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RAPTOR INTERACTIONS WITH WIND ENERGY: CASE STUDIES FROM AROUND THE WORLD

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ABSTRACT.—The global potential for wind power generation is vast, and the number of installations is increasing rapidly. We review case studies from around the world of the effects on raptors of wind-energy development. Collision mortality, displacement, and habitat loss have the potential to cause population-level effects, especially for species that are rare or endangered. The impact on raptors has much to do with their behavior, so careful siting of wind-energy developments to avoid areas suited to raptor breeding, foraging, or migration would reduce these effects. At established wind farms that already conflict with raptors, reduction of fatalities may be feasible by curtailment of turbines as raptors approach, and offset through mitigation of other human causes of mortality such as electrocution and poisoning, provided the relative effects can be quantified. Measurement of raptor mortality at wind farms is the subject of intense effort and study, especially where mitigation is required by law, with novel statistical approaches recently made available to improve the notoriously difficult-to-estimate mortality rates of rare and hard-to-detect species. Global standards for wind farm placement, monitoring, and effects mitigation would be a valuable contribution to raptor conservation worldwide.

KEY WORDS: *avoidance; collision; displacement; energy; mitigation; mortality; raptor; renewable energy; wind farm; wind turbine.*

INTERACCIONES DE AVES RAPACES CON LA ENERGÍA EÓLICA: CASOS DE ESTUDIO DE TODO EL MUNDO

RESUMEN.—El potencial global para la generación de energía eólica es enorme y las infraestructuras para su generación aumentan de manera acelerada. Revisamos casos de estudio de todo el mundo sobre los efectos del desarrollo de la energía eólica en aves rapaces. La mortandad por colisiones, el desplazamiento y la pérdida de hábitat tienen el potencial de causar efectos a nivel poblacional, especialmente en especies que son raras o se encuentran en peligro. El impacto sobre las aves rapaces está muy relacionado con su comportamiento, por lo que el emplazamiento cuidadoso de proyectos de energía eólica que eviten áreas adecuadas para cría, alimentación o migración de rapaces puede reducir dichos efectos. La reducción de mortalidad en parques eólicos ya establecidos y que presentan conflictos con aves rapaces, puede ser posible mediante la reducción de la actividad de las turbinas en momentos de presencia de rapaces y la compensación a través de la mitigación de otras causas humanas de mortalidad como electrocución o envenenamiento, en la medida que los efectos relativos puedan ser medidos. Cuantificar la mortalidad de rapaces en parques eólicos es objeto de estudios intensos, especialmente en aquellos lugares donde la mitigación es requerida por ley, con aproximaciones estadísticas novedosas disponibles recientemente que mejoran la estimación de las tasas de mortalidad, que son particularmente complicadas de estimar en especies raras y de difícil detección. El desarrollo de estándares globales para la ubicación, el seguimiento y la mitigación de los efectos producidos por los parques eólicos serán una contribución valiosa para la conservación de rapaces en todo el mundo.

[Traducción del equipo editorial]

Wind-energy production worldwide has increased rapidly in the last decade; wind power was the leading source of new power generating capacity in Europe and the United States in 2015 and the second largest in China. Globally, a record 63 gigawatts (GW) of wind-energy production was added in 2015 for a total of about 433 GW (REN21 2016). China currently leads the world with 145 GW of installed capacity, about a third of the world's total wind power (Davidson et al. 2016), followed by the United States (74 GW), Germany (45 GW), India (25 GW), Spain (23 GW), Italy (9 GW), and Japan (3 GW; REN21 2016). The potential for wind-power generation globally is vast, potentially supplying >40 times the current worldwide consumption of electricity, and >5 times the total global use of energy in all forms (Lu et al. 2009).

Attempts to measure and mitigate the effects of wind turbines on wildlife have been an integral part of wind-energy development. Raptors are among the species known to be most strongly affected by wind turbines, mostly through direct mortality and secondarily through habitat alteration and loss. In the United States, eagle mortality and mitigation strategies have received most attention because of eagles' legal status under the Bald and Golden Eagle Protection Act. The negative effects of wind turbines on other raptor species are less well understood, and corresponding mitigation responses less well developed.

This review of case studies illustrates the global state of knowledge of the effects of wind-energy development on raptors and is derived from nine presentations at a symposium at the 2015 Raptor Research Foundation annual conference. We begin with an overview of raptor species affected by wind farms worldwide. We introduce case studies of effects of wind farms on raptors from Spain, Norway, Canada, United States, and southern Africa, and follow with an evaluation of the challenges of measuring fatalities of raptors at wind farms and how they may be overcome. We discuss conclusions in common among the case studies, directions for future research, and potential offset and mitigation strategies.

Overview

As the production of wind energy increases worldwide, adverse effects of turbines and development activities have been documented for many avian groups, especially raptors. The risk of collisions is highly variable and dependent upon a complex interaction of site, season, and species-specific factors (Marques et al. 2014). Of these factors, foraging and territorial behaviors (Barrios and Rodríguez 2004, Hoover and Morrison 2005, Smallwood et al. 2009), the interaction of wind and topography (Barrios and Rodríguez 2004, de Lucas et al. 2008), and limitations in the degree to which raptors perceive turbines as dangerous (Martin et al. 2012, May et al. 2015, Hunt and Watson 2016) are thought to contribute to collisions of a number of species worldwide. However, most factors associated with collision risk are related to specific study areas or relatively common species, making it difficult to determine if those factors pose similar risk to uncommon species or those found in other areas. The search effort during post-construction fatality monitoring is rarely sufficient to locate all individuals killed by wind turbines, making it impossible to conclude that rare species are not affected even if none are found (Beston et al. 2015, Huso et al. 2015).

Bird species that share flight morphology are more likely to forage similarly, and thus many of the species killed regularly at turbines are taxonomically related (Herrera-Alsina et al. 2013). For example, Red-tailed Hawks (*Buteo jamaicensis*) and American Kestrels (*Falco sparverius*) found at wind-energy projects in the western U.S., especially the Altamont Pass Wind Resource Area (hereafter Altamont; Smallwood and Thelander 2008, ICF International 2015), make up the majority of known global fatalities for *Buteo* hawks and small falcons, respectively. Where other *Buteo* and *Falco* species, such as Common Buzzards (*Buteo buteo*) in Germany (Hötker et al. 2006), Eurasian Kestrel (*Falco tinnunculus*) in Europe (Hötker et al. 2006, Grünkorn et al. 2016), and the Nankeen Kestrel (*Falco cenchroides*) and Brown Falcon (*Falco berigora*) in Australia (Smales 2015) interact with turbines, they likewise appear to show the same high risk of collisions. Where congeneric species exist together, the more abundant species is more often found among collision victims. Red-tailed Hawks composed the largest percentage of raptors (22%, Johnson and Erickson 2011) found during post-construction fatality monitoring at wind-energy projects throughout the Columbia Plateau Ecoregion (CPE) in Oregon and Washington and nested in higher densities (1.6 pairs/100 km^2) compared with sympatric *Buteo* species such as Swainson's Hawks (*Buteo swainsoni*; 9% of fatalities, Johnson and Erickson 2011; 1.4 pairs/100 km^2, Erickson et al. 2002). However, in other areas of the CPE where the density of Swainson's Hawk pairs was greater (8.8 pairs/100 km^2), they instead composed the majority of reported raptor fatalities (45%) compared with Red-tailed Hawks (8%, P. Kolar and M. Bechard pers. comm.) that nested at half the density (4.4 pairs/100 km^2, Kolar 2013). These observations imply that nesting density is important in determining the probability of turbine collisions, but the evidence of such a relationship from other studies has been mixed (Marques et al. 2014). Predicting collision rates based on abundance of raptors through standardized point counts during pre-construction surveys has been criticized for its poor correlation, likely because collision risk also depends on flight behavior, which can vary with differences in topographic features between wind-energy project sites (de Lucas et al. 2008, Ferrer et al. 2012). Abundance may still be a useful indicator of collisions, but may be best interpreted in relation to the spatial distribution of breeding pairs at larger spatial scales and when assessing fatality rates relative to similar species within raptor groups rather than predicting the number of fatalities at individual wind-energy projects (Carrete et al. 2012).

In some specific cases, collision deaths have been suspected or implicated in population-level effects. The few known collisions of local White-tailed Hawks

(*Buteo albicaudatus*) at wind-energy projects in southern Mexico have generated concern that the area may become a local population sink for this relatively common and nonmigratory species, especially in the light of planned increase in development (Ledec et al. 2011). Likewise, prior to repowering at the Altamont, the number of Burrowing Owl (*Athene cunicularia*) fatalities at older-generation turbines was reported to be similar to the number of breeding pairs at the facility (Smallwood et al. 2007). Collisions of Egyptian Vultures (*Neophron percnopterus*) in Spain, where 80% of its European breeding population is located, have contributed to a local population decline (Carrete et al. 2009). The population of Red Kites (*Milvus milvus*) in Germany is predicted to decline due to additional mortality from turbine collision (Bellebaum et al. 2013). Grünkorn et al. (2016) also predicted the Red Kite population in Germany would decline, along with the widespread Common Buzzard that nests in the region in high densities but has not been considered in the planning process of wind turbine construction.

Species from some raptor groups, such as some kites, large falcons, and Accipiters, are infrequently observed during raptor use surveys and just as infrequently found as collision fatalities worldwide. Others, such as harriers and New World vultures are seldom found as collision fatalities, even when wind-energy projects are constructed in areas of known high population density (Erickson et al. 2002, Hötker et al. 2006, Smallwood et al. 2009, Ferrer et al. 2012, Hernández-Pliego et al. 2015, Wilson et al. 2016). For some raptors, the number of collisions also seems to vary across the species range or between facilities. For example, in general Red Kite fatalities are rarely found under turbines and kites are assumed to utilize avoidance behaviors at wind-energy projects (Whitfield and Madders 2006). Yet, turbine collisions of Red Kites in Germany, where half of the world's breeding population occurs, are reported to be the highest of any raptor species in the area (Hötker et al. 2006). Older-generation wind turbines at Altamont killed hundreds of Burrowing Owls, Barn Owls (*Tyto alba*; 225) and Great Horned Owls (*Bubo virginianus*; 71) over a 12-yr period (Smallwood and Thelander 2008, ICF International 2015). In contrast, studies at wind-energy facilities in Europe report fewer than ten fatalities of Eurasian Eagle-Owls (*Bubo bubo*; Hötker et al. 2006, Ferrer et al. 2012) and few owls of any species have been documented as collision fatalities elsewhere in the world. It is unclear whether these inconsistencies in owl and kite fatality rates between geographic regions result from differences in site-specific factors, breeding densities, or behaviors that result in habituation or avoidance of turbines.

As with any type of anthropogenic development, construction of turbines results in some habitat fragmentation and loss that can cause disturbance or displacement of raptors, but these indirect effects vary among published studies (Drewitt and Langston 2006, Madders and Whitfield 2006, Pearce-Higgins et al. 2009, Garvin et al. 2011, May 2015). The consequences of such effects likely depend upon the extent of development and species-specific tolerances to disturbance (May 2015). Dahl et al. (2012) found that a combination of a high number of turbine collisions by adult White-tailed Eagles (*Haliaeetus albicilla*) and displacement led to vacancies of previously used nesting areas close to turbines. Conversely, Hernández-Pliego et al. (2015) found no difference between pre- and post-construction nest or colony abundances of Montagu's Harriers (*Circus pygargus*) in Spain. Kolar (2013) found that the selection of nesting areas by *Buteo* hawks in Oregon was not related to wind turbines. However, Kolar and Bechard (2016) also found that nest success and post-fledging survival of Ferruginous Hawks (*Buteo regalis*) in the same study area were negatively affected by the density of wind turbines within home ranges. Post-fledging survival of Red-tailed Hawks and Swainson's Hawks, the species that made up most of the raptor fatalities at wind-energy facilities in that study area (P. Kolar and M. Bechard pers. comm.) and surrounding region (Johnson and Erickson 2011), was also lower near greater densities of turbines, but did not appear to be affected to the same degree as that of Ferruginous Hawks. These results suggest effects on reproduction for these three species resulted from some combination of turbine collisions and indirect displacement or disturbance effects associated with operations and maintenance of the facilities and infrastructure.

The variable results of these studies underscore the role of both local and regional factors that may contribute to negative effects on raptor populations at wind-energy projects. Understanding the site-specific factors that influence collisions and displacement, and the resulting population-level consequences will help regional planners to better integrate future wind-energy developments into the landscape while avoiding or mitigating in areas important for the long-term persistence of raptors.

Case Studies

Spain. The first published evaluation of the effects of wind farms on bird populations in Spain was conducted in Tarifa (Andalusia Province, southern Spain) from July 1994 to September 1995 (de Lucas et al. 2004). The area was chosen because of its proximity to the Strait of Gibraltar, one of the most important bird migration routes of the Palearctic. Soaring birds in this study changed flight direction when crossing the wind farm, increasing their altitude and avoiding turbines. During the 14 mo of the study period, researchers found only two raptor carcasses, a number well below the average found in studies of power lines using similar methodology (Janss and Ferrer 1998). The results supported the conclusion that mortality associated with the wind farm was not an important factor, and avian collisions with turbines were infrequent at this location.

To obtain a more detailed understanding of the factors involved in influencing collision mortality of birds at wind farms, de Lucas et al. (2008) carried out a long-term study of avian fatalities at wind farms in Spain between November 1993 and June 2003. The results showed no relationship between density (number of birds crossing the area) and mortality rate of birds at the wind-farm scale. No indication of a change in mortality rates across the study period was found, suggesting that there were no long-term temporal changes in birds' reactions to those wind farms, and implying that they did not habituate to the presence of turbines.

The Griffon Vulture (*Gyps fulvus*) was the species most affected by collision fatalities. However, collision mortality rates did not simply increase with abundance. De Lucas et al. (2008) proposed that differences in mortality were related to species-specific flight behavior and morphology, weather, and topography around the wind farm. In addition, they found a skewed distribution of griffon fatalities per turbine. Taller turbines at higher elevations killed more vultures than did shorter turbines at lower elevations (de Lucas et al. 2008). Likewise, Carrete et al. (2009) found breeding pairs of Egyptian Vulture tended to select roughly the same areas as those preferred for wind turbine locations and that the species' population was decreasing generally and at a faster rate in areas with wind farms.

The effects of wind farms on Griffon Vulture fecundity and mortality can be significant (Martínez-Abraín et al. 2012). Operational mitigation programs to manage these effects have been implemented by selectively stopping turbines when observers detect potential risk to birds (de Lucas et al. 2012). In one project, turbines were stopped on average for 6 h and 20 min each year. Under these mitigation regimes, Griffon Vulture mortality rate declined by 65%, with a reduction in total energy production of the wind farms of only 0.07% per year.

The most relevant factor for predicting collision risk to raptors has been generally assumed to be the local density, usually measured as the number of birds crossing the whole area of the future wind farm. However, studies in Spain provide clear evidence that the probability of bird collisions with turbines also depends critically on species behavior and topographical factors (Barrios and Rodríguez 2004, de Lucas et al. 2008). Ferrer et al. (2012) found no relationship between risk prediction from pre-construction environmental impact assessment studies (i.e., at the scale of the entire wind farm) and the actual post-construction mortality of birds recorded in wind farms located in southern Spain. Relevant factors affecting the frequency of collisions with turbine rotor blades, such as bird flight behavior, topography, and wind speed and direction, were operating at the scale of the individual turbine, and not at the entire wind-farm scale (Ferrer et al. 2012).

Norway. The island of Smøla contains a 68-turbine facility covering 18 km^2 of land and including 28 km of roads. Before construction, White-tailed Eagles bred at high density in and around the wind farm; in total around 50 pairs were breeding on the island in the period 2002–2005. A long-term time series on population size and breeding status of the eagles at Smøla from 1997 allowed the use of a before-after-control-impact (BACI) design study. The study demonstrated that this local population was affected both by disturbance and collision mortality. Eagles did not significantly change their flight behavior when inside the wind farm, possibly explaining the high collision mortality (Dahl et al. 2013). Breeding success was lower in those territories that were close to the wind farm, compared to those that were farther away (Dahl et al. 2012). In addition to direct mortality, there was displacement from the territories within the wind farm (May et al. 2013). Mortality rates were higher for birds that had territories within or close to the wind farm compared to those that lived farther away (Dahl et al. 2012), and the intrinsic growth potential of the population was reduced by the wind-farm development (Dahl 2014). The total population of White-tailed Eagles at Smøla did not decrease, probably due to immigration of birds from nearby islands, and the displacement of breeding pairs to other sites in the surrounding area (Dahl et al. 2012).

Post-construction monitoring at Smøla used trained dogs to find collision fatalities. Because it is an island with no mammalian ground predators, Smøla has the advantage of long carcass persistence rates, especially of large carcasses such as eagles. There is little aerial bird activity on Smøla in winter, so searches mainly focused on spring and early summer (migration and breeding-season) and autumn (migration). The search scheme was not constant in all years, but was probably sufficient to reveal the majority of the casualties. Starting in the spring of 2014, researchers introduced a new search scheme, involving weekly searches at painted turbines and unpainted (control) turbines in a mitigation experiment, with some additional searches of all turbines. During the study from 2005 to October 2016, 73 White-tailed Eagles were found dead under or near turbines at the Smøla wind farm. More adult birds were found killed than were birds of all other age classes combined. This has major implications for the population dynamics, because for long-lived species with a low reproductive rate, adult survival rate is the demographic parameter that has the largest effect on population growth (Eberhardt 2002). Of other raptors, two juvenile Golden Eagles (*Aquila chrysaetos*) were found killed, as well as four Merlins (*Falco columbarius*), one Eurasian Kestrel (*Falco tinnunculus*), and one juvenile Gyrfalcon (*Falco rusticolus*). Most of the eagles were found during spring. At that time of the year, there is much interaction among the territorial eagles, including fighting and chasing. This might reduce the birds' awareness of moving rotor blades, making them more susceptible to collisions (May et al. 2010b, 2011). The White-tailed Eagle is quite gregarious, and that behavior may explain why the particular turbine that killed most eagles at Smøla was one that that was very close to a major roost site in a Sitka spruce (*Picea sitchensis*) plantation.

Mitigation of turbine-induced mortality of birds at wind farms has proven to be difficult, as mitigation may involve sensory, aerodynamic, and habitat-specific factors (May et al. 2015). During the summer of 2014, four turbines at Smøla wind farm had one rotor blade painted black in an effort to see whether mortality could be reduced by increased visibility to birds (as demonstrated in Hodos et al. 2001). In addition, the bases of 10 turbines were painted black up to 10 m above ground during the summers of 2014–2015. All searches for dead birds were performed using trained dogs, in a radius of 100 m of the turbines. This research effort is ongoing, but preliminary results suggest that mortality of Willow Ptarmigan (*Lagopus lagopus*), the species most frequently found dead under the turbines (>180 fatalities), has been reduced following these visual modifications (T. Nygård unpubl. data). The development of a GIS-based micro-siting tool analyzing topographic features that enhance orographic and thermal updrafts, as well as an operational shut-down model for birds, is underway as part of the project. Other mitigation measures, such as scaring devices (DTBird; May et al. 2010a) and UV-lights have been tested at Smøla, but the effectiveness of the latter is doubtful (Hunt et al. 2015).

Proper siting of wind farms is crucial to prevent raptor casualties. Smøla is an example of development that did not incorporate wildlife considerations, as it was built in an important breeding area for White-tailed Eagles. A plan that could reduce bird casualties by repowering the Smøla wind farm with fewer but larger turbines (up from 2–2.3 MW to 3–5 MW) has been proposed but not yet effected. The plan also recommended more bird-friendly placement of the new turbines based on vulnerability maps that identified areas of low use by eagles. Maps were created by plotting the flight paths of 73 satellite-tagged White-tailed Eagles, in combination with direct observations of territorial eagles and radar tracks from a MERLIN Aircraft Birdstrike Avoidance Radar™ (DeTect, Inc., Panama City, FL U.S.A.) placed centrally in the wind farm (Dahl et al. 2015).

Canadian Rocky Mountains. Wind-energy development within the Hart Ranges of the Rocky Mountains in British Columbia, Canada, overlaps with a Golden Eagle migration corridor. Researchers used a BACI study design to document Golden Eagle flight behavior in response to wind turbines at this ridgetop wind-energy development (Johnston et al. 2014). Golden Eagle flights were visually tracked around a ridge containing 15 3-MW turbines during three fall migration seasons, one pre-construction (2009) and two post-construction (2010 and 2011). Surveys were conducted by the same observer in all years from three different observation points to cover the entire ridge. Positions of eagles were estimated in three dimensions as they migrated within 2 km of an observation point. Estimated eagle locations were then incorporated into GIS software to ascertain flight heights above the ground for eagles that flew within 100 m of the turbine string (hereafter termed "ridgetop area"). Of these flights, eagles that were within 150 m of the ground were identified as being within a "risk zone" (i.e., within turbine height). Flights within the risk zone, coupled with wind speeds above turbine cut-in (activation) speed at nacelle height, were classified as "higher-risk" movements.

Observers documented 1134 Golden Eagle passages: 327 during pre-construction (2009) and 807 post-construction (380 in 2010, 427 in 2011). The proportion of observed eagles that crossed the ridgetop where turbines were located, regardless of flight height, were the same in pre-construction as in post-construction (approximately 17%). However, a smaller proportion of eagles crossed the ridgetop area within the risk zone post-construction (1%) compared to pre-construction (6%). In addition, a substantially smaller proportion of higher-risk movements within the risk zone were observed post-construction (0.004%) compared to pre-construction (5%; Johnston et al. 2014). Golden Eagle flight altitude was higher post-construction compared to pre-construction, and a binomial model indicated that the likelihood of an eagle crossing the ridgetop within the risk zone was greater during pre-construction compared to post-construction. The model also indicated that the likelihood of an eagle crossing the ridgetop was greater under headwinds and tailwinds compared to western crosswinds and decreased as wind speed increased. However, higher-risk movements within the risk zone did not occur under tailwinds, which were generally weaker winds. In headwinds however, higher-risk movements did occur, although infrequently.

In conclusion, the proportions of eagles that flew over the ridgetop area were consistent between pre- and post-construction, yet during post-construction these flights were at higher altitudes which reduced the potential for collisions. This suggests that eagles detect the turbines and increase their flight altitude to avoid the structures during migration. However, certain weather conditions, particularly headwinds and potentially tailwinds, resulted in decreases in flight altitude during ridge crossings. Should the winds be sufficient to spin turbine blades during such conditions, these circumstances may pose a greater risk of collision mortality to migrating Golden Eagles.

California, U.S.A. A dense resident population of tree-nesting Golden Eagles breeds in the Diablo Mountains just south of San Francisco Bay in California. It is estimated that between 1000 and 2000 Golden Eagles have been killed at the nearby Altamont Pass Wind Resource Area (Altamont) since the completion of the facility in 1987 (Orloff and Flannery 1992, Hunt 2002, Smallwood and Thelander 2008).

This population has been monitored intermittently since 1994, beginning with a 7-yr investigation involving radiotelemetry, nesting surveys, and demographic analysis (Hunt et al. 1999, Hunt 2002, Hunt and Hunt 2006). When these studies began, the Altamont contained approximately 5400 turbines on about 142 km^2 of open, hilly grassland. At present, the facility is being repowered with fewer, larger turbines that generate greater amounts of power. The terrain is ideally suited to Golden Eagle foraging upon abundant California ground squirrels (*Otospermophilus beecheyi*). This situation is problematic because the squirrels are commonly controlled by ranchers outside the wind farm and, by virtue of ongoing management policy, functionally protected within it (Hunt and Watson 2016).

Research during 1994–2000 was designed to estimate the trend of the Golden Eagle population residing in the vicinity of the wind farm. The study included airplane tracking of 257 radio-tagged eagles of four life stages (juveniles, subadults, floaters, and breeders) and a monitored sample of 58–69 territorial pairs. Radio-tagged eagles generally remained year-round in the study area. Subadults and floaters tended to aggregate in the wind farm in areas where ground squirrels were abundant. Together, although subadults and floaters represented only 53% of the sample, they incurred 92% of the blade-strike fatalities. However, not a single one of the 101 eagles tagged as fledglings was killed by a turbine during its entire first year of life on the wing, from fledging to one year after fledging. The tagged juveniles nonetheless frequently visited the wind farm, in some months in proportions comparable to those of subadults and floaters. A possible explanation is that older eagles are killed while hunting, with juveniles lacking the inclination and experience to hunt effectively. Tagged breeders incurred few turbine strikes because they tended to remain on territory year round. When they did enter the wind farm, however, they appeared as vulnerable to the turbines as subadults and floaters.

Survival and reproductive rates, and their standard errors, were estimated for each of the four life-stages from telemetry data and territory monitoring software. The potential population rate-of-change estimate was consistent with both population stability and decline ($\lambda =$ approximately 1; Hunt et al. 2017). This implies that the local breeding population was not generating enough floaters to strongly buffer itself against loss, and that any sustained increase in human-related mortality might require immigration to maintain the population. Continued monitoring revealed that all the territories surveyed in 2000 were still occupied in 2005, and almost all in 2013, implying stability of the nesting population. Meanwhile, collision risk conditions at the wind farm are expected to improve with a large-scale repowering program currently in progress in which many of the small turbines are being replaced with relatively few large ones, with no overall increase in power generation. New estimates of vital rates will be needed to detect whether repowering delivers on this expectation. All the other human-related mortality agents present earlier are still operating, and, apparently no new ones have been added. There is another problem, however, that is showing its influence, and that is the apparent effect of drought on Golden Eagle reproduction. During the course of the recent surveys in the extremely dry years of 2013 and 2014, Golden Eagle nest success was very much lower than in any previous year for which there is information (Wiens et al. 2015). This may be due to a response of prey populations to reduction in primary productivity.

Southern Africa. The wind-energy industry is in its infancy on the African continent and as a result there are few published data on the effects of wind turbines on raptors in the region. Colyn et al. (2014) published the first recorded raptor mortality at a South African wind farm (a Jackal Buzzard [*Buteo rufofuscus*]). Preliminary results from South Africa, based on 1 yr or 2 yr of post-construction monitoring at eight wind farms, suggest that raptors account for over one-third of carcasses found. Amur Falcon (*Falco amurensis*), Jackal Buzzard, and Common Kestrel (*Falco tinnunculus*) were the most frequently reported raptor fatalities, possibly reflecting the high abundance of these species at the wind farms in the review. Verreaux's Eagle (*Aquila verreauxii*), Martial Eagle (*Polemaetus bellicosus*), Lanner Falcon (*Falco biarmicus*), Lesser Kestrel (*Falco naumanni*), Common Buzzard (*Buteo buteo*) and the near-endemic Black Harrier (*Circus maurus*) have also been recorded as fatalities (S. Ralston-Paton pers. comm.). Many of these species are of conservation concern, either regionally or globally (Taylor et al. 2015, BirdLife International 2016).

Africa installed nearly 1 GW of wind energy in 2014, with most in South Africa, Egypt, and Morocco (Fried et al. 2014) and a five-fold increase in energy demand is expected over the next 25 yr (The World Bank 2011, IRENA 2013, IEA 2015). A large number of wind-energy developments are expected (BirdLife International 2013, Nemaxwi 2013), with specific plans to harness the renewable energy potential in eastern and southern Africa in a "Clean Energy Corridor." In preparation for this expansion, research has focused on predicting risk to inform wind farm placement. Bearded Vultures (*Gypaetus barbatus*) and Cape Vultures (*Gyps coprotheres*) have been a particular focus of research; proposed wind farms in Lesotho and South Africa's Maluti and Drakensberg mountains (a transboundary World Heritage Site) are expected to have negative consequences for small local populations of Bearded Vulture (regionally Critically Endangered) and Cape Vulture (regionally Endangered; Jenkins and Allan 2013, BirdLife International 2013, Rushworth and Krüger 2014, Reid et al. 2015). Literature published thus far includes studies on spatial analyses of Bearded Vulture movements to inform wind-farm placement (Reid et al. 2015), Bearded Vulture population viability analyses (Rushworth and Krüger 2014), flight behavior of Cape Vulture to influence turbine placement (Pfeiffer et al. 2015, Pfeiffer 2016) and investigation of radar to study bird movements (Becker 2016).

Conservation organizations have also provided spatial guidance for wind-farm developers and decision-makers. Sensitivity maps have been prepared for South Africa (Retief et al. 2012), and the Red Sea and northern Rift Valley (BirdLife International 2014), and guidelines for impact assessment and monitoring have also been produced (e.g., Jenkins et al. 2011, 2012, 2015, BirdLife International 2017). However, our understanding of site-specific factors that influence the risk of raptor collisions in Africa is still in its infancy, and predictions of likely risk and species' responses to wind turbines need to be tested through further research, monitoring, and data analysis.

In South Africa, most wind farms monitor their effects on raptors and other birds either voluntarily, or as a condition of their environmental authorization. Best practice guidelines for impact assessment and monitoring (Jenkins et al. 2011) are used to guide the survey protocols. For example, carcass surveys are generally conducted with a search interval of 1–2 wk, with square or circular plots searched in a radius around the turbine of 75% of turbine height. To estimate fatality rates, surveys include searcher efficiency and scavenger removal trials. Monitoring reports are made available to stakeholders either voluntarily or as a condition of environmental authorization, or can be accessed through the Promotion of Access to Information Act. There is limited experience with operational phase mitigation of wind farms in Africa, although this is likely to change as wind farms become operational for longer. Guidance on the use of "shutdown-on-demand" has been developed for migrating soaring birds in the Rift Valley/Red Sea Flyway (BirdLife International 2015).

Monitoring Raptor Fatalities at Wind-energy Facilities, U.S.A. Post-construction fatality monitoring for wind-energy projects presents significant challenges due to the competing needs for precision and affordability. Most wind-energy projects rely on external financing for development and obtaining this financing requires that the costs of development, operations, and monitoring be balanced by potential profitability. There is an implicit tradeoff between economical approaches to development and the need to accurately estimate the effects of each wind-energy project on wildlife species. Recent studies suggest population-level effects of wind-energy development are generally small for most avian species (Erickson et al. 2014, Loss et al. 2015), but may be significant for some raptors (e.g., Carrete et al. 2009, Dahl et al. 2012), and there is still much to learn regarding these effects. Post-construction fatality monitoring is therefore needed to improve our understanding of these effects as well as for regulatory purposes (i.e., permit compliance monitoring). Here, we review current practices within the wind-energy industry to estimate raptor fatalities at wind-energy projects and provide suggestions for improved balance between precision and cost in future fatality monitoring efforts.

Due to factors including, but not limited to, the spatial scale of wind-energy projects and the temporal pattern of collisions with wind turbines (i.e., many collisions occur at night), it is not feasible to produce a complete count of fatalities resulting from collisions at a wind-energy project. Instead, efforts have focused on estimating fatality rates from observed counts adjusted by estimates of probability of detection (Erickson et al. 1998, 2001, Drewitt and Langston 2006, Arnett et al. 2007, 2008, Huso 2011, Strickland et al. 2011). Estimates of fatality rates must account for (1) the probability that a fatality is detected if it is available for detection (searcher efficiency), (2) the probability a fatality is available for detection (i.e., persists from the time of a collision to the next search; carcass persistence), and (3) the proportion of carcasses falling into the searched area. These sources of imperfect detection are accounted for in common field study designs that either measure searcher efficiency and carcass persistence independently (Jain et al. 2007, Good et al. 2011, Huso 2011, Korner-Nievergelt et al. 2011, Warren-Hicks et al. 2013), or produce a combined estimate of detectability (Erickson et al. 1998, Shoenfeld 2004).

Extrapolation of fatality estimates produced by statistical estimators is limited to the spatial extent of the search area around the turbine, especially if the area is relatively small. This is because the distribution of carcasses below the turbine is unknown. Adjustment for the proportion of the carcass distribution searched can be made using empirically derived distributions from publicly available studies or from within the same wind-energy project (e.g., the ratio or "road and pad" approach, Rabie et al. 2014). Additionally, models are available to predict the proportion of the carcass distribution sampled by a given field design by modeling the carcass fall zone (Hull and Muir 2010, Huso and Dalthorp 2014). This allows researchers to adjust fatality estimates for this potentially important source of bias even in the absence of site-specific empirical data. An additional source of bias in fatality estimates arises from the variance among sampled turbines in the number of fatalities detected. This source of bias has a greater influence on less abundant species groups, such as raptors, than with abundant species groups like passerines, due to the smaller samples of fatalities generally observed in the case of less abundant species (Huso 2011).

Available information from post-construction monitoring at wind-energy projects in North America suggests patterns of variation in searcher efficiency and carcass persistence rates (Smallwood 2013 and references therein). These patterns appear to be influenced by carcass size and species, location, ground cover, and season. Development of site-specific estimates of these sources of bias is therefore standard industry practice in North America.

There are numerous statistical approaches that extrapolate an annual fatality rate from a sample of fatalities at a wind-energy project (Erickson et al. 1998, Johnson et al. 2003, Shoenfeld 2004, Huso 2011, Korner-Nievergelt et al. 2011, Etterson 2013, Péron et al. 2013, Warren-Hicks et al. 2013, Wolpert 2015). Each of the statistical estimators accounts for sources of bias and adjusts the estimate to create a relatively unbiased estimate of the true fatality rate at a given project. However, most currently available estimators of fatality rates do not produce accurate and precise estimates when fatalities are rare (≤5–10 fatalities per analysis period; M. Huso pers. comm.). When the goal of fatality monitoring is the detection of rare events, perhaps in association with compliance monitoring for incidental take permits, different analysis methods may be needed (Dalthorp and Huso 2015).

Post-construction fatality monitoring studies at wind-energy projects have typically used large, square search areas around turbines with searchers walking along transects spaced 3–10 m apart to search for raptor carcasses (U.S.F.W.S. 2012). Bias correction trials are usually conducted simultaneously with fatality searches. These trials involve distributing test carcasses without the knowledge of searchers to obtain estimates of detection probability; test carcasses are then either removed after the trial or left in place to monitor for removal (carcass persistence) if combined bias trials are conducted (e.g., Warren-Hicks et al. 2013).

There is a clear need for post-construction fatality monitoring methodology that is powerful enough to produce reliable estimates of avian fatality rates as well as to detect rare events (e.g., fatalities of raptors or threatened and endangered species), yet is also economical enough to be used regularly at wind-energy projects over long time frames. The development of such a methodology will likely be facilitated by the forthcoming availability of fatality data from multiple wind-energy facilities via the American Wind Wildlife Information Center (AWWI 2015). Use of these data may enable development of robust, empirical distributions for carcasses around turbines that can be used to accurately extrapolate from small search areas. The development of new tools such as the Evidence of Absence estimator (Dalthorp et al. 2014, Huso et al. 2015) also provides the means for designing fatality monitoring programs around *a priori* power analysis to ensure that goals of the monitoring are met. This is the case for fatality rate estimation or compliance monitoring. Integration of cost-effective monitoring protocols, meta-analyses of data, and emerging analytical tools will improve our ability to estimate and appropriately mitigate raptor fatalities at wind-energy projects.

Mitigating for Raptor Fatalities at Wind-energy Facilities, U.S.A. The U.S. Fish and Wildlife Service has begun issuing Incidental Take Permits (ITPs) to wind-power developers for take under the Endangered Species Act and the Bald and Golden Eagle Protection Act. Once a take limit is set and minimization and mitigation approaches agreed upon, conditions of the permit often stipulate additional actions necessary if the permitted take limit is exceeded. Accurately collecting and interpreting data to provide evidence that take is within permitted limits presents challenges. To date, monitoring of wind-energy facilities has been mostly carried out by the industry with the objective of estimating general bird and bat fatality rates, not to address compliance with take limits for an individual protected species. Current statistical approaches can usually provide adequate estimates when observed counts are fairly large, even when detection probability is very low. But when the target population is small, as might be expected for endangered species or species with low population densities, the likelihood of finding no carcasses may be high, yet observing no carcasses cannot necessarily be interpreted to mean zero or even low numbers of fatalities (Huso et al. 2015).

Huso et al. (2015) describe an approach based on Bayes' theorem that uses information about the search process and estimated detection probabilities to provide posterior probabilities of the actual mortality. Software to carry out the extensive calculations required by this estimator has been developed simultaneously by Dalthorp et al. (2014) and Korner-Nievergelt et al. (2015) to give managers tools for designing monitoring programs to provide evidence of industry compliance with ITPs.

Dalthorp and Huso (2015) have developed a statistical framework for inferring when observed carcass counts are inconsistent with permitted take levels either in the short-term (3-yr running average) or the long-term (life of project), and define decision-points (triggers) for initiating adaptive management actions (AMAs) when estimated take rates exceed permitted levels, as well as for rescinding previous AMAs when warranted by low take rates. Dalthorp and Huso (2015) evaluate the consequences of choices for certain parameters in terms of species conservation and cost of operations. The purpose is not to define optimal parameters but to provide critical information to guide decision-making in the management of ITPs.

The process of trying to minimize risk of collision can be performed pre-construction, through improved siting of turbines and the avoidance of prey-rich areas, or post-construction. Approaches used to minimize turbine collision post-construction include temporary turbine shut-down upon approach by eagles or endangered species, such as California Condors (*Gymnogyps californianus*). Human observers may be employed to watch for these species in wind farms where they are frequent; other methods of detection being tested include radar, digital image recognition, and radiotelemetry on resident birds (R. Watson unpubl. data). Mitigation of collision fatalities includes mortality offsets from other known causes, such as retrofitting power lines to reduce electrocution, carcass removal from roads to reduce vehicle collisions, and abatement of lead poisoning among avian scavengers that consume the remains of hunter-harvested game shot with lead-based ammunition.

Discussion

Wind-energy development is progressing because of environmental and economic motives including reduced greenhouse gas emission, improved air quality and public health, reduced water consumption, and market benefits such as savings in the costs of electricity, power systems, and other energy sources, and creation of jobs (U.S.D.O.E. 2015). Wind-energy developments can be detrimental to birds of prey. Even low numbers of anthropogenic fatalities of certain species, especially raptors, can be additive with other causes of mortality and significant to their populations. For example, anthropogenic factors were responsible for about 56% of satellite-tagged Golden Eagle mortality in the United States, and reduced annual survival by an estimated 10% (U.S.F.W.S. 2016). Poisoning and shooting were leading causes of fatality, followed by electrocution and collision (U.S.F.W.S. 2016). Many large raptors including vultures are vulnerable to small increases in mortality, due to their longevity and low reproductive rates. They are also often susceptible to collisions with turbine blades, potentially jeopardizing the existence of local or regional populations (Drewitt and Langston 2006, Madders and Whitfield 2006, de Lucas et al. 2008, Carrete et al. 2009, Dahl et al. 2012, Martínez-Abraín et al. 2012). Beyond direct effects of wind turbines, collisions with associated infrastructure such as power lines and guy wires as well as potential displacement and loss of habitat may also influence avian populations (Erickson et al. 2001, 2005). Evidence from some of the sites we reviewed suggests that careful siting and continued research on optimizing coexistence can minimize or even eliminate negative effects on raptors. With the potential for vast expansion of wind energy across the globe, our review reveals some important considerations for siting and questions for further research.

Population-level Effects. Although most studies have focused on measuring mortality rates at wind farms, researchers at Altamont focused on the local Golden Eagle population around the turbines to detect population effects, rather than inferring population effects from killed birds. Occupied territories remained stable over a 13-yr period despite averaging around 60 turbine-related eagle fatalities per year, suggesting that local recruitment may be buffered by a more robust metapopulation. Recent research supports this conclusion (Katzner et al. 2017). Evidence indicates that the population balance seen over past decades might be upset by reduction in productivity caused by drought-related factors related to climate change (Wiens et al. 2015). Population studies should therefore be long-term and consistent.

Studies in Spain found inconclusive evidence of population effects from collision mortality among many birds, and no evidence of mortality being a function of bird density. Yet, for Griffon Vultures in Spain, turbine collisions were found to have a significant effect on fecundity and survival, with likely population effects because they too, like Golden Eagles, are large, slow to mature, long-lived, and slow to reproduce. Elsewhere there is some evidence of population-level effects on White-tailed Hawks, Red Kites, Common Buzzards, Burrowing Owls, and Egyptian Vultures, and some evidence of indirect population effects from habitat loss. Results from studies of indirect effects have been mixed because the effect may vary depending on the extent of wind-energy development and differences among species in their tolerance to disturbance; cause and effect are also notoriously difficult to demonstrate in observational studies. In addition to measuring mortality and its causes, including collision with turbines, understanding the effect of wind-energy development on a raptor population requires an understanding of nest-site occupancy, productivity, immigration, emigration, and movements of raptors through the area using either a BACI study design or a strategy in which spatially separate but similar sites are studied simultaneously for comparison of population and behavior parameters between areas with and without turbines.

For endangered species, a few deaths may have a large effect on a small remnant population. In South Africa, the choice of the Maluti and Drakensberg Mountains for a new wind farm was considered dangerous because that site is thought to be in the top 1% of most sensitive sites for endangered Cape Vultures and Bearded Vultures. Endangered species are typically rare and therefore difficult to detect when they are killed by collision with turbines, necessitating better methods for estimating mortality rates and population effects, such as those described by Huso et al. (2015). Where endangered species such as California Condors are satellite-tagged for other research purposes, this method might also provide early warning of approach to turbines, allowing for shut-down to avoid collision.

Role of Behavior in Collision Risk. Collision mortality in wind farms has much to do with raptor behavior. Among Golden Eagles at Altamont, more subadults were killed than adults or juveniles, possibly because juveniles relied more on scavenging than older age classes, and were therefore less likely to forage and hunt ground squirrels among turbines. Adults, on the other hand, were less likely to leave their territories to enter the neighboring turbine area. This finding contrasts with that of a study of White-tailed Eagles in Norway, where turbines were placed in nesting areas and where territorial battles in spring and gregarious roosting were thought likely explanations of high adult mortality from wind turbine collisions. Studies in Spain indicated evidence of behavioral avoidance of turbines by some raptors, as also shown for Golden Eagles in Canada. Conversely, large soaring Griffon Vultures were susceptible to collision mortality in Spain, most likely as a function of their soaring flight behavior and related morphology, as well as weather and topographic factors, as also suggested for Golden Eagles in Canada. Among raptors other than eagles and vultures, there is also a pattern of collision mortality among species with similar flight styles, with *Buteo* hawks, Burrowing Owls, and Red Kites suffering higher fatality rates where dense nesting populations overlap with wind-energy projects. Kestrel mortality is also high, but large falcons, Accipiters, and New World vultures have relatively low mortality rates from turbine collision. Kites, harriers, and owls are also not frequently found as collision victims in most areas, but they are not immune to these effects, as evidenced by the number of collision fatalities of Black Harriers in South Africa, Red Kites in Germany, and various owl species at Altamont, California.

In Spain, predictive environmental impact assessments based on bird density as an index of collision probability were not useful in terms of the parameters measured. Rather, flight behavior related to turbine-specific characteristics was more likely to predict bird collision, especially of soaring birds, and therefore more useful in making local site adjustments prior to construction. In Africa, the development of avifaunal sensitivity maps, which include a layer for predictable flight corridors based on topography and bird flight paths tracked by telemetry, offers a useful tool.

Informed Turbine Siting and Risk Minimization. Size and location of specific turbines were related to raptor collisions in Spain, with taller and higher-elevation turbines more likely to kill soaring birds than shorter turbines located at lower elevations. That taller turbines killed more raptors in Spain contrasts with findings in the U.S., where repowering with fewer, taller, slower-moving turbines at Altamont seems to have reduced collision fatalities compared to the original installation of short, fast-rotating turbines. This suggests that elevation and topography may be more important factors affecting raptor collisions than turbine size and rotation speed in the study from Spain.

In Spain, post-construction mitigation by shutting turbines down was effective in reducing mortality by 65% while only reducing energy production by 0.07%. Researchers derived the same conclusion for White-tailed Eagles in Norway, where siting turbines close to a communal roost was the cause of much mortality that could easily have been avoided with some care. Repowering with larger turbines is planned and may reduce mortality of White-tailed Eagles. In southern Africa, pre-construction assessment would inform mitigation measures during planning, and post-construction mortality surveys, coupled with measures like turbine curtailment found to be successful in Spain, could mitigate mortality where turbines are already sited in sensitive locations, provided government authorities attend to the findings. Engaging with stakeholders, including government agencies, non-governmental organizations, power companies, development agencies and other financial backers, is essential to ensure that wind-power development occurs responsibly.

Turbine-associated Fatalities and Raptor Conservation. Efforts to mitigate wind farm impacts on raptors by reducing other unrelated human-caused mortality agents, like electrocution (Lehman et al. 2007), lead exposure from hunters' spent ammunition (Golden et al. 2016), poisoning, and trade (Ogada et al. 2015), could have great benefits for survival of large raptor species. However, measuring the relative benefit of these mitigation strategies depends, in part, on reliable estimates of mortality from each source. Reliable post-construction mortality monitoring at wind farms is notoriously difficult and the subject of intense effort to improve reliability of results. Reliable mortality estimates are particularly important for measuring compliance with take permits issued in the U.S.A. by the U.S.F.W.S. under the Bald and Golden Eagle Protection Act to allow wind farms to unintentionally kill these species without risk of prosecution. With strong regulation and diligent oversight, authorities can use these permits to leverage the benefits of mitigation measures by wind farms.

In conclusion, wind farms have the potential to have important population-level effects on some raptor species, especially large soaring raptors that are long-lived, reach maturity at an older age, and have low reproductive rates. Where such species may be affected by wind-farm development, preconstruction analysis of their flight patterns and behaviors in the proposed site should be used to inform turbine siting to avoid frequent flight paths of soaring birds. Avoiding areas of high prey density can dramatically reduce collision mortality, as would repowering with fewer, larger turbines. There is less information about other raptors, and certain groups of species seem to be more at risk of collision than others, especially large *Buteos* and small falcons such as kestrels. The problem of estimating mortality among rare species is being tackled statistically to provide critical information to guide decision-making in the management of incidental take permits in the U.S., but the same methods may prove useful in estimating mortality rates of small, difficult-to-find species that have been largely ignored thus far. The large variability of experience between countries suggests the need for global standards in wind-farm placement, monitoring, and impact mitigation.

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