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Review

Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies

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ABSTRACT

Bird mortality due to collisions with wind turbines is one of the major ecological concerns associated with wind farms. Data on the factors influencing collision risk and bird fatality are sparse and lack integration. This baseline information is critical to the development and implementation of effective mitigation measures and, therefore, is considered a priority research topic. Through an extensive literature review (we compiled 217 documents and include 111 in this paper), we identify and summarize the wide range of factors influencing bird collisions with wind turbines and the available mitigation strategies. Factors contributing to collision risk are grouped according to species characteristics (morphology, sensorial perception, phenology, behavior or abundance), site (landscape, flight paths, food availability and weather) and wind farm features (turbine type and configuration, and lighting). Bird collision risk results from complex interactions between these factors. Due to this complexity, no simple formula can be broadly applied in terms of mitigation strategies. The best mitigation option may involve a combination of more than one measure, adapted to the specificities of each site, wind farm and target species. Assessments during project development and turbine curtailment during operation have been presented as promising strategies in the literature, but need further investigation. Priority areas for future research are: (1) further development of the methodologies used to predict impacts when planning a new facility; (2) assessment of the effectiveness of existing minimization techniques; and (3) identification of new mitigation approaches.

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1. Introduction

Wind energy generation has experienced rapid worldwide development over recent decades as its environmental impacts are considered to be relatively lower than those caused by traditional energy sources, with reduced environmental pollution and water consumption (Saidur et al., 2011). However, bird fatalities due to collisions with wind turbines[1] (WT) have been consistently identified as a main ecological drawback to wind energy (Drewitt and Langston, 2006).

Collisions with WT appear to kill fewer birds than collisions with other man-made infrastructures, such as power lines, buildings or even traffic (Calvert et al., 2013; Erickson et al., 2005). Nevertheless, estimates of bird deaths from collisions with WT worldwide range from 0 to almost 40 deaths per turbine per year (Sovacool, 2009). The number of birds killed varies greatly between sites, with some sites posing a higher collision risk than others, and with some species being more vulnerable (e.g. Hull et al., 2013; May et al., 2012a). These numbers may not reflect the true magnitude of the problem, as some studies do not account for detectability biases such as those caused by scavenging, searching efficiency and search radius (Bernardino et al., 2013; Erickson et al., 2005; Huso and Dalthorp, 2014). Additionally, even for low fatality rates, collisions with WT may have a disproportionate effect on some species. For long-lived species with low productivity and slow maturation rates (e.g. raptors), even low mortality rates can have a significant impact at the population level (e.g. Carrete et al., 2009; De Lucas et al., 2012a; Drewitt and Langston, 2006). The situation is even more critical for species of conservation concern, which additionally sometimes suffer the highest collision risk (e.g. Osborn et al., 1998).

High bird fatality rates at several wind farms[2] (WF) have raised concerns among the industry and scientific community. High profile examples include the Altamont Pass Wind Resource Area[3] (APWRA) in California because of high fatality of Golden eagles (*Aquila chrysaetos*), Tarifa in Southern Spain for Griffon vultures (*Gyps fulvus*), Smøla in Norway for White-tailed eagles (*Haliaatus albicilla*), and the port of Zeebrugge in Belgium for gulls (*Larus* sp.) and terns (*Sterna* sp.) (Barrios and Rodríguez, 2004; Drewitt and Langston, 2006; Everaert and Stienen, 2008; May et al., 2012a; Thelander et al., 2003). Due to their specific features and location, and characteristics of their bird communities, these WF have been responsible for a large number of fatalities that culminated in the deployment of additional measures to minimize or compensate for bird collisions. However, currently, no simple formula can be applied to all sites; in fact, mitigation measures must inevitably be defined according to the characteristics of each WF and the diversity of species occurring there (Hull et al., 2013; May et al., 2012b). A deep understanding of the factors that explain bird collision risk and how they interact with one another is therefore crucial to proposing and implementing valid mitigation measures.

Due to the increasing number of studies, particularly those implementing a Before-After-Control-Impact (BACI) study design, our knowledge of the interactions between birds and WT has increased immensely compared to the early stages of the wind energy industry. However, despite the fact that the impacts of avian collisions with WT have been extensively reviewed (e.g. Drewitt and Langston, 2006; Everaert and Stienen, 2008), information on the causes of bird collisions with WT remains sparse and is often compiled in technical reports that are not readily accessible (Northrup and Wittemyer, 2013). To our knowledge, the review on avian fatalities due to collisions with man-made structures by Drewitt and Langston (2008) was the first major attempt to compile information that, until then, was scattered across many peer-reviewed articles and gray literature. However, it focused on different types of structures, and collisions with WF were only alluded to. Moreover, new questions regarding WF have emerged and valuable research has been conducted on the topic that requires a new and extensive review of bird interactions with WT.

Here, we update and review the causes of bird fatalities due to collisions with WT at WF, including the most recent findings and considering species-specific, site-specific and WF-specific factors. We discuss how this information may be used when planning and managing a WF, based on a mitigation hierarchy that includes avoidance, minimization and compensation strategies (Langston and Pullan, 2003). We also highlight future research needs.

2. Methods

We reviewed a wide range of peer-reviewed and non-peer-reviewed articles, technical reports and conference proceedings

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[1] Wind Turbine – WT.

[2] Wind Farm – WF.

[3] Altamont Pass Wind Resource Area – APWRA.

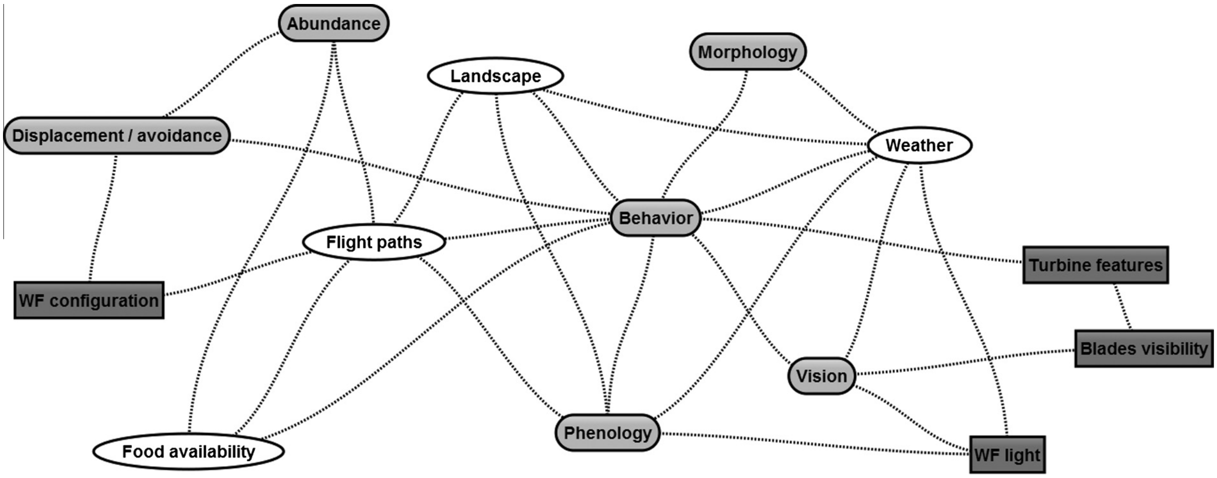

Fig. 1. Relationships between the species-specific (round/gray), site-specific (elliptical/white) and wind farm-specific (square/dark) factors influencing bird collision risk with WT.

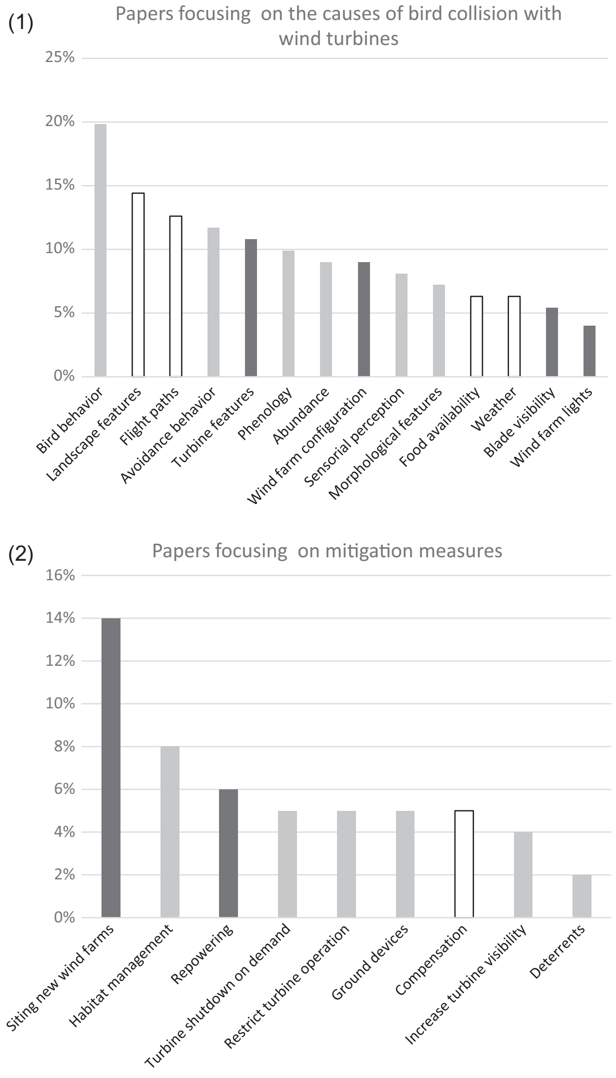

Fig. 2. Percentage of studies that mention: (1) factors influencing bird collisions with wind turbines: species-specific (gray), site-specific (white) and wind farm-specific (dark) and (2) different strategies to mitigate bird collision: avoidance (dark), minimization (gray) and compensation (white).

on topics related to bird fatalities at WF. The literature was found by means of search engines (Web of Knowledge and Google Scholar), conferences and workshops. Beginning with the more general topic of bird fatalities at WF, we refined our search with key phrases such as “bird collision”, “collision with turbines”, “causes of collision”, “morphology” (particularly “wing-loading”), “flight type”, “behavior”, “vision”, “hearing”, “flight patterns”, “weather”, “landscape features”, “migration routes”, “offshore features”, and wind farm features such as “scale”, “configuration”, “layout”, “lights”, “visibility”, “turbine size”, “turbine height”, and “mitigation”, “avoidance”, “minimization” and “compensation”. Due to the vast amount of technical information available, we did not limit our search to the use of a few specific keywords, but we tried several possible combinations to perform an extensive search of the literature on each sub-topic. In total we compiled 217 documents and from those we reference 111 in our paper, 90 regarding bird interacting with WF. We selected a subset of literature presenting (1) evidences based on experimental designs rather than inferences; (2) studies considering different types of birds communities and geographic areas; (3) emphasizing the peer-reviewed studies, when the information was overlapping between documents; and (4) the most recent findings on the subject (60% of the documents considered were published on 2008 or later, after the most recent previous review of this topic).

The studies we found may provide a non-random representation of all data collected regarding this area of research, as not all the documents produced are made publicly available. The data presented are geographically biased, favoring countries that have already had wind energy for more than a decade and with larger investments in wind energy developments, but also those with larger resources to assure monitoring programs and research. Therefore, 60% of the papers regarding WF referenced are from Europe (mainly Spain and UK) and 33% from USA.

We only summarize the aspects relating to WT themselves. Complementary structures at WF facilities, such as power lines or meteorological towers, were not included in order to ensure focused analysis and to keep our review as objective as possible.

3. Causes of bird collisions with wind turbines: factors influencing risk

We identified a wide range of factors influencing bird collisions with WT. Although we examine each factor individually below for simplicity, they are interconnected. To represent these connections, we graphically outline the complex relationships between the explanatory variables of bird collisions in Fig. 1. While we could not identify one particular factor as being the main cause of bird collisions due to these strong interactions, we can group the factors into three main categories: species-, site- and WF-specific. Fig. 2 represents the number of papers that refer or test the importance of each factor, showing that bird behavior is the factor more frequently reported in the literature.

3.1. Species-specific factors

3.1.1. Morphological features

Certain morphological traits of birds, especially those related to size, are known to influence collision risk with structures such as power lines and WT. The most likely reason for this is that large birds often need to use thermal and orographic updrafts to gain altitude, particularly for long distance flights. Thermal updrafts (thermals) are masses of hot, rising wind that form over heated surfaces, such as plains. Being dependent on solar radiation, they occur at certain times of the year or the day. Conversely, orographic lift (slope updraft), is formed when wind is deflected by an obstacle, such as mountains, slopes or tall buildings. As such they are formed depending on wind strength and terrain topography. Soaring birds use these two types of lift to gain altitude (Duerr et al., 2012).

Janss (2000) identified weight, wing length, tail length and total bird length as being collision risk determinant. Wing loading (ratio of body weight to wing area) and aspect ratio (ratio of wing span squared to wing area) are particularly relevant, as they influence flight type and thus collision risk (Bevanger, 1994; De Lucas et al., 2008; Herrera-Alsina et al., 2013; Janss, 2000). Birds with high wing loading, such as the Griffon vulture, seem to collide more frequently with WT at the same sites than birds with lower wing loadings, such as Common buzzards (*Buteo Buteo*) and Short-toed eagles (*Circaetus gallicus*), and this pattern is not related with their local abundance (Barrios and Rodríguez, 2004; De Lucas et al., 2008). Hence, this is probably because species with a high wing-loading need to rely more on the use of updrafts to gain altitude and to soar, particularly for long-distance flights, compared to species with lower wing-loading that tend to use the metabolically less efficient flapping (Mandel et al., 2008). High wing-loading is also associated with low flight maneuverability (De Lucas et al., 2008), which determines whether a bird can escape an encountered object fast enough to avoid collision.

3.1.2. Sensorial perception

Birds are assumed to have excellent visual acuity, but this assumption is contradicted by the large numbers of birds killed by collisions with man-made structures (Drewitt and Langston, 2008; Erickson et al., 2005). A common explanation is that birds collide more often with these structures in conditions of low visibility, but recent studies have shown that this is not always the case (Krijgsveld et al., 2009).

The visual acuity of birds seems to be slightly superior to that of other vertebrates (Martin, 2011; McIsaac, 2001). Unlike humans, who have a broad horizontal binocular field of 120°, some birds have two high acuity areas that overlap in a very narrow horizontal binocular field (Martin, 2011). Relatively small frontal binocular fields have been described for several species that are particularly vulnerable to collisions, such as Griffon vultures and African vultures (*Gyps africanus*) (Martin and Katzir, 1999; Martin and Shaw, 2010; Martin, 2012, 2011; O'Rourke et al., 2010). Furthermore, for some species, their high resolution vision areas are often found in the lateral fields of view, rather than frontally (e.g. Martin and Shaw, 2010; Martin, 2012, 2011; O'Rourke et al., 2010). Finally, some birds tend to look downwards when in flight, searching for conspecifics or food, which puts the direction of flight completely inside the blind zone of some species (Martin and Shaw, 2010; Martin, 2011). For example, the visual fields of Griffon vultures and African vultures include extensive blind areas above, below and behind the head and enlarged supra-orbital ridges (Martin et al., 2012). This, combined with their tendency to angle their head toward the ground in flight, might make it difficult for them to see WT ahead, which might at least partially explain their high collision rates with WT compared to other raptors (Martin, 2012).

Currently, there is little information on whether noise from WT can play a role in bird collisions with WT. Nevertheless, WT with whistling blades are expected to experience fewer avian collisions than silent ones, with birds hearing the blades in noisy (windy) conditions. However, the hypothesis that louder blade noises (to birds) result in fewer fatalities has not been tested so far (Dooling, 2002).

3.1.3. Phenology

It has been suggested that resident birds would be less prone to collision, due to their familiarity with the presence of the structures (Drewitt and Langston, 2008). However, recent studies have shown that, within a WF, raptor collision risk and fatalities are higher for resident than for migrating birds of the same species. An explanation for this may be that resident birds generally use the WF area several times while a migrant bird crosses it just once (Krijgsveld et al., 2009). However, other factors like bird behavior are certainly relevant. Katzner et al. (2012) showed that Golden eagles performing local movements fly at lower altitudes, putting them at a greater risk of collision than migratory eagles. Resident eagles flew more frequently over cliffs and steep slopes, using low altitude slope updrafts, while migratory eagles flew more frequently over flat areas and gentle slopes, where thermals are generated, enabling the birds to use them to gain lift and fly at higher altitudes. Also, Johnston et al. (2014) found that during migration when visibility is good Golden eagles can adjust their flight altitudes and avoid the WT.

At two WF in the Strait of Gibraltar, the majority of Griffon vulture deaths occurred in the winter. This probably happened because thermals are scarcer in the winter, and resident vultures in that season probably relied more on slope updrafts to gain lift (Barrios and Rodríguez, 2004). The strength of these updrafts may not have been sufficient to lift the vultures above the turbine blades, thereby exposing them to a higher collision risk. Additionally, migrating vultures did not seem to follow routes that crossed these two WF, so the number of collisions did not increase during migratory periods. Finally, at Smøla, collision risk modeling showed that White-tailed eagles are most prone to collide during the breeding season, when there is increased flight activity in rotor swept zones (Dahl et al., 2013).

The case seems to be different for passerines, with several studies documenting high collision rates for migrating passerines at certain WF, particularly at coastal or offshore sites. However, comparable data on collision rates for resident birds is lacking. This lack of information may result from fewer studies, lower detection rates and rapid scavenger removal (Johnson et al., 2002; Lekuona and Ursua, 2007). One of the few studies reporting passerine collision rates (from Navarra, northern Spain) documents higher collision rates in the autumn migration period, but it is unclear if this is due to migratory behavior or due to an increase in the number of individuals because of recently fledged juveniles (Lekuona and Ursua, 2007). Another study, at an offshore research platform in Helgoland, Germany, recorded disproportionate rates of collision (almost 2 orders of magnitude) for nocturnal migratory passerines compared to non-passerines (Hüppop et al., 2006).

3.1.4. Bird behavior

Flight type seems to play an important role in collision risk, especially when associated with hunting and foraging strategies. Kiting flight, which is used in strong winds and occurs in rotor swept zones, has been highlighted as a factor explaining the high collision rate of Red-tailed hawks (*Buteo jamaicensis*) at APWRA (Hoover and Morrison, 2005). The hovering behavior exhibited by Common kestrels (*Falco tinnunculus*) when hunting may also explain the fatality levels of this species at WF in the Strait of Gibraltar (Barrios and Rodríguez, 2004). Kiting and hovering are associated with strong winds, which often produce unpredictable gusts that may suddenly change a bird's position (Hoover and Morrison, 2005). Additionally, while birds are hunting and focused on prey, they might lose track of WT position (Krijgsveld et al., 2009; Smallwood et al., 2009).

Collision risk may also be influenced by behavior associated with a specific sex or age. In Belgium, only adult Common terns (*Sterna hirundo*) were impacted by a WF (Everaert and Stienen, 2007) and the high fatality rate was sex-biased (Stienen et al., 2008). In this case, the WF is located in the foraging flight path of an important breeding colony, and the differences between fatality of males and females can be explained by the different foraging activity during egg-laying and incubation (Stienen et al., 2008). Another example comes from Portugal, where recent findings showed that the mortality of the Skylark (*Alauda arvensis*) is sex and age biased, affecting mainly adult males. This was related with the characteristic breeding male song-flights that make birds highly vulnerable to collision with wind turbines (Morinha et al., 2014).

Social behavior may also result in a greater collision risk with WT due to a decreased awareness of the surroundings. Several authors have reported that flocking behavior increases collision risk with power lines as opposed to solitary flights (e.g. Janss, 2000). However, caution must be exercised when comparing the particularities of WF with power lines, as some species appear to be vulnerable to collisions with power lines but not with WT.

Several collision risk models incorporate other variables related to bird behavior. Flight altitude is widely considered important in determining the risk of bird collisions with offshore and onshore WT, as birds that tend to fly at the height of rotor swept zones are more likely to collide (e.g. Band et al., 2007; Furness et al., 2013; Garthe and Hüppop, 2004).

For marine birds, the percentage of time flying and the frequency of time flying during the night period have also been used as indicators of vulnerability to collision, since birds that spend more time flying, especially at night, are more likely to be at risk of collision with WT (Furness et al., 2013; Garthe and Hüppop, 2004). This factor varies seasonally, perhaps because flight activity increases during the chick rearing and breeding seasons or because of a peak of flight activity during migration (Furness et al., 2013).

3.1.5. Avoidance behaviors

Collision fatalities are also related to displacement and avoidance behaviors, as birds that do not exhibit either of these behaviors are more likely to collide with WT. The lack of avoidance behavior has been highlighted as a factor explaining the high fatality of White-tailed eagles at Smøla WF, as no significant differences were found in the total amount of flight activity within and outside the WF area (Dahl et al., 2013). However, the birds using the Smøla WF are mainly subadults, indicating that adult eagles are being displaced by the WF (Dahl et al., 2013).

Two types of avoidance have been described (Furness et al., 2013): 'macro-avoidance' whereby birds alter their flight path to keep clear of the entire WF (e.g. Desholm and Kahlert, 2005; Plonczkier and Simms, 2012; Villegas-Patraca et al., 2014), and 'micro-avoidance' whereby birds enter the WF but take evasive actions to avoid individual WT (Band et al., 2007).

Displacement due to WF, which can be defined as reduced bird breeding density within a short distance of a WT, has been described for some species (Pearce-Higgins et al., 2009). Birds exhibiting this type of displacement behavior when defining breeding territories are less vulnerable to collisions, not because of morphological or site-specific factors, but because of altered behavior.

3.1.6. Bird abundance

To date, research on the relationship between bird abundance and fatality rates has yielded distinct results. Some authors suggest that fatality rates are related to bird abundance, density or utilization rates (Carrete et al., 2012; Kitano and Shiraki, 2013; Smallwood and Karas, 2009), whereas others point out that, as birds use their territories in a non-random way, fatality rates do not depend on bird abundance alone (e.g. Ferrer et al., 2012; Hull et al., 2013). Instead, fatality rates depend on other factors such as differential use of specific areas within a WF (De Lucas et al., 2008). For example, at Smøla, White-tailed eagle flight activity is correlated with collision fatalities (Dahl et al., 2013). In the APWRA, Golden eagles, Red-tailed hawks and American kestrels (*Falco spaverius*) have higher collision fatality rates than Turkey vultures (*Cathartes aura*) and Common raven (*Corvus corax*), even though the latter are more abundant in the area (Smallwood et al., 2009), indicating that fatalities are more influenced by each species' flight behavior and turbine perception. Also, in southern Spain, bird fatality was higher in the winter, even though bird abundance was higher during the pre-breeding season (De Lucas et al., 2008).

3.2. Site-specific factors

3.2.1. Landscape features

Susceptibility to collision can also heavily depend on landscape features at a WF site, particularly for soaring birds that predominantly rely on wind updrafts to fly (see Sections 3.1.1 and 3.1.3). Some landforms such as ridges, steep slopes and valleys may be more frequently used by some birds, for example for hunting or during migration (Barrios and Rodríguez, 2004; Drewitt and Langston, 2008; Katzner et al., 2012; Thelander et al., 2003). In APWRA, Red-tailed hawk fatalities occur more frequently than expected by chance at WT located on ridge tops and swales, whereas Golden eagle fatalities are higher at WT located on slopes (Thelander et al., 2003).

Other birds may follow other landscape features, such as peninsulas and shorelines, during dispersal and migration periods. Kitano and Shiraki (2013) found that the collision rate of White-tailed eagles along a coastal cliff was extremely high, suggesting an effect of these landscape features on fatality rates.

3.2.2. Flight paths

Although the abundance of a species *per se* may not contribute to a higher collision rate with WT, as previous discussed, areas with a high concentration of birds seem to be particularly at risk of collisions (Drewitt and Langston, 2006), and therefore several guidelines on WF construction advise special attention to areas located in migratory paths (e.g. Atienza et al., 2012; CEC, 2007; USFWS, 2012).

As an example, Johnson et al. (2002) noted that over two-thirds of the carcasses found at a WF in Minnesota were of migrating birds. At certain times of the year, nocturnally migrating passerines are the most abundant species at WF, particularly during spring and fall migrations, and are also the most common fatalities (Strickland et al., 2011).

For territorial raptors like Golden eagles, foraging areas are preferably located near to the nest, when compared to the rest of their home range. For example, in Scotland 98% of movements were registered at ranges less than 6 km from the nest, and the core areas were located within a 2–3 km radius (McGrady et al., 2002). These results, combined with the terrain features selected by Golden eagles to forage such as areas closed to ridges, can be used to predict the areas used by the species to forage (McLeod et al., 2002), and therefore provide a sensitivity map and guidance to the development of new wind farms (Bright et al., 2006).

WF located within flight paths can increase collision rates, as seen for the WF located close to a seabird breeding colony in Belgium (Everaert and Stienen, 2008). In this case, WT were placed along feeding routes, and several species of gulls and terns were found to fly between WT on their way to marine feeding grounds. Additionally, breeding adults flew closer to the structures when making frequent flights to feed chicks, which potentially increased the collision risk.

3.2.3. Food availability

Factors that increase the use of a certain area or that attract birds, like food availability, also play a role in collision risk. For example, the high density of raptors at the APWRA and the high collision fatality due to collision with turbines is thought to result, at least in part, from high prey availability in certain areas (Hoover and Morrison, 2005; Smallwood et al., 2001). This may be particularly relevant for birds that are less aware of obstructions such as WT while foraging (Krijgsveld et al., 2009; Smallwood et al., 2009).

Higher food density can strongly increase collision risk at offshore sites. For example, the “reef effect” whereby fish aggregate around offshore turbine foundations and submerged structures can attract piscivorous birds and increase collision probability with WT (Anderson et al., 2007).

3.2.4. Weather

Certain weather conditions, such as strong winds that affect the ability to control flight maneuverability or reduce visibility, seem to increase the occurrence of bird collisions with artificial structures (Longcore et al., 2013). Some high bird fatality events at WF have been reported during instances of poor weather. For example, at an offshore research platform in Helgoland, Germany, over half of the bird strikes occurred on just two nights that were characterized by very poor visibility (Hüppop et al., 2006). Elsewhere, 14 bird carcasses were found at two adjacent WT after a severe thunderstorm at a North American WF (Erickson et al., 2001). However, in these cases, there may be a cumulative effect of bad weather and increased attraction to artificial light.

Besides impairing visibility, low altitude clouds can in turn lower bird flight height, and therefore increasing their collision risk with tall obstacles (Langston and Pullan, 2003).

For WF located along migratory routes, the collision risk may not be the same throughout a 24-h period, as the flight altitudes of birds seem to vary. The migration altitudes of soaring birds have been shown to follow a typically diurnal pattern, increasing during the morning hours, peaking toward noon, and decreasing again in the afternoon, in accordance with general patterns of daily temperature and thermal convection (Kerlinger, 2010; Shamoun-Baranes et al., 2003).

Collision risk of raptors is particularly affected by wind. For example, Golden eagles migrating over a WF in Rocky Mountain showed variable collision risk according to wind conditions, which decreased when the wind speed raised and increased under head- and tailwinds when compared to western crosswinds (Johnston et al., 2014).

3.3. Wind farm-specific factors

3.3.1. Turbine features

Turbine features may play an important role in bird collision risk, but as such turbine features are often correlated, it is not possible to partition this risk according to individual features. Older lattice-type towers have been associated with high collision risk, as some species exhibiting high fatality rates used the turbine poles as roosts or perches when hunting (Osborn et al., 1998; Thelander and Rugge, 2000). However, in more recent studies, tower structure did not influence the number of bird collisions, as it was not higher than expected according to their availability when compared to collisions with tubular turbines (Barrios and Rodríguez, 2004).

Turbine size has also been highlighted as an important feature, as higher towers have a larger rotor swept zone and, consequently, a larger collision risk area. This is particularly important in offshore sites, as offshore WT tend to be larger than those used onshore. Even so, the relationship between turbine height and bird collision rate is not consistent among studies. In some cases, fatalities increased with turbine height (De Lucas et al., 2008; Thelander et al., 2003), while in others turbine height had no effect (Barclay et al., 2007; Everaert, 2014). This suggests that, like bird abundance, the relationship between turbine height and collision risk may be site- or species-dependent.

Rotor speed (revolutions per minute) also seem to be relevant, as faster rotors are responsible for higher fatality rates (Thelander et al., 2003). However, caution is needed when analyzing rotor speed alone, as it is usually correlated with other features that may influence collision risk as turbine size, tower height and rotor diameter (Thelander et al., 2003), and because rotor speed is not proportional to the blade speed. In fact, fast spinning rotors have fast moving blades, but rotors with lower resolutions per minute may drive higher blade tip speeds.

3.3.2. Blade visibility

When turbine blades spin at high speeds, a motion smear (or motion blur) effect occurs, making WT less conspicuous. This effect occurs both in the old small turbines that have high rotor speed and in the newer high turbines that despite having slower rotor speeds, achieve high blade tip speeds. Motion smear effect happens when an object is moving too fast for the brain to process the images and, as a consequence, the moving object appears blurred or even transparent to the observer. The effect is dependent on the velocity of the moving object and the distance between the object and the observer. The retinal-image velocity of spinning blades increases as birds get closer to them, until it eventually surpasses the physiological limit of the avian retina to process temporally changing stimuli. As a consequence, the blades may appear transparent and perhaps the rotor swept zone appears to be a safe place to fly (Hodos, 2003). For example, McIsaac (2001) showed that American kestrels were not always able to distinguish moving turbine blades within a range of light conditions.

3.3.3. Wind farm configuration

WF layout can also have a critical influence on bird collision risk. For example, it has been demonstrated that WF arranged perpendicularly to the main flight path may be responsible for a higher collision risk (Everaert et al., 2002 & Isselbacher and Isselbacher, 2001 in Hötker et al., 2006).

At APWRA, WT located at the ends of rows, next to gaps in rows, and at the edge of local clusters were found to kill disproportionately more birds (Smallwood and Thellander, 2004). In this WF, serially arranged WT that form wind walls are safer for birds (suggesting that birds recognize WT and towers as obstacles and attempt to avoid them while flying), and fatalities mostly occur

Table 1
Summary of the effectiveness and costs of the avoidance and minimization techniques analyzed and their relationships to the factors influencing risk (+ low; ++ medium; +++ high).

Mitigation strategy	Technique	Short description	Effectiveness	Financial cost	Target bird species/groups	Target collision risk factor
Avoidance	Siting new wind-farms	Strategic planning, pre-construction assessment and EIA Whenever a new wind project is planned	Proven	+/++	– All groups and species, with a focus on species vulnerable to collision or endangered species	– Bird abundance – Phenology – Landscape features – Flight paths – Food availability – Wind farm-specific factors
	Repowering	Whenever a new wind project is remodeled and based on post-construction monitoring programs	Proven	+/++	– All groups and species. Opportunity to have a new wind farm layout, problematic turbines and areas can be decommissioned	
Minimization	Turbine shutdown on demand	Selective and temporary shutdown of turbines during at risk periods Observers or automatic devices detect birds at risk and selective shutdown of turbines is undertaken	Proven	++/+++	– All bird species, particularly large birds or during pronounced migratory events	– Bird abundance – Flight paths – Weather – Phenology
	Restrict turbine operation	Turbine shutdown during periods with high collision risk, identified through collision risk modeling	High potential	+++	– Species highly vulnerable to collision or endangered species – Pronounced migratory periods	
	Habitat management	Promote bird activity in areas away from the turbines and decrease bird activity near the turbines	High potential	+/++/+++	– Species with marked preferences regarding habitat selection	– Bird abundance – Food availability – Flight paths
	Increasing turbine visibility	Blades painted with colored patterns or ultraviolet-reflective paint	High potential	+	– Only a limited range of species (not an option for vultures or other species that constantly look down when flying)	– Sensorial perception – Blade visibility
	Ground devices	Conspecific models that attract birds Decoy towers to displace birds	Possible	+/++	– Conspecific models may be applicable to social or gregarious species – Decoy towers may be applied for species exhibiting avoidance behaviors for such structures	– Bird behavior – Avoidance behaviors
	Deterrents	Auditory and laser deterrents that displace birds	Possible	++	– May benefit only a small range of species – Lasers applicable only to nocturnally-active birds	– Bird abundance – Flight paths

at single WT or WT situated at the edges of clusters (Smallwood and Thellander, 2004). However, this may be a specificity of APWRA. For instance, De Lucas et al. (2012a) found that the positions of the WT within a row did not influence the turbine fatality rate of Griffon vultures at Tarifa. Additionally, engineering features of the newest WT require a larger minimum distance between adjacent WT and in new WF it is less likely that birds perceive rows of turbines as impenetrable walls. In fact, in Greece it was found that the longer the distance between WT, the higher is the probability that raptors will attempt to cross the space between them (Cárcamo et al., 2011).

3.3.4. Wind farm lights

Lit WT can attract birds, increasing the risk of collision, especially in conditions of poor visibility where visual cues are nonexistent and birds have to depend mostly on magnetic compass navigation (Poot et al., 2008). Nocturnally migrating birds can be particularly disoriented and attracted by red and white lights (Poot et al., 2008). In contrast, resident birds seem to be less affected, as they get used to the presence of artificial light and do not use magnetic compass orientation (Mouritsen et al., 2005). As a consequence, there are records of large fatalities at a variety of lit structures, arising from nocturnal-migrant songbirds being disorientated by lights (Gauthreaux and Belser, 2006). Nevertheless, an analysis of the impact of flashing red lights recommended by the US Federal Aviation Administration did not reveal significant differences between fatality rates at WT with or without flashing red lights at the same WF (Kerlinger et al., 2010).

Bird collisions with lit structures are likely to be more pronounced at sea than on land, and particularly during nights of heavy migration and adverse weather conditions (Hüppop et al., 2006). At an offshore WF in Germany, a high number of bird collisions occurred at a platform that was brightly lit at night (Hüppop et al., 2006).

4. Strategies to mitigate bird collisions

Here, we explore the mitigation options that have been proposed to decrease the risk of bird collisions caused by WF, categorized in terms of avoidance, minimization and compensation in accordance with best management practice. Fig. 2 represents the number of papers that mention each mitigation measure. The factors presented in Section 3 inform the WF planning process and facilitate the elaboration of mitigation measures. The relationships between collision risk factors and mitigation strategies are outlined in Table 1.

4.1. Avoidance

The most important stage of mitigation is initial WF planning, as WT location is one of the most significant causes of impacts on wildlife. In addition, good early planning could avoid the need for costly minimization and compensatory measures.

4.1.1. Siting new wind farms

Over the years, several national and regional guidelines for WF development that take into account the impact on wildlife have been developed, namely in the USA, Europe and Australia (e.g. Atienza et al., 2012; CEC, 2007; European Union, 2011; SGV, 2012; USFWS, 2012).

At the early stages, WF planning should be conducted from an expanded strategic perspective. Managing WF over a broad geographical area is one of the most effective means of avoiding their impacts on nature (Northrup and Wittemyer, 2013) and is also helpful in reducing the risk of problems at later stages of a project (European Union, 2011).

General opinion is that the most effective way to lessen impacts on birds is to avoid building WF in areas of high avian abundance, especially where threatened species or those highly prone to collisions are present. Therefore, guidance suggests that strategic planning should be based on detailed sensitivity mapping of bird populations, habitats and flight paths, to identify potentially sensitive locations. Based on these recommendations, several sensitivity maps have been developed on a national and regional scale (e.g. Bright et al., 2008, 2009; Fielding et al., 2006; Tapia et al., 2009).

It is important to note that sensitivity mapping does not replace other impact assessment requirements such as SEA and EIA. Local assessments are essential and several authors and authorities have proposed guidelines or standard methodologies to characterize a study area (e.g. Furness et al., 2013; Kunz et al., 2007; Strickland et al., 2011). Bird collision risk is usually estimated during pre-construction surveys and monitoring programs. The most commonly used method to estimate collision rates is the Band collision risk model (Band et al., 2007), which takes into account factors such as flight height, avoidance behavior, ratio aspect and turbine characteristics. Another example is the Bayesian method proposed by the U.S. Fish and Wildlife Service, which provides a standard methodology to predict eagles' fatalities at WF (USFWS, 2013).

Regarding soaring birds, De Lucas et al. (2012b) proposed wind tunnels to perform the WT micro-siting. This approach uses local wind flows and topographic data to build an aerodynamic model to predict the areas more frequently used by soaring birds, and thus determine which areas should be avoided when selecting WT locations.

However, there is a lack of studies comparing prior risk evaluation with subsequent fatalities recorded at an operational WF, which could validate these approaches. The first study that compared predicted versus observed fatalities, Ferrer et al. (2012) found a weak relationship between predicted risk variables in EIA studies in Andalusia, Spain, and actual recorded fatalities, but just for two species – Griffon vultures and Common kestrels. These results suggest that not all factors influencing collision risk are being considered in pre-construction studies. Ferrer et al. (2012) also propose that such factors should be analyzed at the individual WT and not at the entire WF scale, as birds do not move randomly over the area, but follow the main wind currents, which are affected by topography and vary within a WF.

It is therefore essential to understand why birds collide with WT in order to plan and conduct a comprehensive and appropriate analysis. It is essential at this phase to focus attention at the species or group level, as studying at a broader community level introduces excessive complexity and does not facilitate effective assessment. The analysis should be focused on species susceptible to collisions with WT and also to endangered species present in the study area.

4.1.2. Repowering as an opportunity

WT have a relatively short life cycle (ca. 30 years) and equipment remodeling must be undertaken periodically. Repowering is considered an opportunity to reduce fatalities for the species of greatest concern: (1) WF sites that have adverse effects on birds and bats could be decommissioned and replaced by new ones that are constructed at less problematic sites or (2) WT of particular concern could be appropriately relocated. It is essential that monitoring studies are carried out first, before undertaking such potentially positive steps.

Also, as technology has rapidly progressed in recent years, there is a trend to replace numerous small WT by smaller numbers of larger ones. The main changes have been a shift toward higher rotor planes and increased open airspace between the WT. Despite taller towers having larger rotor swept zones and therefore a higher collision risk area than an old single small WT, there is increasing evidence that fewer but larger, more power-efficient WT may have a lower collision rate per megawatt (Barclay et al., 2007; Smallwood and Karas, 2009). However, repowering has been raising major concern for bats, so a trade-off analysis must be conducted.

4.2. Minimization

Although good planning might eliminate or reduce impact risks, some may persist. In those cases, it is still possible to mitigate them, i.e. decrease the impact magnitude through the implementation of single or multiple measures to reduce the risk of bird collisions with WT. The need for minimization measures (also called operational mitigation) should be analyzed whenever a new WF is being planned and during project operation if unforeseen impacts arise as a result of the post-construction monitoring program.

Here, we analyze the main strategies that have been proposed or implemented in WF to reduce bird fatalities. We also discuss some techniques that are commonly used in wildlife management plans and some strategies we consider important to address when considering the factors influencing bird collisions. We point out that, in general, published evidence of their effectiveness is still lacking.

4.2.1. Turbine shutdown on demand

To date, WT shutdown on demand seems to be the most effective mitigation technique. It assumes that whenever a dangerous situation occurs, e.g. birds flying in a high collision risk area or within a safety perimeter, the WT presenting greatest risk stop spinning. This strategy may be applied in WF with high levels of risk, and can operate year-round or be limited to a specific period.

De Lucas et al. (2012a) demonstrate that WT shutdown on demand halved Griffon vulture fatalities in Andalusia, Spain, with only a marginal (0.07%) reduction in energy production. In this region, WF surveillance takes place year-round, with the main objective being to detect hazardous situations that might prompt turbine shutdown, such as the presence of endangered species flying in the WF or the appearance of carcasses that might attract vultures (Junta de Andalucia, 2009). Depending on the species and the number of birds, there are different criteria for stopping the WT. However, this approach requires a real-time surveillance program, which requires significant resources to detect birds at risk. In Andalusia, WF surveillance programs use human observers and the number of observers depends on the number of turbines (De Lucas et al., 2012a).

In addition to human observers, there are emerging new independent-operating systems that detect flying birds in real-time and take automated actions, for example radar, cameras or other technologies. These systems may be particularly useful in remote areas, where logistic issues may constrain the implementation of surveillance protocols based on human observers; or during night periods, where human visual acuity is limited in detecting birds. These new systems are based on video recording images such as DTbird® (Collier et al., 2011; May et al., 2012b), or radar technology such as Merlin SCADA™ Mortality Risk Mitigation System (Collier et al., 2011). For example, an experimental design at Smøla WF showed that the DTbird® system recognized between 76% and 96% of all bird flights in the vicinity of the WT (May et al., 2012b). Analyzing the characteristics of these technologies and taking into account factors influencing the risk of collision, cameras can be particularly useful in small WF, for specific high risk WT or when it is necessary to identify local bird movements. Radar systems appear to be a more powerful tool for identifying large-scale movements like pronounced migration periods, particularly during night periods.

Currently, several other systems are under development or being implemented to detect bird-WT collisions or to monitor bird activity close to WT (using acoustic sensors, imaging and radar) (see Collier et al., 2011; Desholm et al., 2006). Hence, it is likely that new automated tools will be available in the future.

4.2.2. Restrict turbine operation

Turbine operation may be restricted to certain times of the day, seasons or specific weather conditions (Smallwood and Karas, 2009). This curtailment strategy is distinct from that described in Section 4.2.1 in that it is supported by collision risk models and not necessarily by the occurrence of actual high risk scenarios. This approach may imply a larger inoperable period and, consequently, greater losses in terms of energy production. As a result, it has not been well-received by wind energy companies.

Based on collision risk models, Smallwood et al. (2007) showed that if all WT in the APWRA area could be shutdown with fixed blades during the winter, Burrowing owl (*Athene cunicularia*) fatalities would be reduced by 35% with an associated 14% reduction in annual electricity generation.

Restrict turbine operation revealed to be very effective for bats. Arnett et al. (2010) showed that reducing turbine operation during periods of low wind speeds reduced bat mortality from 44% to 93%, with marginal annual power loss (<1% of total annual output). For birds it might not be so easy to achieve such results. However, restricting turbine operation could be implemented when particularly high risk factors overlap. For example, WT on migratory routes could be shutdown on nights of poor weather conditions for nocturnal bird migration.

4.2.3. Habitat management

Habitat modification techniques, like vegetation management or the creation of alternative feeding areas, are commonly used in wildlife management plans for sites such as airports (Bishop et al., 2003).

The WF surveillance programs in Andalusia, Spain, include as a prevention measure the location and elimination of carcasses that might attract scavenger species to the WT (Junta de Andalucia, 2009). This practice has also been suggested for vultures by Martin et al. (2012), who specifies that decreasing the probability of attracting vultures to a WF by reducing food availability near WT or improving foraging areas sited far away should be a high priority.

The high density and high fatality of raptors at APWRA is thought to result from, at least in part, high prey availability (Smallwood et al., 2001). This has led to the proposal of controlling prey populations in the immediate vicinity of WT as a minimization measure. However, the effects of a widespread control program would have collateral effects on other species (Smallwood et al., 2007).

There are other examples of habitat management practices, but these are carried out at a smaller scale than that proposed at APWRA. A management plan had been implemented at Beinn an Turic WF in Scotland, where Golden eagles occur. It aimed to reduce the risk of collision by reducing prey availability within the WF and by creating new areas of foraging habitat away from the WF, increasing the abundance of the eagles' potential prey. Results from 1997 to 2004 showed that eagles tended to use the managed area more frequently, but the results failed to demonstrate a reduction in collision risk (Walker et al., 2005).

In Candeeiros WF, Portugal, a 7-year post-construction monitoring program (2005–2012) revealed a high fatality rate of Common kestrels and showed that birds frequently used the areas near the WT for foraging, as these open areas that are more suitable for searching for prey when compared to the highly dense scrub typical of the vicinity. A mitigation plan involving habitat management was proposed and has been implemented since 2013, which aims at promoting a shift in the areas used by kestrels for foraging by planting scrub species in the surroundings of turbines and the clearance of shrub areas through goat grazing in areas far from the WT (Bio3, 2013; Cordeiro et al., 2013).

4.2.4. Increasing turbine visibility

Although the efficiency of increasing turbine visibility has not yet been demonstrated in the field, laboratory experiments show encouraging results for such techniques. Various attempts to increase blade visibility and consequently reduce avian collision have been made by using patterns and colors that are more conspicuous to birds. Based on laboratory research, McIsaac (2001) proposes patterns with square-wave black-and-white bands across the blade to increase their visibility, and Hodos (2003) proposes a single black blade paired with two white blades as the best option.

As some birds have the ability to see in the ultraviolet spectrum (Bennett and Cuthill, 1994; Hart and Hunt, 2007; Jacobs, 1992), ultraviolet-reflective paint has been suggested for increasing blade visibility. Although this method has proved to be effective in avoiding bird strikes against windows (Klem, 2009), its applicability in WF remains to be proven (Young et al., 2003). However, this may not be an option for raptors, as recent findings pointed out that raptors like Golden eagle or Common buzzard likely are not sensitive to ultraviolet (Doyle et al., 2014; Lind et al., 2013).

Additionally, Martin (2012) suggests that the stimuli used to draw attention to an obstacle, such as a WT, should incorporate movement and be large, i.e. well in excess of the size calculated to be detectable based upon acuity measures.

4.2.5. Ground devices

Martin et al. (2012) argued that increasing the conspicuousness of man-made obstacles would only marginally reduce collision risk because the obstacles are often simply not seen by foraging birds. Based on avian sensory ecology and on the idea that birds are more likely to be looking down and laterally rather than forwards when foraging, Martin (2012) proposes that specialists should find ways to "warn" birds well in advance. For example, he suggests using devices on the ground, such as models of conspecifics, that “divert” or “distract” birds from their flight path.

However, the effectiveness of these tools is inconclusive. Experimental studies with Common eider (*Somateria mollissima*) in Denmark involving the placement of models of conspecifics at different distances from the WT and based on the principle that birds are more likely to settle where conspecifics are located show that birds avoided flying close to and within the WF (Guillemette and Larsen, 2002; Larsen and Guillemette, 2007). Although this avoidance was not an evident effect of the conspecific models, but was more likely caused by the presence of the turbine structures themselves (Larsen and Guillemette, 2007).

The use of decoy towers (rotorless structures used as obstacles placed around the WF) has also been suggested as an option to keep birds away from WT in the APWRA. However, it has raised some concerns in that it might also attract birds to the general area of the WT or encourage them to remain for longer periods (Curry and Kerlinger, 2000; Smallwood and Karas, 2009). Currently, there are no data regarding their effectiveness. We assert that the efficacy of decoy towers is likely to be limited to the species displaced by WT, which are necessarily less prone to collisions. Also, it is necessary to address that additional structures may arise additionally impacts, both on birds and other groups, in terms of habitat loss and barrier effects.

4.2.6. Deterrents

Deterrent devices that scare or frighten birds and make them move away from a specific area have been broadly used as tools for wildlife management. Auditory deterrents are considered the most effective, although their long-term use has been proven to be ineffective due to habituation by birds to certain stimuli (Bishop et al., 2003; Dooling, 2002). Bioacoustic techniques are thought to be the most effective because they use the birds’ natural instinct to avoid danger (Bishop et al., 2003). Preliminary data on the use of the acoustic deterrent LRAD (Long Range Acoustic Device) in WF showed that 60% of Griffon vultures had strong reactions to the device, and its efficacy depended on the distance between the bird and the device, the bird’s altitude and flock size (Smith et al., 2011).

Laser deterrents have also been suggested as relevant tools to deter birds during night-time and have been considered a mitigation option for WF (Cook et al., 2011).

Deterrents can also be activated by automated real-time surveillance systems as an initial mitigation step and prior to blade curtailment (May et al., 2012b; Smith et al., 2011). Systems such as DTbird® or Merlin ARS™ incorporate this option in their possible configurations.

Although results are preliminary, we consider that this type of methodology may have an unpredictable effect on the flight path of a bird, so caution is needed if it is applied at a short distance from a WT or within a WF. Nevertheless, it may be used as a potential measure to divert birds from flying straight at a WT.

4.3. Compensation

Although a detailed discussion of this complex subject is not within the scope of this review, we present a general overview of this topic. In compliance with the mitigation hierarchy, the general consensus is that compensation should be a last resort and only considered if the first steps of the mitigation hierarchy (avoidance and minimization) do not reduce adverse impacts to an acceptable level (e.g. Langston and Pullan, 2003).

In broad terms, compensation can be achieved through: (1) enhancing bird populations by acting on biological parameters that influence population levels and (2) minimizing other impacts by influencing other human actions that limit bird populations. The actions to be implemented should be selected based on the limiting factors that affect the target species population in each area.

Some examples of actions for enhancing populations are: (1) habitat expansion, creation or restoration (reproduction, foraging or resting areas); (2) prey fostering; (3) predator control; (4) exotic/invasive species removal; (5) species reintroductions; and (6) supplementary feeding (e.g. CEC, 2007; Cole, 2011; USFWS, 2013).

Minimization of other impacts can be achieved by: (1) applying minimization measures to human infrastructures besides the WF, such as existing power lines, roads or railways; (2) minimizing human disturbance in key habitats; and (3) awareness campaigns to educate hunters/lawmakers/landowners (e.g. CEC, 2007; Cole and Dahl, 2013; Cole, 2011; USFWS, 2013).

In the USA, governmental entities propose a compensatory mitigation approach for eagles species affected by WF that follows the “no net loss” principals at local and regional scales. The evaluation of impacts is performed at a project level, and its cumulative effect with other sources is also determined. If a wind project exceeds the thresholds defined for a certain area compensation should be implemented (USFWS, 2013).

5. Future research: what is left to understand

Nowadays, wildlife researchers and other stakeholders already have a relatively good understanding of the causes of bird collisions with WT. Through our extensive literature review, we have been able to identify some of the main factors responsible for this type of fatality and acknowledge the complexity of the relationships between them.

From the factors described in Section 3, we find that lighting is the one least understood, and further studies should address this topic by testing different lighting protocols in WT and their effects on bird fatalities, with a special focus on migratory periods during bad weather conditions.

We also anticipate that the expansion of WF to novel areas (with different landscape features and bird communities) or innovative turbine technologies may raise new questions and challenges for the scientific community. This is currently the case for offshore developments. To date, the main challenge in offshore WF has been the implementation of a monitoring plan and making accurate predictions of collision risk due to the several logistical constraints. The major constraints include assessing accurate fatality rates, as it is not possible to perform fatality surveys, and studying bird movements and behavior at an offshore WF, since this usually implies deployment of automatic sampling devices, such as radar or camera equipment (e.g. Desholm et al., 2006).

Due to the complexity of factors influencing collision risk, mitigating bird fatality is not a straightforward task. Mitigation should therefore be a primary research area in the near future. As species-specific factors play an important role in bird collisions, specialists should ideally strive to develop guidance on species-specific mitigation methods, which are still flexible enough to be adaptable to the specificities of each site and WF features.

Appropriate siting of WF is still the most effective measure to avoid bird fatalities. Since there are no universal formulas to accomplish this, it is essential to fully validate the methodologies used to predict impacts when planning a new facility and when assessing the environmental impact of a forthcoming project. In this context, comparing prior risk evaluations with the fatalities recorded during an operational phase should be a priority.

In many cases, pre-construction assessments may be sufficient to prevent high bird fatality rates but in others, it will be essential to combine this approach with different minimization techniques. Political and public demand for renewable energy may prompt authorities and wind energy developers to implement WF in areas that pose risks to birds. In these cases, minimization techniques are a crucial element for limiting bird fatalities.

In this context, the development of efficient mitigation techniques that establish the best trade-off between bird fatality reduction, losses in energy production and implementation costs is a high priority. Although turbine shutdown on demand seems to be a promising minimization technique, evidence of its effectiveness in different areas and for different target species is lacking. In addition, research should also focus on other options, as in certain situations less demanding approaches may also achieve positive results.

It is also important to ensure that the monitoring programs apply well designed experimental designs, for example a Before-After-Control Impact (BACI) approach (Anderson et al., 1999; Kunz et al., 2007; Strickland et al., 2011). BACI is assumed to be the best option to identify impacts, providing reliable results. However, some constraints have been identified and there are several assumptions that need to be fulfilled to correctly implement these types of studies (see Strickland et al. (2011) for a review on experimental designs).

Finally, it is important to ensure that monitoring programs are implemented and that they provide robust and comprehensive results. Also, monitoring programs results, both on bird fatalities and the effectiveness of the implemented mitigation measures, should be published and accessible, which is not always the case (Subramanian, 2012). Sharing this knowledge will facilitate the improvement of the mitigation hierarchy and the development of WF with lower collision risks.

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