play a role in collision vulnerability [44], since raptors are not selected to detect obstacles in front of them. While birds of prey are foraging, flying at high altitudes and looking downward, no large objects are expected to be present in open areas. This situation has evolved, in certain large raptors, to a blind spot in the direction of their travel when foraging. This is well documented in griffon vultures, one of the species with the highest collision sensitivity, as well as in the short-toed eagle (*Circaetus gallicus*) or great bustard (*Otis tarda*) [45].

Linked to the visual sense, the phenomenon of motion smear is recognized as a likely collision predictor, which has been investigated and evidenced in laboratory experiments. While a bird approaches a rotating blade, the blade velocity creates a transparent blurry retinal image of the rotor that can be interpreted as a clear area to fly through [46].

Finally, low visibility has been regularly cited as a factor in bird collisions. However, numerous collisions occur on clear days [47].

2.1.4. Landscape Topography

Topography is a predictor of flight path and area use probability in raptors. For instance, migratory birds of prey are known to favour paths with rifts and slopes to benefit from orographic uplift formation. They also tend to concentrate on passing corridors where wind conditions and relative heights are favourable. In this sense, a study in Germany on red kite (*Milvus milvus*) found that developing a wind farm at a mountain pass used as a migratory route could result in higher bird mortality [48]. Similarly, an increase in the number of deaths of large raptors in wind turbines built on a coastal cliff used as a migration path was recorded [49]. Above a cliff and a steep slope, eagles fly at a lower altitude than above a flat landscape, thus increasing collision risk. As shown in a previous section, the flight behaviour of some raptors in a specific landscape can result in increased turbine-killing. Thus, wind farm implementation should avoid areas with certain topographic features.

2.1.5. Weather

Since bird movement relies on wind and thermal currents, weather is an important driver of bird death probability. Large-bodied soaring raptors are exposed to higher collision risks as they use the wind and updrafts to avoid high energy expenditure and employ flight techniques to gain altitude. A study of adaptive flights dependent on changing weather in migratory golden eagles proved that as wind speed increases, eagles rely more on orographic lift and less on thermal lift, leading to higher speed variation and decreased elevation [50]. Therefore, in strong wind conditions, fewer thermals are created, imposing a high-collision-risk flight based on orographic lifts closer to the topography. In mountainous landscapes, orographic lifts intensify when rising above the topography, which can drive migrant birds of prey straight to the turbine height [51].

2.1.6. Prey Availability

A high density of food near or within a wind farm increases collision vulnerability by a larger passage rate across turbines. In addition to wind farm size and topography factors, the high prey base in the vicinity of turbines has been attributed to the abnormal raptor fatalities at Altamont [19]. Some authors [52] pointed out that red-tailed hawk mortality was related to the distribution and occurrence of pocket gopher burrows (*Thomomys bottae*) living at the tower's base. In Spain, a study comparing the mortality rate of common kestrels in a wind farm with a before-after experiment reducing prey availability showed a decrease in the collision rate by 75% - 100% [53]. Thus, kestrels were no longer attracted to this unprofitable hunting area and fed in other, less dangerous areas.

2.1.7. Turbine Features

Since the beginning of wind power development, turbines have changed significantly, both in size and design. At Altamont wind farm, lattice turbines lead to perching and nesting behaviour, which is supposed to increase collision probability. However, no proper study has compared collision rates with lattice turbines as opposed to tubular turbines, and this debate is no longer relevant since very few lattice turbines are still operating [54]. Wind turbines tend to be built higher with larger rotor blades to improve energy production [55]. The effect of wind tower height on the probability of fatalities is the subject of a divided discussion. Several studies have enumerated an increasing number of dead birds under taller turbines [11] [36], while other studies observed the contrary [14] [56].

2.1.8. Wind Farm Configuration

The configuration of a wind farm can vary in tower distribution, the number of towers, and the distance between them. For instance, a negative correlation between the growth rates of the red kite population, the number of turbines, and their spatial setup has been found in Switzerland [48]. However, these results strongly rely on the relationship between the collision risk and the distance between wind turbines and red kite nests. For instance, at Altamont, isolated turbines and turbines situated at the end of the tower string were involved in high bird mortality [40]. Besides, wind turbines in clusters or in "wind wall" configuration showed a decrease in collision risks [40]. But these last results are not consistent among studies. Indeed, a study in the Netherlands did not find significant differences in mortality between "clustered" and "in line" wind farm configurations [55]. The same conclusion was drawn for griffon vulture fatalities in Tarifa, Spain, with no effect of turbine string organization [57].

2.2. Displacement

Displacement effects have been ignored for a long time in favor of the collision risk. Despite there still being gaps, the growing knowledge allows for investigation of the underlying mechanisms of behavioural responses. In this context, the displacement phenomenon has been divided into two types: macro- and micro-displacement. Macro-displacement is characterized by the avoidance of the entire wind farm and may result in a loss of suitable habitat or changes in migratory paths, leading to a decrease in energy stores and fitness. Micro-displacements, described as the avoidance of individual turbines, may trigger changes in flight behaviour. The type and magnitude of the avoidance effect are strongly associated with the site and the species [58].

2.2.1. Avoidance Behaviour

Macro and micro-avoidance behaviours depend on the occurrence of the species in the wind facility area. In the United States, several before-after experiments have evidenced a post-construction reduction in raptor abundance. Some authors have shown a lower breeding success of white-tailed eagles near the turbines after construction, resulting in a decrease in population growth [38]. Furthermore, more subadults than adult eagles have been observed inside the area, which could be a consequence of adult displacement. Since the eagle abundance was substantial before the wind farm development, part of the population has been repelled further, increasing the post-development density outside of the wind facility area. To escape this density and enhance their fitness, subadults may find wind turbine zones more suitable. However, because of the increased collision risk due to repeated crossing, wind farm habitat may become an ecological trap, especially due to any lack of clear avoidance flight response to towers in white-tailed eagles [38] [59]. Following the same pre- and post-construction method, some authors showed

[60] both micro and macro-avoidance behaviours at the Forward Energy Wind Center (FEWC). Indeed, they measured a 47% decrease in raptor abundance after the construction of a wind farm and distinguished high scores in avoidance behaviour, especially in northern harrier (*Circus hudsonius*) and turkey vulture (*Cathartes aurea*). In contrast, Montagu's harriers (*Circus pygargus*) displayed no sign of displacement throughout a wind facility development [61] and, in fact, the number of nests increased. Unfortunately, most studies on this topic are short-term assessments and do not allow for an investigation of the possible resilience of the surrounding population after several years of wind farm operation. Partly to fill this gap, some authors [62] gathered long-term data from previous studies at FEWC. They found some abundance resilience after 7 - 8 years for turkey vultures, red-tailed hawks, sharp-shinned hawks (*Accipiter striatus*) and Cooper's hawks (*Accipiter cooperii*). This result is species dependent, since northern harriers and American kestrel populations never rebounded throughout the assessment period.

2.2.2. Migratory Route

The development of wind facilities in the middle of migratory corridors is of concern since they can create a barrier effect. Before-after experiments have enumerated fewer eagles flying within an operating area during migration, suggesting macro-avoidance behaviour [51]. Migratory soaring birds may perceive the wind park as a barrier and try to avoid them, resulting in consequent extra energy expenditure [63]. However, no studies to date have deeply studied the potential macro-avoidance effect.

Establishing a general model of species-, site-, and wind farm-specific factors is complex. Even if this part draws up a non-exhaustive list of factors, it is a starting point for conservation measures and environmental assessment before wind facility development. Indeed, vulnerable species and intensively used areas can be identified to set up appropriate mitigation measures and the optimal turbine location. Thus, it is strongly advised to conduct a detailed study of the raptor community, habitat use, behaviour, and site topography at each location of the future site during the planning stage, and this requires rigorous methodologies and adapted models.

3. Methods and Models

Wind facilities have been identified as potentially harmful to the environment. Risk assessments of ecological impacts typically require knowledge of baseline population estimates and demographics [64]. Thus, systematic environmental monitoring is needed, especially for avian fauna [65]. The reliability of the results and the impact derived from them are both based on the methods of data collection during these monitoring activities and the analyses or models used. The designs of experiments vary from one study to another, and these differences lead to divergent results.

3.1. Experimental Design

More and more widely spread in recent years, the Before-After-Control-Impact (BACI) design fits particularly well with studies on displacement disturbance. Its goal is to compare environmental components before and after anthropogenic activity development, and between the area expected to be affected by the development and a control area. The comparison with a reference area makes the impact quantification more reliable [66]. In the case of wind farm development effects, the BACI design compares bird abundance or behaviour both before and after the wind facility development between an impacted area (*i.e.*, a wind farm) and a control area. Other similar alternative approaches exist, such as Impact-Reference (IR), which compares environmental variables between a site of interest and a reference one. The Impact-Gradient (IG) approach does not compare with a reference site but rather looks for a gradient of impacts. Basically, a gradually decreasing negative effect from the wind farm area to the surrounding area is expected. For instance, a study on the displacement of bird abundance would expect an increasing number of birds with distance from turbine plants if an effect were noticeable. The Before-After (BA) study evaluates the effect of wind facility construction and operation by comparing bird abundance before and after the development of this renewable energy production site. However, such studies should be carefully carried out since a change in bird abundance may be caused by many other concurrent factors than wind farm development. Controlling for confounding environmental factors influencing bird abundance independently is thus crucial to avoid any erroneous interpretation. In addition, it is advised to run the study over several years, long enough to detect a potential return to pre-construction abundance or as a control site [67].

3.2. Data Collection

The experimental designs previously shown mostly assess abundance, spatial distribution, flight patterns, or avoidance rates, depending on the aims of the study, by means of a systematic monitoring effort recording observations of raptors and their behaviours while passing through the areas of interest. Observations are often performed with binoculars and field scopes at certain vantage points inside or outside the survey area. Depending on the scientific rigor of the experiment, the vantage point location allows for complete or incomplete coverage of the survey area. The most common information recorded during an observational survey includes the species, their number, their activity (hunting, foraging), their flight behaviour (flying, soaring, hovering), or their height and distance from the turbines [68].

Specifying the weather, the date, the time of daily light, and the observer is also important to account for potential environmental and observational biases. The use of radar or cameras coupled with bird identification software (IdentiFlight, EchoTrack TM) is developing. Indeed, it limits bias by allowing for species identification and continuous and simultaneous tracking of bird movements regardless of the time of day, visual acuity of the observer, and their number [69]-[71]. Species-specific population studies are also more likely to fit birds with automated remote sensors such as GPS or radio transmitters and data loggers, which can record high spatial-temporal resolution movements over a long period of time.

3.3. Collision Risk Models

In the last decades, different models predicting bird collision risk at wind farms have emerged: Tucker's, Podolsky's, Biosis Research's model, etc. However, these models are often considered too simplistic regarding the number of integrated factors [8]. Therefore, the commonly used model is the Collision Risk Model [72]. It is a two-step process model based on data describing the bird (size, speed, flapping, etc.) and the wind facility (number of blades, rotor size, speed, etc.). Stage 1 estimates the number of birds flying through the rotor, and Stage 2 predicts the proportion of collisions among these birds. The Collision Risk Model formula is the multiplication of the strike likelihood by the number of birds crossing the wind farm area at risk height. Originally, the model did not assume any bird avoidance behaviour when encountering a turbine. But since the opposite has been evidenced, an adjustment has been made by multiplying the predicted collision risk by the avoidance rate. This modification is crucial and lies at the heart of the prediction accuracy, raising criticisms [73]. Indeed, the rate of avoidance is often high, heavily influencing the prediction of collision risk. Criticism has questioned how this avoidance rate is assessed in the field and how reliable it can be considered. One way of assessing this rate is the difference between predicted fatality and observed fatality. However, conventional experiments evaluating the mortality rate at operating wind farms have faced several issues of bias on which the criticisms are based: observer's carcass detection and scavenger's carcass removal.

The method classically relies on a systematic search along parallel transects beneath the turbine area or circular plots with a radius of 50 m centred at each sample turbine site [74]. The size of the search plot is commonly determined according to the radius of the total height of the wind turbine [74]. Depending on the weather, the vegetation density, the landscape, or the victim size, some corpses might be less conspicuous. Two studies at different sites yet with the same experimental design detected, respectively, 30% versus 57% of small bird carcasses and 49% versus 90% of large bird carcasses [75] [76]. This difference in results encourages an adjustment of the mortality rate for observer detection.

To decide if correction factors to account for search biases are necessary and to build them, some studies evaluate the observer search efficiency by a preliminary study. In one of them, small and large carcasses were placed at random on the plot, and observers performed a search session in the normal way. Then, the observer's findings were compared to the number of carcasses that had been dropped to determine the search efficiency. The removal rate of the carcasses by scavengers can also be the subject of a preliminary study. In the case of a too large time lapse between collisions and the field survey, the activity of the scavengers can make the collision rate estimates decrease. A prior study assessing the time of disappearance of corpses allows the calibration of this time lapse. By laying out carcasses and visiting them daily until they disappear, scientists can estimate the rate of scavenger carcass removal based on the time of disappearance and the carcass size [25] [74].

Other statistical approaches assessing the bird fatality rate at a wind farm adapt their estimate to build a relatively unbiased estimate of the real mortality occurring at a given project. Moreover, the estimate is often less accurate in the case of rare fatalities [39]. Finally, the Band collision risk model implicitly assumes a direct positive relationship between fatalities and the size of the bird population, but as I detailed in a previous section, this link is questioned or falsified in other studies. Thus, the use of this model as a predictive tool could be a substantial fallacy if this assumption turns out to be false [36]. To deal with these uncertainties, other authors [77] built their own collision risk model, incorporating uncertainty directly into bird mortality estimates. Since primary estimates are based on pre-construction monitoring, updates can be added in case the fatality number is refined with post-construction monitoring. This approach uses a Bayesian analytical framework to integrate uncertainties in the three parameters considered: hazardous footprint, turbine bird exposure, and collision probability. This simple model could be accessible to scientists, managers, or policymakers.

4. Mitigation Measures

Wind turbines may generate different effects on bird fauna, particularly on raptors. As with any other infrastructure with potential adverse effects, the planning, construction, operation, and management phases of wind farm developments should assess the type and intensity of any negative impact on the bird population and set appropriate mitigation measures to avoid or minimize them [78]. Mitigation measures (see **Table 2**) are diverse and necessitate rigorous pre-experiment information to determine the most appropriate and successful strategy. They must be determined on a case-by-case basis according to the species present, the wind farm features, and the development stage [58]. These measures can be set up at two main separate stages of the project development: at the design stage before construction and during functioning after construction.

Table 2. Summary of the described mitigation measures with their effectiveness and limitations.

Mitigation measure	Description	Effectiveness	Limits	Studies
		Pre-construction measures		
New wind-farm siting	Avoid wind energy development in inappropriate locations.	Proven	Trade-off between high energy production potential and wildlife protection	Marques *et al.*, 2014; Bright, Langston & Anthony, 2009

Continued

Turbine configuration	Avoid turbine organisation suspected to be harmful (turbine string).	Not proven but likely	Trade-off between high energy production potential and wildlife protection	Ferrer *et al.*, 2012; De Lucas *et al.*, 2012
Building period	Avoid wind farm construction during the sensitized period.	Not proven but likely	Wind farm construction duration	Drewitt & Langston, 2006
		Post-construction measures		
Turbine shutdown	Selective and momentary turbine shutdown in the case of a high-risk situation detected by observers or automated devices.	Proven	None	Marques *et al.*, 2014; Watson *et al.*, 2018
Turbine operation restriction	Turbine shutdown is temporary during the sensitive period determined by the collision risk model.	Not proven but highly potential	Loss of energy production	Smallwood *et al.*, 2007
Habitat management	Modify the habitat to limit the attractiveness of the wind farm area and promote activity in more distant habitats.	Proven	Collateral effect on other species	Paula *et al.*, 2011; Pescador, Ramíres & Peris, 2019
Deterrent devices	Use the bird's natural instinct to frighten them and deter them from flying through the wind farm.			
• Acoustic deterrents	Use of bio-acoustic (distress call or bird alarm) or high-intensity sounds (shotguns or horns).	Proven at other man-made structures, not at wind farms. High potential	Habituation	Gartman *et al.*, 2016
• Visual deterrents	Use of lasers to create contrast with the ambient light and frighten birds.	Proven at other man-made structures, not at wind farms. High potential	Limited in daylight	Bishop *et al.*, 2003
Ground devices	Established on the ground at a certain distance from wind farms, it is supposed to warn and frighten birds to induce a change in their flight paths.	Possible	Visibility	Martin *et al.*, 2012
Blade visibility	Painting the blade rotor with a specific pattern or ultraviolet paint to limit motion smear.	Partly proven High potential	Limited at night and dependent on the species' ability to see ultraviolet wavelengths	May *et al.*, 2020

4.1. Pre-Construction

Nowadays, national and international legislations obligate any anthropogenic activities or developments impacting the environment to plan environmental impact assessment procedures beforehand [8]. This is even more relevant as the number of renewable energy production sites is constantly growing, inducing greater cumulative pressure on the environment [78]. An environmental impact assessment allows identification of sensitive characteristics of the site to establish adapted mitigation measures and alleviate the negative effects of the wind farm installation. Currently, these measures are an integral part of any project of wind turbine park construction.

At the initial planning of the wind plants area, mitigation measures focus on avoiding inappropriate locations. Since landscape topography, bird abundance, and occurrence of vulnerable species, or the location of individual turbines, are identified as predictors of impact, they must be considered at the pre-construction stage of wind turbines. Avoiding, for example, areas of high bird abundance, especially those most vulnerable or that commonly use wind corridors, reduces the risk of problems to be managed at later stages of a project. Thus, the precautions taken in choosing the wind farm location should be adopted as a standard of development [79]. A useful tool in identifying sensitive areas would be to model a sensitivity map of the habitat, territory, and activity of birds during the environmental impact assessment. Once created, this map guides the location of the whole wind facility as well as that of turbines at the individual level [80]. Indeed, special attention should be paid to the spatial configuration of turbines within the park to avoid turbine strings perpendicular to migratory routes or turbines near wind currents and topographic structures preferably used by soaring birds [57] [81]. Wind tunnels and simulation software have also been adapted as predictive tools used for the optimum design of facilities with lower impact. A high-resolution orographic and thermal updraft modelling tool to determine the probability of white-tailed eagles crossing was used [82]. Here, wind currents predict the presence of eagles, their flight behaviour, and therefore the likelihood of collision. Finally, a good pre-construction measure would be to avoid building wind farms during sensitive periods such as the breeding or juvenile fledging period [69].

4.2. Post-Construction

Despite an adequate risk-based design and the precautionary measures applied before the development, disturbances may persist or appear during the subsequent operational stage. New mitigation measures can thus be established to minimize bird collision or displacement phenomena. To determine the degree and type of minimization required, systematic monitoring of the post-construction impact is needed.

4.2.1. Operation Management

One of the few operations that have proved its positive effects is shutting down the turbine and stopping the blade rotation on demand under high-risk collision situations. Poor weather conditions, low visibility, birds flying at rotating blade altitude, or crossing flocks of rare migratory birds are all specific situations requiring the spin to be stopped [79]. The relevance of this measure lies in the possibility of specifically choosing the period and turbine that need to be shut down. Indeed, as mortality distribution differs periodically and from one turbine to another, this allows operators to focus turbine-stopping surveillance efforts on only the most dangerous turbines. A monitoring study comparing collision rates in the Strait of Gibraltar, an important migratory bottleneck, before and after the implementation of a turbine shutdown protocol as a mitigation measure, found that griffon vulture mortality decreased by more than 50% just by selectively stopping individual turbines when vultures were observed nearby [57]. Regarding the profitability of energy production, some authors [57] recommended short curtailments of turbine operations with stops between the first and last two hours at sunrise and sunset, respectively, for a 0.07% reduction in energy production per year only. This minimization measure mitigates the impact of wind facilities with only a limited effect on renewable energy production [39] [57]. In addition, automatic tools to turn off turbines after the detection of birds are increasingly being developed, allowing for more efficient detection, especially under certain conditions limiting human visual acuity (bad weather or night), while lowering the average non-functioning periods [79]. A wind farm's Radar Assisted Shutdown on Demand (RASOD) program with pre-setting sensitive to intense migration or soaring birds' presence was tested [83]. While 570 to 1550 individuals were detected as high-risk of striking, no collision of soaring birds was recorded, thanks to the efficiency of the RASOD.

Conversely, measures restricting turbine operation impact wind farms' productivity more heavily and are thus less accepted by wind energy companies. The restricted operation of the turbine differs from turbine shutdown because it relies on collision risk predictive models and not on the actual occurrence of high-risk situations. This results in limiting blade spinning according to season, weather, or a part of the day, *i.e.*, keeping turbines non-operating over a long period of time. For instance, stopping rotors during winter has been shown to reduce burrowing owl mortality by 36%, but at the expense of a 14% loss in energy production [41]. However, this kind of measure should not be dismissed since it has been shown to be efficient for bats with minimal impact on wind farm productivity, as already discussed in the introduction of this review [84].

4.2.2. Habitat Management

A completely different mitigation strategy is habitat management by moving away, displacing, or restoring far from an indispensable resource. At the Altamont Pass Wind Resource Area, prey availability was expected to partly explain the important mortality rate. Following the principle of habitat management would entail removing or at least reducing the prey population in the area, with many collateral effects on other species dependent on this resource [41]. One way to avoid additional effects is the surrounding habitat enhancement, which improves feeding opportunities or foraging habitat offsite [78]. An intense use made by a golden eagle couple of a managed area with a restored wild rabbit (*Oryctolagus cuniculus*) population, in comparison to their neglecting of a control area with a dangerous power line, was reported [85]. Although this experiment was carried out on a power line installation, the successful conclusion led them to apply this strategy to a wind farm. This is rather consistent since wind facilities are not only composed of turbines but of power lines as well [25]. Concerning scavenger birds, foraging area management to limit scavenger attraction is simple, as it implies removing carcasses or creating feeding stations away from wind farms [45].

Another way of controlling prey availability or hunting behaviour is vegetation management. Indeed, some birds of prey are more prone to hunt in open areas like wind farm-induced landscapes. To counteract this behaviour, some authors suggested [85] planting scrubs under turbines in order to densify the vegetation of the area and restrict the hunting behaviour of common kestrels close to the turbines. Following the same goal of reducing kestrel collisions, other authors [53] did exactly the opposite, that is, decreased the vegetation density by tilling underneath turbines to limit the prey population and attained a 75% - 100% collision reduction after two years of monitoring. These two opposite strategies focusing on the same aim and species highlight the complexity of minimizing wind facility impacts.

4.2.3. Deterrent Devices

Mitigation measures can also use the birds' natural instinct to deter them from flying into the risk area by frightening them. These deterrent devices can be based on various sensory cues depending on the targeted animals. For birds, the acoustic deterrent is viewed as the most effective, especially bio-acoustic devices like distress calls or bird alarms [78]. However, this strategy is species-specific and sometimes may attract other species that investigate the threat before flying away. High-intensity sounds such as shotguns or horns are interesting to use because they trigger a reaction at greater distances than a distress call, though they may generate noise nuisance for human neighbours. The main negative point of acoustic deterrence is the habituation phenomenon that can emerge. Birds are more likely to become accustomed to high-intensity sounds than to alarm calls since they have no relevant biological meaning. Furthermore, a single sequence played regularly from the same area is more likely to trigger the habituation mechanism quickly. Ideally, the device should be played manually only when flocks or individual birds displaying high-risk behaviours are detected [86]. These sound-based minimization measures have not yet been the subject of any scientific research on wind farms, and the evidence comes from old studies carried out mainly in airports. Further studies should investigate their efficiency as a mitigation strategy at wind facilities [78].

Visual deterrent devices are proposed as an attractive alternative. Usually based on lasers, they are advantageous since they can be used at a great distance, regardless of the weather conditions, and can be directed straight at birds. Birds' fright comes from the contrast between the laser beam and the ambient light. While efficient under low light conditions or at night on nocturnal birds, their use is limited in daylight [86]. Another deterrent strategy relies on the fact that birds look down while flying. Diverting this characteristic, which is at the origin of the non-detection of turbines, to derive a mitigation mechanism is the principle of ground devices. Ground devices are expected to make man-made structures, such as wind facilities, more conspicuous by placing them at a certain distance from turbines to scare birds and induce a change in their flight path [47]. Poorly developed and requiring no verification of effectiveness for their implementation, little literature exists on the subject. At Altamont Pass Wind Resource Area, a decoy tower, *i.e.*, a turbine without rotor blades, was placed around the wind farm to reduce bird collisions, especially at the ends of the rows of turbines where the risk of collision is highest [87], but no experiment testing their effectiveness has been performed so far. However, some concerns have been expressed about the possible attraction of and perching on these decoy towers, which would lead to an increase in the presence of birds [87].

The role of blade visibility and the above-mentioned phenomenon of motion smear have also been used to develop visual deterrent systems. Hodos' experiments on blade paintings have determined paint patterns more likely to be detected by birds [46]. For instance, a thin-stripe staggered pattern and a single black blade are better distinguished than other paintings. These lab-obtained results could be different in the field. A BACI study [88] comparing avian fatalities before and after the blades were painted found a decrease of over 70% in the annual mortality for painted turbines. However, this experiment was based on only four turbines with a black blade. This device should be investigated on larger samples and other wind farms to attain reliable results. Similarly, the use of ultraviolet paint has been tested since some birds are known to see in the ultraviolet spectrum [89]. This technique is already applied against avian window strikes, and a proposal for its use at wind facilities has been made, but its efficiency still needs to be proven. Nevertheless, raptors like the golden eagle or common buzzard, lacking this visual spectrum, would not benefit from this measure [79] [90].

5. Conclusions

The growing number of wind facilities throughout the world and the concern about their effect on biodiversity have led to extensive monitoring of onshore structures in recent decades. As a result, the main disturbance factors and the affected taxa are currently well documented. Particular attention is paid to avian communities, and especially to raptors, as these long-lived, slow-maturing, and low-productivity species are identified as usual victims of wind turbines. This literature review compiled a list of the main predictors of collision probability and displacement effect, and, although not exhaustive, it discusses factors that have been experimentally tested to date, regardless of their results. While well identified, some of these factors, such as the role of visibility or acuity of raptors in fatal collisions, are still not fully understood, and further studies could help to address this issue. On the contrary, extensive investigation on mortality aggregation or flight behaviour, for instance, has ended up providing a wide-ranging comprehension of the underlying causes, which are the interaction of topography and wind currents. However, not all predictor interactions have been studied in detail and unclear areas remain regarding the impacts of wind farms on different species.

The lack of long-term studies is a recurring criticism because it does not allow us to grasp the whole picture; only short-term effects are observed, although a wind farm has a lifespan of 30 years. Long-term studies are even more relevant given that mitigation measures are crafted based on the impact they assess. Fortunately, this trend is changing, partly thanks to environmental protection legislation. In addition, each wind farm has its own characteristics, ranging from the species present and their abundance to the topography of the location and configuration of the wind turbines. Because of their complex interactions, the resulting environmental effects can vary from one wind farm to another. This is the reason why legislation requires a case-by-case impact assessment of wind farm projects. Rigorous and well-designed specific monitoring programs, such as BACI designs, are thus essential for comprehensive and reliable results.

Studies have particularly emphasized the importance of the choice of location for wind facility development, and nowadays, this is the main mitigation measure set at the pre-construction stage. In the case of unexpected or non-weakened impacts evidenced during post-monitoring, various additional minimization measures can be established. However, the efficiency of some of the strategies shown has not been investigated. Therefore, further research would be necessary to rule out onerous measures with no proven usefulness, which can sometimes discourage wind energy companies from putting wildlife protection at the core of their policy. Currently, turbine shutdown protocols are considered the most promising strategies since they allow for the best trade-off between loss in energy production, decrease in bird mortality, and installation costs. In addition, simultaneously implementing several mitigation measures rather than a single one is recommended in order to establish optimal cost-benefit minimization measurement programs [79].

Avian mortality is one of the most negative impacts of wind energy. Consequently, techniques that effectively reduce avian collision rates are necessary. As far as we know, the best result published to date was that obtained using the method of the stop-turbine system [91] [92], otherwise known as a Turbine Shutdown System (TSS). Analyzing changes in mortality over 15 years, starting two years before the application of a selective stopping protocol (2006-2007) and after 13 years of application (2008-2020), this protocol was applied in the Cadiz area (southern Spain) to 20 wind farms, totaling 269 wind turbines. The priority in the shutdown protocol was to avoid large soaring bird collisions, mainly raptors. In total, 2903 birds were found to have collided with wind turbines in this 15-year period. This represents a rate of 0.830 birds/turbine/year. After implementation of the selective stopping protocol, a significant reduction of 61.7% in mortality of soaring birds (mainly raptors and storks) was found. Considering only mortality records of Griffon Vultures, a reduction of 92.8% was achieved. Counts of Griffon Vultures increased more than 7-fold during the study period, and the number of turbine stops due to vultures at risk in wind farms also increased by around 2.5 times. These findings of Griffon Vulture mortality being reduced by over 92% through turbine shutdowns were associated with only an estimated loss of less than 0.51% in energy production. This substantial disparity in conservation benefits versus industrial costs suggests that this mitigation method could have net-beneficial application elsewhere.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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