Griffon vulture mortality at wind farms in southern Spain: Distribution of fatalities and active mitigation measures

Manuela de Lucas [a,⇑], Miguel Ferrer [a], Marc J. Bechard [b], Antonio R. Muñoz [c]

[a] Department of Ethology and Biodiversity Conservation, Estación Biológica de Doñana (CSIC), Av. Américo Vespucio s/n, 41092 Seville, Spain
[b] Raptor Research Center, Department of Biological Sciences, Boise State University, 1910 University Dr., Boise, ID 83725, USA
[c] Fundación Migres, Complejo Huerta Grande, Crta. N 340 Km 97.6, 11390 Pelayo, Algeciras, Spain

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abstract

Wind is increasingly being used as a renewable energy source around the world. Avian mortality is one of the negative impacts of wind energy and a new technique that reduces avian collision rates is necessary. Using the most frequently-killed species, the griffon vulture (Gyps fulvus), we studied its mortality at 13 wind farms in Tarifa, Cadiz, Spain, before (2006–2007) and after (2008–2009) when selective turbine stopping programs were implemented as a mitigation measure. Ten wind farms (total of 244 turbines) were selectively stopped and three wind farms (total of 52 turbines) were not. We found 221 dead griffon vultures during the entire study and the mortality rate was statistically different per turbine and year among wind farms. During 2006–2007, 135 griffon vultures were found dead and the spatial distribution of mortality was not uniformly distributed among turbines, with very few turbines showing the highest mortality rates. The 10 most dangerous turbines were distributed among six different wind farms. Most of the mortalities were concentrated in October and November matching the migratory period. During 2008–2009, we used a selective stopping program to stop turbines when vultures were observed near them and the griffon vulture mortality rate was reduced by 50% with a consequent reduction in total energy production of by the wind farms by only 0.07% per year. Our results indicate that the use of selective stopping techniques at turbines with the highest mortality rates can help to mitigate the impacts of wind farms on birds with a minimal affect on energy production.

1. Introduction

The development of wind energy is a central component of the European objective to reduce the emission of greenhouse gases by increasing the proportion of energy derived from renewable sources. The European Commission has set a target of 20% of EU energy generated by renewable sources by 2020. Indeed, the Spanish government is committed to attaining this goal and, by 2010, 14% of the energy production in Spain was generated by renewable sources (IDAE, 2010). The exploitation of wind as a renewable and pollution-free source of energy has led to the proliferation of wind facilities across Spain, where more than 737 wind farms consisting of a total of 16,842 turbines are currently operational and generating more than 16 GW (gigawatts) of electricity annually (AEE, 2009).

Despite the obvious benefit of wind as a clean energy source, wind farms can potentially have adverse effects on flying animals such as birds and bats by either causing avoidance behavior, disturbance (Pruett et al., 2009), or fatality through collision with rotating turbine rotor blades (e.g. Orloff and Flannery, 1992; Osborn et al., 2000; Langston and Pullan, 2003; Arnett, 2005; Horn et al., 2008; de Lucas et al., 2008). Although collision mortality may have an insignificant impact on some avian populations (Kuvlesky et al., 2007; Desholm, 2009), collisions may have a higher impact on raptor populations because they have longer life spans and lower reproductive rates (Madders and Whitfield, 2006). Nevertheless, studies conducted at other wind farm developments in Europe indicate that raptor populations are not impacted by collisions with turbines and, in the United States, either no raptor collisions have been reported at some wind farms (Strickland et al., 2011) or low collision rates such as 0.065 birds/turbine/year (Erikson et al., 2003), 0.04 and 0.06 birds/turbine/year (de Lucas et al., 2008) and 0.001 birds/turbine/year have been found (Hunt, 1999). Other studies (Ferrer et al., 2011) have shown some of the highest collision rates ever published for birds (1.33/turbine/year) with the griffon vulture Gyps fulvus being the most frequently killed species (0.41 deaths/turbine/year). These findings indicate that mortality rates per turbine are quite variable because the probability of collisions depends on a range of factors such as the species, species-specific flight behavior, weather and topography around wind turbines (de Lucas et al., 2008).

⇑ Corresponding author. Tel.: +34 954 46 67 00; fax: +34 945 62 11 25.
E-mail address: manuela@ebd.csic.es (M. de Lucas).

Some techniques as the aerodynamic study of griffon vulture flight have been developed to reduce avian mortality in the preconstruction phase of wind farms (de Lucas, 2007). However, there is a fundamental gap in our knowledge since there is a lack of proven and published methods of reducing bird mortality at operating wind farms. In our study, the distribution of griffon vulture mortalities among 13 wind farms was studied to detect which turbines were most dangerous and caused most fatalities. Secondly, we tested if stopping these turbines in dangerous situations, when the vulture flight trajectories may result in collision, could significantly reduce the rate of mortality. Finally, we assessed the consequences of stopping turbines on total wind energy production. As far as we know, this is the first published study that has attempted to determine the magnitude and characteristics of the distribution of mortality at wind farms and to test the effectiveness of a method to decrease fatalities such as the selective stopping of some turbines under high risk situations.

2. Material and methods

2.1. Study area and species

The Strait of Gibraltar separates southernmost Spain from northernmost Morocco (35°45′–36°10′N and 5°10′–6°00′W). It is the shortest sea crossing between Europe and Africa and it acts as a major concentration point for Palearctic soaring migrants (Bernis, 1980; Finlayson, 1992; Bildstein and Zalles, 2000).

The griffon vulture population in Cadiz province is the third largest population of Spain consisting of about 2000 breeding pairs (del Moral, 2009). In our study area, the griffon vulture breeding population consists of about 300 pairs (MIGRES Foundation, unpublished data) and the population is surrounded by several other breeding colonies so the area is constantly used by vultures during their local movements. Throughout the course of October and into November vultures from other areas, mainly northern Spain, accumulate in our study area, when a maximum of 1800 birds can be present daily, waiting for good weather conditions before crossing to Africa during their dispersive movements (Griesinger, 1996). Each autumn between four and five thousand of juvenile griffon vultures disperse from their breeding colonies and cross the Strait of Gibraltar to West Africa (MIGRES Foundation, unpublished data). Other species such as common kestrel Falco tinnunculus, peregrine falcon Falco peregrinus, Egyptian vulture Neophron pernopterus and eagle owl Bubo bubo are common in the area, as well as some tree-nesting species such as short-toed eagle Circaetus gallicus. Except Egyptian vulture (Madroño et al., 2004), none of these species are endangered in Spain. Besides being an important breeding area, during the migration period, around 70,000 honey buzzards Pernis apivorus, 120,000 black kites Milvus migrans, 110,000 white storks Ciconia ciconia, and 20,000 booted eagles Aquila pennata and short-toed eagles, pass through this area. The vegetation in the study area is characterized by brushwood and wild olive Olea europaea var. sylvestris and cork oak Quercus suber woodland with patches of scrub and rocky areas on the mountain ridges, and pasture land used for cattle grazing predominating in the lower areas.

2.2. Wind farms and stopping protocol

We studied 13 wind farms containing a total of 296 wind turbines with different power ratings (Table 1). Turbines were arranged in rows running north–south so they optimized the use of prevailing easterly and westerly winds. The total height of the turbines (including the blades) ranged from 106 to 170 m, rotor diameters ranged from 56 to 90 m, and distances between turbines ranged from 115 to 180 m, which was twice the rotor diameter.

These wind farms were constructed and began operation between 2006 and 2007. According to environmental impact (EID) regulations, the facilities were required to develop surveillance programs (Ferrer et al., 2011; Janss et al., 2010). The main goal of these programs is to document all mortalities caused by collisions of birds with turbine blades. These programs have been conducted annually every day of the year (365 days) from dawn to dusk (between 8 and 14 daylight hours in winter and summer, respectively) by eight trained observers who are coordinated and interconnected by cellular telephones. Mortality searches are made at every turbine on a daily basis, with a fixed search effort to find dead medium- to large-sized birds (pigeon size or bigger). The observers are evenly distributed throughout the area covered by the wind farms and this high search effort reduces the need to apply corrections for search efficiency and scavenger removal.

Data gathered consists of the species and number of individuals that collide with turbines, the injuries, the distance to the nearest turbine, and the weather conditions when the collisions occur. Data pertaining to the ages of dead birds are obtained when possible. These data enable us to determine the extent of mortalities and how they are distributed in space and time among the different wind farms and their turbines.

In some cases, the surveillance programs have included selective stopping of turbines by observers when dangerous situations are detected. A typical dangerous situation occurs when, for example, a griffon vulture flies in a trajectory which will potentially result in a collision with turbine blades, or when a group of vultures flies within or nearby a wind farm. In these cases the observers telephone the wind farm control office to switch off the turbines involved in the risk stopping the turbine within a maximum of

Table 1
Characteristics of wind farms in this study and their griffon vulture mortality rates (vulture/turbine/year) during the two study periods (2006–2007 and 2008–2009).

Wind farm	No. of turbines	Number of operating months until December 2009	Power output (mW)	Selective stops	Vulture/turbine/year 2006–2007 (number of dead vulture)	Vulture/turbine/year 2008–2009 (number of dead vulture)
WF 1	16	55	1.5	No	0.156 (5)	0.000 (0)
WF 2	11	51	1.9	Yes	0.863 (19)	0.363 (8)
WF 3	15	27	1.7	No	0.200 (6)	0.400 (12)
WF 4	11	29	1.9	Yes	0.818 (18)	0.636 (14)
WF 5	17	53	0.8	Yes	0.176 (6)	0.117 (4)
WF 6	30	53	0.8	Yes	0.133 (8)	0.033 (2)
WF 7	11	38	2.2	No	0.454 (10)	0.727 (16)
WF 8	20	53	0.8	Yes	0.175 (7)	0.050 (2)
WF 9	28	53	1.6	Yes	0.375 (21)	0.107 (6)
WF 10	15	53	0.8	Yes	0.166 (5)	0.133 (4)
WF 11	6	53	1.6	Yes	0.166 (2)	0.083 (1)
WF 12	16	53	0.8	Yes	0.156 (5)	0.250 (8)
WF 13	100	60	0.3	Yes	0.115 (23)	0.045 (9)

3 min. Ten of the 13 wind farms (Table 1) have been required to conduct trials of this stopping procedure and the selective stopping protocol started in 2008–2009. As a result, we were able to obtain data from the 296 wind turbines at these 13 wind farms from 2006 to 2009. During the first period (2006–2007) none of them used selective stopping programs. However from 2008 to 2009, 10 wind farms (total of 244 turbines) could be selectively stopped and three wind farms (total of 52 turbines) could not be stopped.

The data were recorded according to the protocol designed by MIGRES Foundation and collected by the Andalusia Environmental Ministry. Since not all wind farms became operational at the same time, to standardize the mortality data, the monthly mortality rate was calculated for each wind farm by dividing the sum of fatalities recorded in a given wind farm by the number of turbines in the wind farm and by the number of months the wind farm was operating, and then an annual mortality rate was calculated by multiplying by 12.

2.3. Statistical methods

We used generalized linear models (GLM) with Poisson distribution and log link functions to perform parametric analyses (Sokal and Rohlf, 1981). We used non-parametric analyses to determine the distribution of mortalities among turbines (Sign test), the differences in mortality ages distribution and the differences in the monthly distribution of mortalities between the 2006–2007 and 2008–2009 periods (Chi-square test for homogeneity, including Yates' correction for continuity). All tests were 2-tailed. The Statistica 7.0 software package was used to perform statistical procedures and we used an alpha value of 0.05 to assess significance of results.

3. Results

We recorded a total of 221 dead griffon vultures at the 13 wind farms during this study. The average vulture mortality rate at these wind farms was 0.186 vulture deaths/turbine/year (Table 1). Statistical differences in vulture mortality rates per turbine and year among wind farms were found (GLM Poisson distribution and log link function, Wald statistic = 150.94, df = 12, $p < 0.001$), with the Wind Farm 4 being the most dangerous exhibiting a mean of 0.727 vulture deaths/turbine/year and the Wind Farm 1 being the least dangerous with a mean of only 0.078 vulture deaths/turbine/year being (Table 1).

A total of 117 were aged of which 74.36% (87) were juveniles and 25.64% (30) were in matures and adults. During the January–August period a total of 47 griffon vulture were aged and no statistical differences were detected between juveniles (27) and adults (20) (expected ratio 50%; $X^2 = 1.04$, df = 1, $p = 0.307$). During the September–December period a total of 70 griffon vultures were aged, and no statistical differences were detected between observed juveniles and adults and expected (expected ratio 80% juveniles, 10% adults (A.R. Muñoz, obs. pers.); $X^2 = 1.42$, df = 1, $p = 0.232$).

3.1. Pre-selective stopping results

Using only mortality data for the 2006–2007 period (i.e. the period without selective stopping programs at any wind farm) as the baseline, 135 vultures died at the 13 wind farms (mean value 0.228 vulture deaths/turbine/year). Again, statistical differences in vulture mortality rates among wind farms were found (GLM Poisson distribution and log link function, Wald statistic = 79.90, df = 12, $p < 0.001$) with the Wind Farm 2 being the most dangerous with a mean of 0.863 vulture deaths/turbine/year, and the Wind Farm 13 being the least dangerous with a mean of only 0.115 vulture deaths/turbine/year (Table 1).

No significant differences in mortality rates between both years were found (GLM Poisson distribution and log link function, Wald statistic = 1.24, df = 1, $p = 0.248$). Nevertheless, highly significant differences among months were found (GLM Poisson distribution and log link function, Wald statistic = 2.90, df = 11, $p = 0.991$) with most of the fatalities concentrated in October (14.44%) and November (23.34%, Fig. 3), matching the period in which migratory birds concentrate around the Strait of Gibraltar.

The distribution of griffon vulture mortalities among the wind turbines was not uniform (Sign test, N = 296, Z = 6.22, $p < 0.001$). Mortality showed a trend to be concentrated at certain turbines, showing a quasi-Poisson distribution with most of the turbines causing no mortality and a few of them causing most of them (Fig. 1). The 10 most dangerous turbines were distributed among six different wind farms. As some of the wind turbines showed most of the mortality and others did not, the overall accumulated mortality rate seems to follow a logarithmic curve (Fig. 2).

3.2. Selective stopping results

In 2008, selective stopping programs were established at 10 of the 13 wind farms. Taking into account the distribution of mortalities among turbines as well as the monthly distribution of mortalities, we increased the surveillance program at the most dangerous turbines during the most dangerous period (i.e. from September to December). Based on the baseline data from 2006 to 2007, in order to reduce griffon vulture mortality by about 50%, we needed to concentrate the stopping protocols at approximately 10% of the turbines (those with higher accumulated mortality records, see Fig. 2) during the September–December period.

Using only data for the 2008–2009 period, when the selective stopping programs were activated, 86 vultures died at the 13 wind farms (mean value 0.145 vulture deaths/turbine/year). Again, statistical differences in vulture mortality rates among wind farms were found (GLM Poisson distribution and log link function, Wald statistic = 83.14, df = 12, $p < 0.001$) with the Wind Farm 7 being the most dangerous with a mean of 0.727 vulture deaths/turbine/year and the Wind Farm 1 being the least dangerous with no collisions found (Table 1).

Statistically significant differences in vulture mortality at the 10 wind farms with selective stopping programs were found when comparing the period 2006–2007 (without stops) to 2008–2009 (GLM Poisson distribution and log link function, Wald

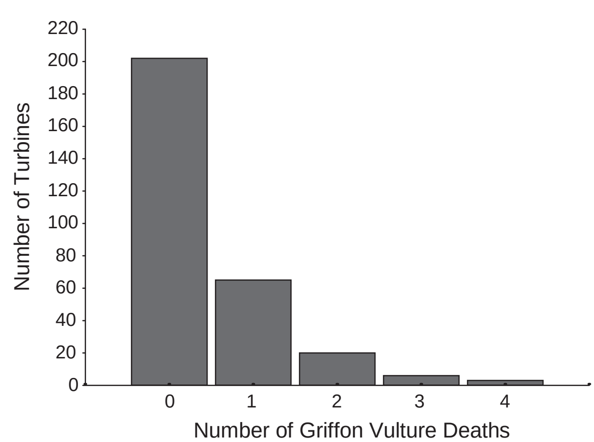

Fig. 1. Distribution of the number of dead griffon vultures per turbine. There are more than 200 turbines without griffon vulture fatality and less than 10 turbines cause four fatalities.

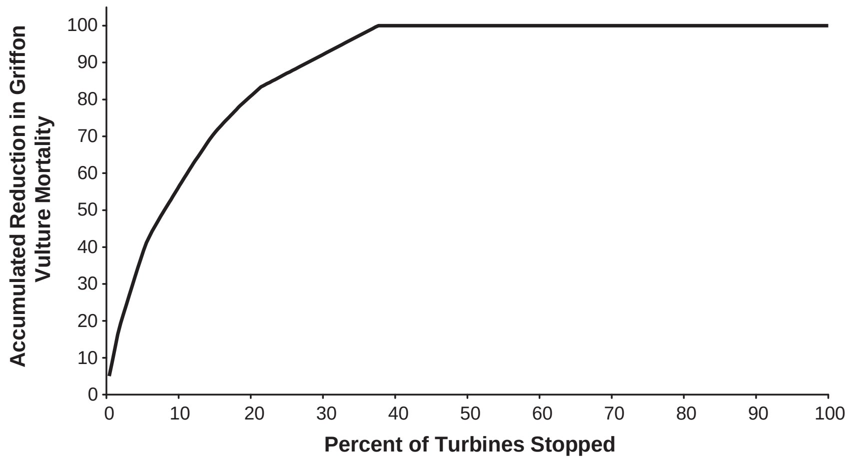

Fig. 2. Percentage of turbines and their cumulative griffon vulture mortality. Selective stopping of only 10% of the turbines reduced the griffon vulture mortality around 55%.

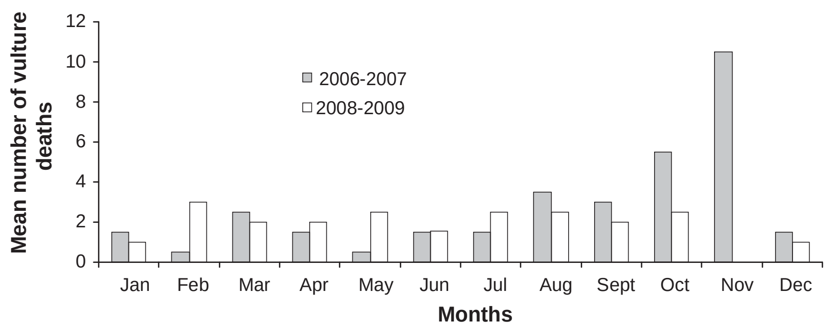

Fig. 3. Distribution of the mean number of dead griffon vultures per month during the two study periods (2006–2007 and 2008–2009). The peak of mortality during September–December in the first study period did not appear in the second study period.

statistic = 17.45, df = 1, $p < 0.001$). Mean mortality for these 10 wind farms decreased by 50.8% from 0.2244 vulture deaths/turbine/years in 2006–2007 to 0.1141 vulture deaths/turbine/year in 2008–2009. In contrast, no differences were found when comparing the three wind farms without selective stopping programs between both periods (GLM Poisson distribution and log link function, Wald statistic = 0.99, df = 1, $p = 0.319$, mean 2006–2007 = 0.250 vulture deaths/turbine/year; mean 2008–2009 = 0.333 vulture deaths/turbine/year).

No significant differences in vulture mortality between the 10 wind farms with selective stopping programs and the three without them were found during the 2006–2007 period (GLM Poisson distribution and log link function, Wald statistic = 0.21, df = 1, $p = 0.649$). However, there were significant differences between the two groups of wind farms for the 2008–2009 period (GLM Poisson distribution and log link function, Wald statistic = 21.59, df = 1, $p < 0.001$).

The monthly distribution of mortality also changed significantly when comparing the first (2006–2007) period without selective stopping programs to the second which had them (2008–2009, Chi-Square = 34.52, df = 11, $p < 0.001$). The characteristic peak of mortality during September–December disappeared when selective stopping programs were started (Fig. 3).

3.3. Consequences in energy production

During the second period (2008–2009) when selective stopping programs were used, a total of 4408 turbine stops per year occurred, with a mean of 18.06 stops per turbine. For 458 of these stops, the median duration of a stop was 22 min, 11 s. Consequently, turbines were stopped on average for 6 h and 20 min each year. Assuming that the total energy production is equally distributed among months and the 24-h of the day (although this seem unlikely because for instance nocturnal energy production tend to be higher than diurnal one in this area), each turbine stooped on average 380 min of the 525,600 min of the year, representing an average reduction in total energy production of only 0.07% each year.

4. Discussion

To date, several avian mortality rates have been recorded at wind farms around the world (Winkelman, 1990; Orloff and Flannery, 1993; Musters et al., 1996; Howell, 1997; Dirksen et al., 1998; Morrison et al., 1998; Osborn et al., 2000; Erickson et al., 2002; Johnson et al., 2002; Thelander and Smallwood, 2003; Barrios and Rodríguez, 2004; Arnett, 2005; Dorin et al., 2005). Unlike the majority of studies, our vulture mortality rates per turbine were relatively high. In fact, mortality rates found in our study were among the highest ever published for wind farms. However, they were similar to mortality rate estimates at other power structures such power lines (Ferrer et al., 1991).

Ferrer et al. (2011) found the highest mean collision rates ever reported for all bird species and for just raptors. All of these wind farms have been authorized with the requirement that they study the environmental impacts of the facilities, including a full-year study of the avifauna in the area. Therefore their results indicate that the commonly-used procedure to assess mortality risk at wind farms must be revised (Janss et al., 2010).

We found highly significant differences in mortality rates among individual wind turbines, suggesting that factors affecting the risk of collision are related to local conditions, such as small scale topographical features and wind patterns at individual wind turbines (thus confirming Barrios and Rodríguez, 2004; de Lucas et al., 2008). These authors also suggested wind directions, in relation to bird behavior, could be another factor involved in concentration of fatalities. In our study, available meteorological data for 57% of mortality events showed that 60% of the collisions occurred on days with easterly wind, which was higher during the months with higher mortality (68%).

Furthermore, within a wind farm the mortality rates can differ among individual turbines, indicating that the site selection of individual turbines can play an important role in limiting the number of collision fatalities (Everaert and Stienen, 2007).

The species-specific factor could be another serious role because other soaring-bird species, chiefly birds that occur in the study region in large numbers but only during their migration periods (e.g. white stork C. ciconia), were rarely involved in risk situations and collisions (Barrios and Rodríguez, 2004; de Lucas et al., 2008). The aggregation of juveniles during autumn and winter is usual in the Strait of Gibraltar (Griesinger, 1996), being most of them birds that cross over to Africa in major number. The higher percentages of juveniles collided during this period is according to the age of observed vultures in flight when crossing to Africa (eight juveniles per immature/adult, A.R. Muñoz obs. pers.). In addition, it may be a perceptual basis to collision vulnerability in this species. In a recent study it is shown that the visual field of griffon vulture contains a small binocular region and large blind areas above, below and behind the head, which may facilitate vultures to be often sightless in the direction of travel (Graham Martin, personal communication).

The fact that the 10 most dangerous turbines in our study were distributed among six different wind farms supports the idea that mortality varies greatly among turbines even within the same wind farm. This is an important finding from a mitigation perspective. If the distribution of fatalities tends to be concentrated at just a few turbines during a few months of the year, we can expect to get a significant reduction in mortality rates by selectively stopping certain wind turbines with a minimal reduction in energy production.

Taking into account the distribution of fatalities among turbines as well as among months, we suggest that trained observers can be effectively used to mitigate mortality rates in operating wind farms. Our results show that it is possible to reduce mortality more than 50% by concentrating turbine stopping surveillance efforts at certain turbines (around 10% in our case) during certain months (September–December in our case). As vultures are large, diurnal, soaring raptors, most of the accidents occur from 2 h after sunrise until 2 h before sunset. Therefore, short stops of wind turbines are necessary only during daylight hours. Since turbines can operate normally at night, the decrease in energy production is minimized. As our data show, mortality of griffon vultures can be decreased by one half with only a 0.07% reduction in energy production. As far as we know, this is the first time that a successful mitigation method to decrease avian mortality at wind farms has been published.

There are two complementary strategies to make the coexistence of wind farms and birds possible. First, we must increase our ability to determine the right locations not only for wind farms but for each of the wind turbines to avoid the placement of any turbine in dangerous sites (Ferrer et al., 2011). In these safe places, no bird collisions would be detected when the turbines are installed there. Some authors have proposed that features of turbine design or location may affect the collision risk (Orloff and Flannery, 1992; Smallwood and Thelander, 2004). This is not consistent with this study where all of the most dangerous turbines have a similar design (tubular tower, tower height, three blades) and their position within the row is no an influential factor on mortality rates. Other factor that could have been affected is the altitude (meters above sea level) and in our study area the relief is practically scarce; it is a plain without strong slopes situated among 10–150 m above sea level.

The development of automatic systems which are capable of determining the trajectories of birds flying toward turbines and automatically stopping turbines with enough time to avoid collisions would improve the results and further reduce the loss of energy production and the cost of using trained observers.

5. Conclusion and management implications

Mortality in wind farms is one of the main adverse effects on birds and bats thought collision with turbines. In this study we have obtained one of the highest mortality rates cited in literature in spite of which no method was proven until now to reduce the level of collision. The stopping turbine protocol has showed as a good program focused on reducing the mortality of griffon vultures, and its application does not affect significantly the total energy production of the wind farms. Furthermore other species as Spanish Imperial Eagles Aquila adalberti have benefitted from this program. The first breeding pairs in Cadiz province located their nest less than 2 km for a wind farm that started the selective stopping program to avoid any risk for the adults and the two young they raised (Muriel et al., 2011).

The aggregation of collisions in few different turbines gives us the opportunity to study why they are the most dangerous. Technical features, meteorological conditions and avian community are similar in all turbines. Therefore some details at small scale could determine the difference between a safe turbine and a dangerous turbine. New approaches using models of wind movement patterns around topographical features will be necessary. Griffon vultures depend heavily on winds for flying (Pennycuick, 1975) and slight changes in topography could affect their maneuverability and their risk of collision.

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