Weak relationship between risk assessment studies and recorded mortality in wind farms

Miguel Ferrer[1], Manuela de Lucas[1], Guyonne F. E. Janss[2], Eva Casado[3], Antonio R. Munoz[3], Marc J. Bechard[4] and Cecilia P. Calabuig[1]

[1]Department of Ethology and Biodiversity Conservation, Estación Biológica de Doñana (CSIC), c/Américo Vespucio s/n, 41092 Seville, Spain; [2]Asistencias Técnicas Clave SL c/Progreso 5, 41013 Seville, Spain; [3]Fundación Migres, Complejo Huerta Grande, Crta N 340, km 96Æ7, 11390 Pelayo, Algeciras, Spain; and [4]Raptor Research Center, Department of Biological Sciences, Boise State University, 1910 University Dr, Boise, ID 83725, USA

Summary

1. Wind farms generate little or no pollution. However, one of their main adverse impacts is bird mortality through collisions with turbine rotors.
2. Environmental impact assessment (EIA) studies have been based on observations of birds before the construction of wind farms. We analysed data from 53 EIAs in relation to the actual recorded bird mortalities at 20 fully installed wind farms to determine whether this method is accurate in predicting the risk of new wind farm installations.
3. Bird data from EIAs were compared with bird collisions per turbine and year at functional post-constructed wind farms to identify any relationship between pre- and post-construction studies.
4. Significant differences in birds recorded flying among the 53 proposed wind farms were found by the EIAs. Similar results were obtained when only griffon vultures Gyps fulvus and other raptors were considered. There were significant differences in indexes, including the relative index of breeding birds close to proposed locations, among the 53 proposed wind farm sites.
5. The collision rate of birds with turbines was one of the highest ever recorded for raptors, and the griffon vulture was the most frequently killed species. Bird mortality varied among the 20 constructed wind farms.
6. No relationship between variables predicting risk from EIAs and actual recorded mortality was found. A weak relationship was found between griffon vulture and kestrel Falco sp. mortality and the numbers of these two species crossing the area.
7. Synthesis and applications. There was no clear relationship between predicted risk and the actual recorded bird mortality at wind farms. Risk assessment studies incorrectly assumed a linear relationship between frequency of observed birds and fatalities. Nevertheless, it is known that bird mortality in wind farms is related to physical characteristics around individual wind turbines. However, EIAs are usually conducted at the scale of the entire wind farm. The correlation between predicted mortality and actual mortality must be improved in future risk assessment studies by changing the scale of these studies to focus on the locations of proposed individual wind turbine sites and working on a species specific level.

Key-words: bird collision, environmental impact assessment, Falco sp., Gyps fulvus, mortality data, raptors, Tarifa, wind farm

Introduction

Wind farms have received public and government support as alternative energy sources because they do not contribution to air pollution, which is typically associated with fossil fuel technologies (Huntley et al. 2006). At the end of 2008, the global wind energy capacity surged by 28Æ8% and the total installed capacity reached 120Æ8 GW. Spain is the world's third largest wind energy market with 16Æ8 GW of installed electric generation capacity (Pullen, Qiao & Sawyer 2008).

Wind farms can affect birds through collisions with turbines (Orloff & Flannery 1992; Everaert & Stienen 2007; Smallwood 2007; Thelander & Smallwood 2007) or through

*Correspondence author. E-mail: mferrer@ebd.csic.es

displacement because of disturbance (Hotker, Thomsen & Koster 2004; Drewitt & Langston 2006). Although low collision rates have been recorded at many wind farms (Erickson et al. 2001; Percival 2005; de Lucas et al. 2008), some poorly sited wind farms have caused high collision mortality rates (de Lucas et al. 2008) and the potential for wind farms to cause problems for bird populations should not be underestimated (Hunt 2002; Madders & Whitfield 2006).

The prevention of bird collisions in newly built wind farms is a critical issue. When a wind project is proposed in European countries, an environmental impact assessment (EIA) is required by environmental authorities (either the Ministry or Environmental Department of a region). EIAs must include a section assessing the impact that the development is likely to have on the site's bird populations (Environmental Impact Assessment Directive 97/11/EC). Environmental authorities use the overall assessment to reach a 'declaration on the environmental impact' stating the significance and acceptability of the predicted effects. Mostly, these declarations identify additional measures to mitigate and compensate potential negative environmental consequences and other conditions that should be met by the project developer such as the monitoring of the environmental impacts.

Baseline data collection must be adjusted to different requirements depending on the area, so a fixed baseline survey is not possible. Langston & Pullan (2003) recommended that EIAs should include, at a minimum, a 12-month baseline field survey to determine the bird populations that use the development site annually. In some cases, 24 months of baseline surveys may be required for EIA assessment, where the bird species likely to be affected are subject to protective legislation (e.g. in Scotland for raptors listed on Annex I of the EC Birds Directive, SNH 2005).

This basic procedure is followed in European countries like Spain (RDL 2008), the UK (Percival, Band & Leeming 1999; SNH 2005), Denmark (Bro 2008) and Norway (NORAD 2003), and in other countries like Canada (Kingsley & Whittam 2005) and Mexico (Martınez 2008). Wind power regulations and wildlife guidelines in the United States vary by state (Stemler 2007), sometimes using voluntary guidelines to provide recommendations for minimising the potential impacts of wind development. Other states like Colorado, Maryland, Minnesota, Ohio and Oregon have mandatory and comprehensive guidelines for pre-construction evaluation, design, construction recommendations and monitoring post-construction.

In Andalusia, risk assessment studies are regulated by both regional and national legislation, although additional data can be required by local authorities. In the case of wind farm developments, additional data on bird and bat presence are often requested.

Nevertheless, we failed to find any study comparing previous risk evaluation with actual mortality recorded after a wind farm was operational. This lack of pre- and post-construction mortality comparisons is alarming because these previous risk evaluations are an integral part of the procedure of accepting or rejecting installations of new wind farms in several countries.

The main objective of our study was to analyse the relationship between risk prediction according to the environmental impact assessment studies (i.e. at the scale of entire wind farm) and the actual recorded mortality of birds in wind farms located in southern Spain after they became operational. The aim was to determine whether the assessment methods were accurate and to recommend improvements where necessary.

Materials and methods

STUDY AREA

The 53 potential locations for wind farms studied (20 finally approved and 33 rejected) were all located in Tarifa, Andalusia region, southern Spain, near the Strait of Gibraltar (Fig. 1). The Strait of Gibraltar is one of the most important migrating routes of the Palearctic birds (Bernis 1980; Finlayson 1992; Bildstein & Zalles 2000).

Cliff-breeding species such as griffon vultures *Gyps fulvus*, common kestrels *Falco tinnunculus*, Bonelli's eagles *Hieraaetus fasciatus*,

Fig. 1. Google Earth map with two different areas shows permitted wind farms (20 wind farms, in black colour) and unpermitted wind farms (33 wind farms, in white colour). Study area was in the extreme south-west of Spain.

peregrine falcons *Falco peregrinus*, Egyptian vultures *Neophron pernopterus*, short-toed eagles *Circaetus gallicus* and eagle owls *Bubo bubo* are common in this area. Three of these species are endangered in Spain: Bonelli's eagle, Egyptian vulture and peregrine falcon (Madrono, Gonzalez & Atienza 2004). In addition, during the migration period, thousands of soaring species such as honey buzzards *Pernis apivorus*, black kites *Milvus migrans*, white storks *Ciconia ciconia*, booted eagles *Hieraaetus pennatus* and short-toed eagles pass through this area. The vegetation in the study area is characterised by brushwood and scattered trees (*Quercus suber*, *Q. rotundifolia*) on the mountain ridges and by pasture land used for cattle grazing in the lower areas.

The 20 approved wind farms consisted of 252 wind turbines and nine different models (see Table 1). Turbines were arranged in rows running north–south, so they optimised the use of prevailing east and west 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 with the distance between turbines double the rotor diameter.

FIELD METHODS DURING RISK ASSESSMENT STUDIES

All the methods we used were in accordance with environmental administration requirements and were very similar to those of other autonomous administrations in Spain as well as other parts of the world. The studies of environmental impacts prior to wind farm construction were carried out from 1999–2000. During these studies, the 53 proposed wind farm locations (i.e. areas where turbines were due to be installed) were sampled to estimate bird use of the areas over an entire year. Eventually 20 wind farms received construction licences from the local environmental authorities, and they were built at locations where the least risk was expected based on several criteria, including bird use, proximity to breeding and roosting sites, and the presence of endangered species or potential collision victims (i.e. raptors).

The numbers of birds crossing the 53 potential wind farm locations were recorded from fixed observation points inside each area. At these points, birds were observed using binoculars that allowed detection up to 1 km away. Because of relief in some cases, the whole location could not be covered from one observation point, in which case bird crossings were recorded from different points and average use of the entire site was calculated.

Birds were recorded by two observers during 3621 independent observation sessions of 1–3 hours each. Sessions were evenly distributed over the study area (about 60 sessions per observation point), the year (about 1800 hour per season) and daylight hours. Days with similar meteorological conditions for visibility were selected to avoid biases in our ability to detect birds. Observations from different locations were conducted on the same days but at different times to ensure complete coverage of all daylight hours. Mean observation time per potential wind farm location varied between 107 and 228 hours (total effort: 7267 hours and 42 minutes). During observation sessions, any bird or group of birds detected was recorded, and its flight altitude through the area was recorded. Each record included (i) species, (ii) number of birds and (iii) categorised flight altitude at each location (beneath rotor/rotor height/above rotor).

For each proposed wind farm location, we recorded the total number of birds observed per hour and the total number of birds at rotor height (risk). Additionally, these values were calculated separately for griffon vultures, kestrels and other raptors (not vultures).

Classification of the mortality threat of the 53 potential wind farm locations was made using two indexes, the Relative Risk Collision Index (RRCI) and the Breeding Birds Relative Risk Index (BBRRI):

$$\mathrm{RRCI} = [(\mathrm{birds/hour}) + (\%\mathrm{bird\ at\ risk/hours}) + (\exp(\mathrm{CS})) + (\exp(\mathrm{ES}))]$$

where CS equalled the percentage of bird species sensitive to collision according to the literature and ES the percentage of endangered species according to the Spanish Red Book. The RRCI was standardised to 0–1 range.

$$\mathrm{BBRRI} = \left[\sum \exp(-d) + (\mathrm{N.nests})\right]$$

where d was the distance from the potential wind farm area to a breeding site (with negative value) and N. nest was the number of nests in the breeding area. The BBRRI was standardised to 0–1 range.

Based on these indexes, the locations were classified into three risk levels (1, 2 or 3), according to a subjective judgment by planning authorities. Most of the 20 projected wind farms that finally obtained positive environmental impact evaluations had a risk level of 1, but some had risk levels of 2 if they showed low values of RRCI and BBRRI.

Table 1. Wind farm characteristics

Wind farm Number	Number of turbines	Turbine power (MW)	Height (Without blades)	Rotor diameter
1	11	1·91	67	87
2	11	1·91	80	90
3	17	0·8	57	59
4	30	0·8	57	59
6	20	0·8	50	56
7	11	2·0	80	90
8	28	1·6	80	80
9	15	0·8	57	59
10	8	2·0	67	87
11	6	2·0	67	87
12	6	1·6	74	74
13	9	1·7	80	90
14	9	1·7	80	90
15	9	1·7	80	90
16	16	0·8	50	56
17	9	2·1	80	90
18	10	2·0	57	71
19	8	2·1	80	90
20	9	2·2	57	71

FIELD METHODS WITH OPERATING WIND FARMS

Wind farms started to operate between 2005 and 2008 in the study area (Fig. 1). Every operational wind farm activated a Surveillance Program with the main goal of registering the actual bird mortality by finding all of the dead birds that had collided with turbines. This mortality monitoring was made on a daily basis from the day the wind farms began to operate. Every wind farm was monitored from dawn to dusk by 13 trained observers who coordinated their observations to ensure that they surveyed the total area of influence of each wind farm.

Searches for birds killed by collisions were made on a daily basis at every turbine. As we were interested in mid-sized and large birds (pigeon-sized or bigger) and the surveys were conducted daily, we did not conduct carcass disappearance experiments. All turbines in our study area were arranged in rows; therefore, the most efficient search method was to walk transects and/or drive unpaved roads along the rows (Smallwood & Thelander 2004). The data included the number of birds killed by each turbine, with information on species, age and sex if possible, injuries, distance to turbine and weather conditions when the mortality occurred.

As not all wind farms became operational at the same time, and to standardise mortality data, the daily 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 and by the number of days which it was operating; annual mortality rate was calculated by multiplying by 365.

We calculated two different mortality rates: total bird mortality across all observed species and raptor mortality, with raptors selected because of their importance in conservation. Both variables are used in EIAs. We also selected two additional species for the analyses: griffon vultures and kestrels (*Falco tinnunculus* plus *Falco naumanni*) to determine whether the aggregation of raptor species would introduce errors in estimating mortality risk. Griffon vultures were selected because they are the most common large raptor species in the area. Kestrels were the most frequent raptor after vultures.

STATISTICAL METHODS

Because of the distributional characteristics of our data, we used nonparametric statistics to perform most of the analyses. The data set for the 53 proposed locations was tested for differences in the number of birds crossing each site and any of the indexes used to determine risk level.

Any possible relationships between the total number of birds killed by collisions with each turbine and year, and the number of birds crossing per hour or the number of birds at risk crossing the area per hour in the same location, as determined in the pre-construction studies, were analysed using nonparametric correlations. The number of raptors killed and the number of griffon vultures and kestrels killed were analysed in the same way. To account for inter-seasonal variation, we conducted correlation analyses between the total number of birds across all species, raptors, and vultures and kestrels counted in each season during pre-construction studies and mortality recorded in the same season when wind farms were operating.

To estimate the ability of EAI studies to predict the potential for collision rates, we used the linear relationship between pre-construction flight activity and subsequent frequency of collisions in the 20 authorised wind farms, log or square transforming variables when necessary to meet normality criteria (Shapiro–Wilk test). We used the prediction limits (95%) of this regression to estimate the potential predictive power according to pre-construction information, which is a common approach in EIAs. It was possible that we might not have been able to detect a significant relationship between pre-construction risk and actual recorded mortality at wind farms because only those wind farms with low risk were constructed; therefore, we attempted to predict the likely collision rates of the non-authorised wind farms by assessing the overlap between the two single species we analysed. For mortality variables, we also calculated the coefficient of variation among turbines inside the same wind farm and the coefficient of variation of mean mortality values among wind farms.

We also performed anova analyses, log or square transforming variables when necessary to meet normality criteria (Shapiro–Wilk test), to analyse differences in mean mortality per turbine and year among operating wind farms. All tests were two tailed. Statistica 7.0 was used to perform statistical procedures, and we used an alpha value of 0·05 to assess the significance of results.

Results

RISK ASSESSMENT STUDIES

A total of 291 278 birds were counted in the 53 study locations, averaging 40·08 birds per hour. Of those birds, 111 180 (38·17%) were griffon vultures and 4682 were raptor species.

According RRCI and BBRRI, and after a subjective judgment by planning authorities (i.e. weighting species according to regional status as well as national conservation status), the 53 locations were classified into three levels of mortality danger (Fig. 2). These levels of danger showed significant differences in the rates of bird crossings (birds per hour: Kruskal–Wallis test = 7·75, $P = 0·0207$; birds at risk per hour: Kruskal–Wallis test = 14·77, $P < 0·001$; raptors per hour: Kruskal–Wallis test = 16·91, $P < 0·001$; raptors at risk per hour: Kruskal–Wallis test = 22·21, $P < 0·001$; vultures per hour: Kruskal–Wallis test = 6·36, $P = 0·041$; vultures at risk per hour: Kruskal–Wallis test = 15·52, $P < 0·001$; kestrel per hour: Kruskal–Wallis test = 10·54, $P = 0·005$; kestrel at risk per

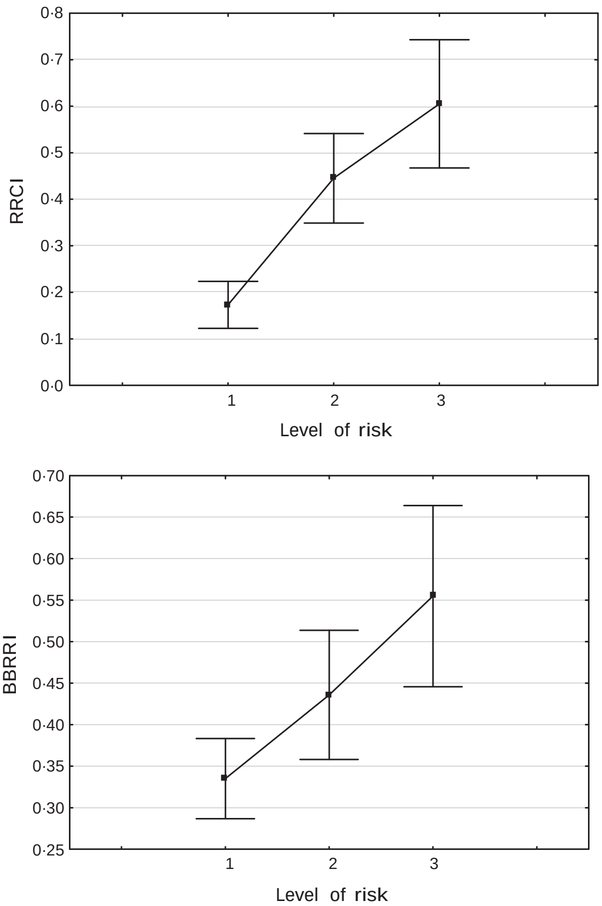

Fig. 2. Classification of the 53 potential wind farm locations according to level of risk, using the Relative Risk Collision Index and the Breeding Birds Relative Risk Index. See text for definitions.

Table 2. Differences between authorised (Yes, n = 20) and non-authorised (No, n = 33) wind farm locations. Kruskal–Wallis test was used. See text for calculation of the Relative Risk Collision Index (RRCI) and the Breeding Birds Relative Risk Index (BBRRI)

	Mean (SD)		
Variables	No	Yes	P
RRCI	0·52 (0·26)	0·24 (0·13)	<0·001
BBRRI	0·49 (0·21)	0·35 (0·07)	0·009
Birds/hour	45·65 (27·65)	30·89 (8·74)	0·004
Birds at risk/hour	22·53 (20·84)	11·54 (5·35)	0·001
Raptors/hour	7·90 (5·36)	3·81 (2·02)	0·002
Raptors at risk/hour	3·84 (3·24)	1·71 (0·61)	0·005
Vultures/hour	14·93 (9·87)	11·51 (4·50)	0·018
Vultures at risk/hour	7·05 (3·31)	4·24 (3·08)	0·003
Kestrels/hour	0·65 (0·06)	0·36 (0·05)	0·001
Kestrels at risk/hour	0·17 (0·01)	0·08 (0·01)	0·002

hour: Kruskal–Wallis test = 8·92, P = 0·011). For all the variables analysed, the mean values of birds flying were higher at the highest, most dangerous sites.

Based on the findings, 20 wind farm locations were finally authorised. Mean values of the rates of bird crossing and the statistical differences between authorised and unauthorised wind farm locations are shown in Table 2. In all cases, the 20 authorised locations showed significantly lower values than did the unauthorised ones.

MORTALITY IN OPERATING WIND FARMS

We found a total of 596 dead birds at all of the wind farms during the time they were operational (see Table S1 in Supporting Information). The griffon vulture was the most frequently killed species with 138 individuals (23·15%) colliding with turbines. Another 76 raptors other than vultures were found killed (23 common kestrels, 13 lesser kestrels and 16 short-toed eagles, among others). Raptors including vultures represented 36% of the total number of birds found dead, which was the same proportion as passerines (36%). Taking into account the time that the different wind farms have been operating (from 11 to 34 months), 337 birds of all species and 124 raptors died annually because of collisions with turbines, including 87 griffon vultures. The mean number of bird mortalities per turbine per year was 1·33, and there were significant differences in the mortality of all birds (anova F = 5·185, d.f. = 19, 232, P < 0·001) as well as raptors alone (anova F = 2·245, d.f. = 19, 232, P = 0·002) among the 20 wind farms. Differences were also significant when only griffon vulture (anova F = 8·276, d.f. = 19, 232, P < 0·001) and only kestrel (anova F = 9·004, d.f. = 19, 232, P = 0·009) mortalities were considered.

COMPARING ESTIMATED AND RECORDED MORTALITY THREATS

No significant relationship was found between bird mortality and either RRCI (r_s = −0·291, n = 20, P = 0·212) or BBRRI (r_s = −0·403, n = 20, P = 0·177). Recorded bird mortality in operating wind farms showed no differences according to the level of threat of the wind farm (Kruskal–Wallis test, H = 0·353, P = 0·552). Also, no difference between wind farm risk level and vulture mortality (Kruskal–Wallis test, H = 2·391, P = 0·122) was found. Bird flying rates in pre-construction locations and actual subsequent mortality in operating wind farms are given in Table S2, Supporting Information. No relationship was found between birds per hour and bird collisions per turbine and year (Spearman correlation; r_s = −0·118, n = 20, P = 0·617), nor was there a difference between birds at risk and bird mortality (r_s = 0·163, n = 20, P = 0·491). Raptor mortality was not related to raptors per hour (r_s = −0·376, n = 20, P = 0·101) nor to raptors at risk per hour (r_s = 0·024, n = 20, P = 0·917).

Considering single-species analyses, a marginal relationship was found between vultures per hour and mortality of vultures (r_s = 0·443, n = 20, P = 0·0503) but not between vultures at risk and mortality (r_s = 0·304, n = 20, P = 0·191). Kestrel mortality again was marginally related to kestrels per hour, although not significantly (r_s = 0·395, n = 20, P = 0·084), but not to kestrels at risk (r_s = 0·376, n = 20, P = 0·102).

To control for seasonal variation, we conducted comparisons between different bird flying rates during pre-construction studies and actual subsequent bird mortality, separately by season. Again, no relationship was found for any of the variables analysed (Table S3 Supporting Information).

EIA PREDICTION POWER

A non-significant regression between birds counted per hour and birds killed per turbine and year (both variables transformed to meet normality) was found, with birds per hour explaining only four per 10 000 of the variance (r = −0·0209, n = 20, P = 0·930). Given the lack of positive slope (see Fig. 3), this regression did not produce useful predictions. When we considered only raptors, again a non-significant

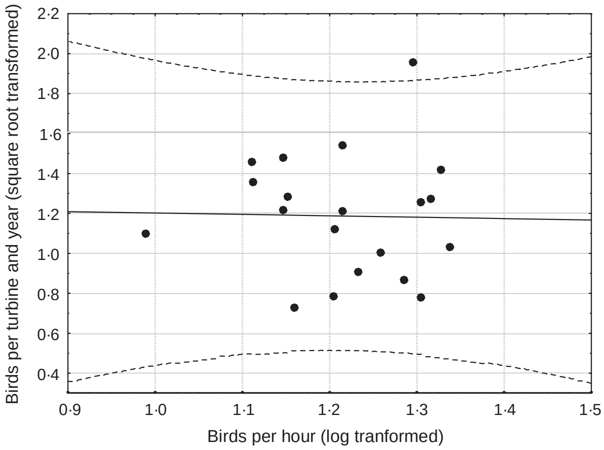

Fig. 3. Non-significant correlation between bird mortality recorded in operating wind farms and observations of birds flying over the area [both variables transformed to meet normality, (r = −0.0209, n = 20, P = 0.930)]. Dotted lines represent 95% of prediction.

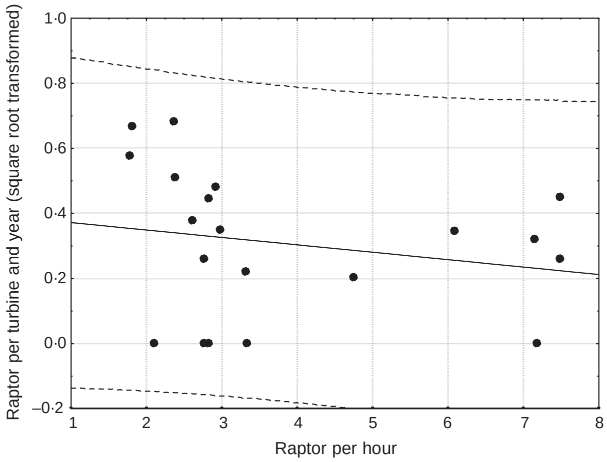

Fig. 4. Non-significant correlation between raptor mortality recorded in operating wind farms and observations of raptors flying over the area [both variables transformed to meet normality, (r = −0.204, n = 20, P = 0.382)]. Dotted lines represent 95% of prediction.

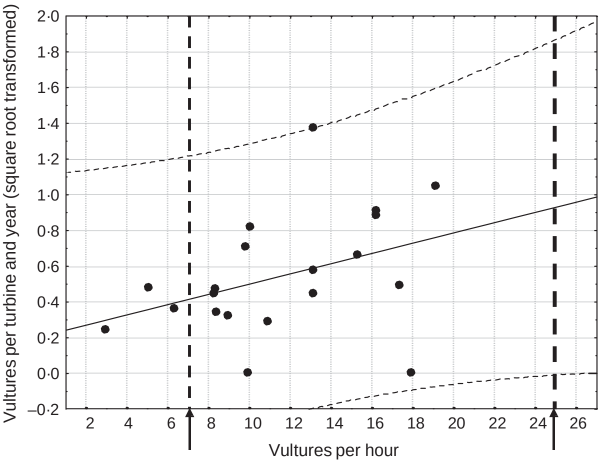

Fig. 5. Non-significant correlation between vulture mortality recorded in operating wind farms (square root transformed) and observations of vultures flying over the area (r = 0.379, n = 20, P = 0.099). Dotted curves represent 95% of prediction. Arrows and dotted lines represent the range limits of vultures per hour in the refused wind farms.

regression was found (raptor per hour and square root of raptor per turbine and year, r = −0·204, n = 20, P = 0·382, 4% of variance explained). Using the 95% prediction limits for this regression (see Fig. 4), we again obtained the limits of predictions for raptor mortality values for raptors recorded per hour. Prediction limits were the same for any value of raptors counted per hour, including those values recorded in the proposed wind farm sites that did not receive permits. No relationships between RRCI and raptor mortality (r = 0·1663, n = 20, P = 0·4835, 3% of variance explained) or BBRRI and raptor mortality (r = 0·1714, n = 20, P = 0·469, 3% of variance explained) were found.

A marginal although non-significant regression between vultures per hour and mortality of vultures per turbine and year (this last variable squared root transformed to meet normality) was found, with vultures per hour explaining 14% of the variance (r = 0·379, n = 20, P = 0·099). Using the 95% prediction limits for this regression (see Fig. 5), we obtained the limits of predictions expected according to increasing values for the independent variable, assessing the overlap of those wind farms receiving and not receiving permits (see Fig. 5). Considering the highest values of vultures per hour recorded during EIAs in the unauthorised wind farms (24·6 vultures per hour), expected vulture mortality would be between 0 and 3·4 vultures per turbine and year (back transformed). With the lowest values for vultures per hour recorded, the expected mortality would be between 0 and 1·46.

Mortality of kestrels showed a marginal, although non-significant, relationship with kestrels per hour (kestrels per hour and square root of kestrels per turbine and year, r = 0·380, n = 20, P = 0·0979, 14% of variance explained, Fig. 6). As before, considering the highest values of kestrels per hour recorded during EIAs in the unauthorised wind farms (1·04 kestrels per hour), expected mortality would be between 0 and 0·828 kestrels per turbine and year (back transformed). With the lowest recorded values for kestrels per hour, the expected mortality would be between 0 and 0·336. To summarise, Figs 5

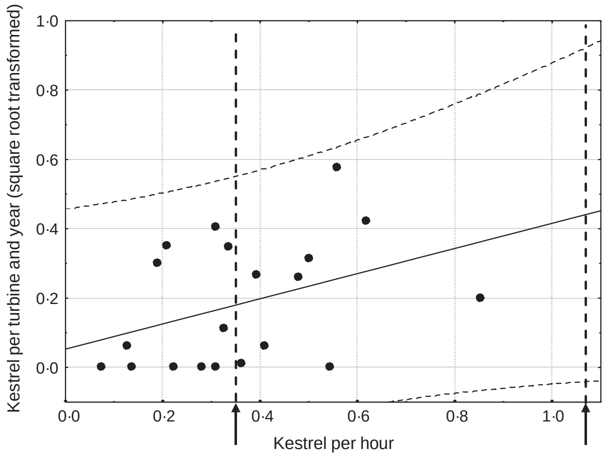

Fig. 6. Non-significant correlation between kestrel mortality recorded in operating wind farms [square root transformed) and observations of kestrels flying over the area (r = 0.380, n = 20, P = 0.0979]. Dotted curves represent 95% of prediction. Arrows and dotted lines represent the range limits of kestrels per hour in the unpermitted wind farms.

and 6 indicate that the previous weak correlations between bird activity and subsequent mortality after wind farm construction do not appear to be a consequence of a large difference in the initial activity levels, and hence likely collision levels, between operating and unauthorised wind farms.

Variance, measured as the coefficient of variation, of the mortality values among wind farms was 113·8% in total bird mortality, 101·5% in only raptors and 51·9% in only vultures. Coefficients of variation among turbines inside the same wind farm were calculated, and mean values for all the wind farms were 178·6% in bird mortality, 212·8% in raptor mortality and 150·5% in vulture mortality. Consequently, coefficients of variation among turbines were more than twice than those among wind farms.

Discussion

Avian fatalities in wind farms have been reported around the world (Orloff & Flannery 1992; Erickson et al. 2001; Fiedler et al. 2007; de Lucas et al. 2008). Herein, we present one of the highest mean collision rates ever reported for all bird species (1·33 birds per turbine per year) and for raptor species alone (Orloff & Flannery 1992; Drewitt & Langston 2006; Lekuona & Ursua 2007; de Lucas et al. 2008). These mortality rates are similar to those reported in coastal areas of Belgium, the Netherlands and Great Britain where principal victims are sea birds (Still et al. 1994; Musters, Noordervliet & Terkeus 1996; Everaert & Stienen 2007). All of these high-mortality wind farms have been, according to the law, licensed after risk assessment studies were conducted prior to construction according to accepted methodology.

Our results suggest that there is no clear relationship between predicted risk identified during EIAs and actual mortality of birds (particularly raptors) after wind farms have been constructed. Only weak relationships were found for single species. Although there were significant differences among wind farms in the frequency of birds observed flying, and there were significant differences in mortality rates when the wind farms were operating, no relationship between both groups of variables was evident. Consequently, some of the more a priori safe sites showed some of the higher collision rates when operating and vice versa.

This finding is relevant because the location of a wind farm is one of the few certainties known to affect the impact of a wind energy facility on birds (Madders & Whitfield 2006; de Lucas et al. 2008). Therefore, if criteria used in the prediction of the greatest risk areas are not valid tools for planning wind farm developments, as in our case, there are at least two problems. First, during at least the last decade, environmental administrations might have been giving licences to construct wind farms based on the wrong criteria, enabling them to be constructed in unsuitable places, as well as in safe ones. Second, there is an urgent need for a new or modified tool to adequately select locations for new wind farms to be constructed in future years.

Some factors could explain the lack of correlation between estimated risk a priori and actual mortality recorded after wind farms are constructed. It is possible that only those locations showing low to medium potential risk were authorised. As no 'unsuitable' places were authorised, we do not have any data for wind farms operating in these potentially high-risk areas. The lack of extreme data may affect the probability of detecting significant correlations, but regression analysis with prediction limits of 95% clearly showed that the power of prediction for mortality based on bird counts, raptor counts or indexes (including distances to nest sites) at the scale of the complete wind farm was very low because of the lack of positive slopes. As a result, the amplitude for predictions was the same for the lowest and the highest values of the independent variable (including unauthorised wind farms). In the single-species analyses (i.e. vultures and kestrels), the overlap of independent variable values (i.e. observation of vultures or kestrel per hour) between wind farms receiving permits and those not receiving permits was so large that we can conclude that we have enough data for the analyses. Consequently, we can suggest that this approach (estimation of potential mortality according to bird observation records during EIA) is inaccurate, demonstrating low predictive power.

Obviously, we cannot discount the fact that with more mortality data coming from unpermitted wind farm sites, some of the regression would be significant or marginally significant, but it is difficult to believe because the mortality recorded at the approved wind farms was among the highest ever recorded. In considering only the approved wind farms, mortality records in some locations were so high that clearly the risk assessment method was inadequate if the aim was to grant permission for low-impact installations only.

Another potential source of error is selection of groups of birds or the definition of indexes that are in fact aggregates of different species. Our results showed that assessment based on a single-species approach would be much more accurate than those used in the EIAs. Interestingly, regressions were improved using total observations of vultures or kestrels per hour compared to observations of birds flying at risk (i.e. at rotor height). This suggests that estimating risk introduces more variability and error into the assessment. In conclusion, we recommend the use of species-specific approaches (as in other countries like UK; SNH 2005) and total observations in the area.

It is possible that data collection during previous studies did not take into account the real distribution of wind direction during the year, a variable that affects bird behaviour and use of space mainly in soaring birds' species (Barrios & Rodrıguez 2004; de Lucas et al. 2008). Indeed, a comparison of the study hours by wind direction showed that east and west wind directions were surveyed more than their occurrence. These potential differences between wind directions recorded during EIAs and the annual pattern of wind direction would explain discrepancies between a priori studies and actual recorded mortality after wind farms became operational.

Additionally, the methods used in our risk assessment studies might have been inappropriate. Records taken at fixed observation points are potentially skewed towards the locations of observers, and the actual use of some areas might be underestimated because of the large distance between the area and the observation points, especially for medium- to small-sized birds. Estimates based on transect counts or supported by radar data might have provided more accurate data. However, this should have not been an issue for vultures, and our results would have been similar to those for kestrels, clearly a smaller bird than vultures.

We contend that there are some weaknesses in the common methodology used in risk assessment studies because they wrongly assume a linear relationship between the frequency of observed birds and fatalities of birds (Langston & Pullan 2003;

Smallwood & Thelander 2004; Telleria 2009). There is clear evidence that the probability of bird collisions with turbines depends critically on species behaviour and topographical factors, and not only on local abundance (Barrios & Rodrıguez 2004; de Lucas et al. 2008). This challenges the main assumption of wind farm assessment studies: birds do not move over the area at random, but follow main wind currents, which are affected by topography. Consequently, certain locations of wind turbines could be very dangerous for birds even where there is a relatively low density of birds crossing the area, whereas other locations would be relatively risk free even with higher densities of birds. If relevant factors affecting the frequency of collisions with turbine rotor blades are operating at the individual turbine scale, and not at the entire wind farm scale, EIAs must be conducted at the level of individual proposed turbines. Our results demonstrate that mortality variation among wind turbines inside the same wind farm was more than double the variation among wind farms. As turbine locations were not defined in the EIA in our study, it was impossible to focus observations on birds crossing close to future individual turbine locations. Differences in working scales would explain the low correlation between predicted risks and observed actual mortality. In the future, it would be useful to map bird flight paths at the scale of proposed turbines as well as recording the number of birds observed crossing proposed development sites. We realise that this will probably need a higher intensity of pre-construction fieldwork than is usually conducted, in order to be accurate.

An interesting development is proposed by de Lucas (2007) to test a model of the proposed development area in a wind tunnel to determine the location of the main passages for birds prior to construction. At a finer scale, these models could be used to evaluate the relative effects of individual turbines within particular locations, using data from a meteorological mast recording wind speed in the area. The use of this kind of aerodynamic model, as well as any statistical model using existing wind and topographical data, at an early planning stage could help to streamline the process of selecting potential locations and reduce the uncertainty associated with wind farm development.

Acknowledgements

The editors H. Riley and J. Pearce-Higgins greatly improved earlier versions of this manuscript. M. Carrete and two anonymous referees made interesting contributions. The preliminary studies were conducted by the consultant agency Asistencias Tecnicas Clave, and SL. Migres Foundation thanks Asociacion Eolica de Tarifa for their collaboration and to the workers of the Surveillance Program.

References

Barrios, L. & Rodrıguez, A. (2004) Behavioural and environmental correlates of soaring-bird mortality at on-shore wind turbines. Journal of Applied Ecology, 41, 72–81.

Bernis, F. (1980) La Migración de Las Aves En El Estrecho de Gibraltar, 1st edn. Universidad Complutense de Madrid, Madrid.

Bildstein, K. & Zalles, J.L. (2000) Raptor Watch: A Global Directory of Raptor Migration Sites, 1st edn. Birdlife Conservation, London.

Bro, C. (2008) Environmental Impact Assessment on Wind Farms. Grontmij/Carl Bro Report. Aarhus, Denmark.

Drewitt, A.L. & Langston, R.H.W. (2006) Assessing the impacts of wind farm on birds. Ibis, 148, 29–42.

Erickson, W.P., Johnson, G., Strickland, D., Young, D., Sernka, K.J. & Good, R. (2001) Avian Collisions with Wind Turbines: A Summary of Existing Studies and Comparisons to Other Sources of Avian Collision Mortality in the United States. West, Inc. Report. National Wind Coordinating Committee (NWCC), Washington, USA.

Everaert, J. & Stienen, E.W.M. (2007) Impact of wind turbines on birds in Zeebrugge (Belgium). Biodiversity and Conservation, 16, 3345–3359.

Fiedler, J.K., Henry, T.H., Tankersley, R.D. & Nicholson, C.P. (2007) Results of Bat and Bird Mortality Monitoring and the Expanded Buffalo Mountain Windfarm. Tennessee Valley Authority Report, Tennessee, USA.

Finlayson, C. (1992) Birds of the Strait of Gibraltar, 1st edn. T. & A. D. Poyser, London.

Hotker, H., Thomsen, K.M. & Koster, H. (2004) Impacts on Biodiversity of Exploitation of Renewable Energy Sources: The Example of Birds and Bats. NABU Report. Endbericht, Germany.

Hunt, G. (2002) Golden Eagles in a Perilous Landscape: Predicting the Effects of Mitigation for Wind Turbine Blade-Strike Mortality. California Energy Commission Report, Santa Cruz, USA.

Huntley, B., Collingham, Y.C., Green, R.E., Hilton, M., Rahbek, C. & Willis, S.G. (2006) Potential impacts of climatic change upon geographical distribution of birds. Ibis, 148, 8–28.

Kingsley, A. & Whittam, B. (2005) Wind Turbines and Birds. A Background Review for Environmental. Assessment Bird Studies Canada Report. Canadian Wildlife Service, Quebec, Canada.

Langston, R. & Pullan, J. (2003) Wind Farms and Birds: An Analysis of the Effects of Wind Farms on Birds, Guidance on Environmental Assessment Criteria and Site Selection Issues. RSPB/BirdLife International Report, Strasbourg, France.

Lekuona, J.M. & Ursua, C. (2007) Avian mortality in wind plants of Navarra (Northern Spain). Birds and Wind Farms (eds M. de Lucas, G. Janss & M. Ferrer), pp. 177–192. Quercus Editions, Madrid.

de Lucas, M. (2007) Aves Y Parques Eólicos: Efectos E Interacciones. PhD Thesis. Universidad Autonoma of Madrid, Spain.

de Lucas, M., Janss, G.F.E., Whitfield, D.P. & Ferrer, M. (2008) Collision fatality of raptors in wind farms does not depend on raptor abundance. Journal of Applied Ecology, 45, 1695–1703.

Madders, M. & Whitfield, D.P. (2006) Upland raptors and the assessment of wind farms impacts. Ibis, 148, 43–56.

Madrono, A., Gonzalez, C. & Atienza, J.C. (2004) Libro Rojo de las Aves de España, 2nd edn. SEO/BirdLife, Madrid.

Martınez, C. (2008) Proyecto de Norma Oficial Mexicana NOM-151-SEMARNAT. Evaluación de los Impactos de la Generación de la Energía Oleoeléctrica sobre la Vida Silvestre, Abril 2008. CONABIO, Mexico D.F., Mexico.

Musters, C.J.M., Noordervliet, M.A.W. & Terkeus, W.J. (1996) Bird casualties caused by a wind energy project in an estuary. Bird Study, 43, 124–126.

NORAD (2003) Environmental Impact Assessment. Norwegian Ministry of Environment Report. Oslo, Norway.

Orloff, S. & Flannery, A. (1992) Wind Turbine Effects on Avian Activity, Habitat Use, and Mortality in Altamont Pass and Solano County Wind Resource Areas. California Energy Commission, USA.

Percival, S.M. (2005) Birds and windfarms: what are the real issues? British Birds, 98, 194–204.

Percival, S.M., Band, B. & Leeming, T. (1999) Assessing the Ornithological Effects of Wind Farms: Developing a Standard Methodology. Wind Power Comes of Age, September 1999. British Wind Energy Association Conference, Cambridge, UK.

Pullen, A., Qiao, L. & Sawyer, S. (2008) Global Wind 2008 Report. Global Wind Energy Council (GWEC) Report, Brussels, Belgium.

RDL (2008) Aprobacion del texto refundido de la Ley de Evaluacion de Impacto Ambiental de proyectos. Boletín Oficial del Estado, 23, 4986–5000.

Smallwood, K.S. (2007) Estimating wind turbine-caused bird mortality. Journal of Wildlife Management, 71, 2781–27791.

Smallwood, K.S. & Thelander, C.G. (2004) Developing Methods to Reduce Bird Mortality in the Altamont Pass Wind Resource Area. California Energy Commission, USA.

SNH (2005) Survey Methods for use in Assessing the Impacts of Onshore Wind Farms on Bird Communities. SNH Guidance Note Series, SNH, Batleby.

Stemler, J. (2007) Wind Power Siting Regulations and Wildlife Guidelines in the United States. Jodi Stemler Report. Association of Fish & Wildlife Agencies & U.S. Fish & Wildlife Service, Denver, USA.
Still, D., Little, B., Lawrence, S. & Carver, Y.H. 1994. The birds of Blyth Harbour. Proc. British Wind Energy Assoc. No. 16.
Tellerıa, J.L. (2009) Wind power plants and the conservation of birds and bats in Spain: A geographical assessment. Biodiversity and Conservation, 18, 1781–1791.
Thelander, C.G. & Smallwood, K.S. (2007) The Altamont Pass Wind Resource Area's effects on birds: a case history. Birds and Wind Farms (eds M. de Lucas, G. Janss & M. Ferrer), pp. 25–45. Quercus Editions, Madrid.

Received 14 February 2011; accepted 20 July 2011
Handling Editor: Des Thompson

Supporting Information

Additional Supporting Information may be found in the online version of this article.

Table S1. Mortality records in the 20 approved wind farms.

Table S2. Number of birds observed flying and number of dead birds per wind farm location.

Table S3. Correlations by season between bird flying rates and bird mortality in the 20 approved wind farms.

As a service to our authors and readers, this journal provides supporting information supplied by the authors. Such materials may be re-organized for online delivery, but are not copy-edited or typeset. Technical support issues arising from supporting information (other than missing files) should be addressed to the authors.