Collision fatality of raptors in wind farms does not depend on raptor abundance

Manuela de Lucas[1]*, Guyonne F. E. Janss[1], D. P. Whitfield[2] and Miguel Ferrer[1]

[1]*Biodiversity Conservation and Applied Ecology, Estación Biológica de Doñana (CSIC), Av. Ma Luisa s/n, Pabellón de Perú, 41013 Seville, Spain; and* [2]*Natural Research Ltd., Banchory Business Centre, Burn O'Bennie Road, Banchory AB31 5ZU, UK*

Summary

1. The number of wind farms is increasing worldwide. Despite their purported environmental benefits, wind energy developments are not without potential adverse impacts on the environment, and the current pace and scale of development proposals, combined with a poor understanding of their impacts, is a cause for concern.

2. Avian mortality through collision with moving rotor blades is one of the main adverse impacts of wind farms, yet long-term studies are rare. We analyse bird fatalities in relation to bird abundance, and test several factors which have been hypothesized to be associated with bird mortality.

3. Bird abundance was compared with collision fatality records to identify species-specific death risk. Failure time analysis incorporated censored mortality data in which the time of event occurrence (collision) was not known. The analysis was used to test null hypotheses of homogeneity in avian mortality distribution according to several factors.

4. There was no clear relationship between species mortality and species abundance, although all large-bird collision victims were raptors and griffon vulture *Gyps fulvus* was most frequently killed. Bird mortality and bird abundance varied markedly among seasons, but mortality was not highest in the season with highest bird abundance. Mortality rates of griffon vultures did not differ significantly between years.

5. Bird collision probability depended on species, turbine height (taller = more victims) and elevation above sea level (higher = more victims), implicating species-specific and topographic factors in collision mortality. There was no evidence of an association between collision probability and turbine type or the position of a turbine in a row.

6. *Synthesis and applications*. Bird abundance and bird mortality through collision with wind turbines were not closely related; this result challenges a frequent assumption of wind-farm assessment studies. Griffon vulture was the most frequently killed species, and species-specific flight behaviour was implicated. Vultures collided more often when uplift wind conditions were poor, such as on gentle slopes, when thermals were weak, and when turbines were taller at higher elevations. New wind installations and/or repowering of older wind farms with griffon vulture populations nearby, should avoid turbines on the top of hills with gentle slopes.

Key-words: bird abundance, censored data, collision risk, failure time analysis, *Gyps fulvus*, Tarifa, wind energy, wind farm

Introduction

The use of wind as a renewable energy source has been increasing in many countries. Despite the obvious benefit of wind turbines as a clean energy source, it is known that wind farms can have adverse effects on birds, notably fatality through collision with rotating turbine rotor blades (e.g. Langston & Pullan 2003). At the current level of development, wind turbines have been estimated to comprise less than 0·01% of the total annual avian mortality from human-caused sources in the USA (Erickson *et al*. 2002). Although such analyses do not acknowledge that some bird species may be affected more by wind turbines than other anthropogenic mortality sources, at least one study has concluded that wind

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

Table 1. Turbine characteristics at EEE and PESUR wind farms

	MADE AE-23	ECOTÉCNICA 20/150	AWP 56–100	MADE AE-20
Wind farm	EEE	EEE	PESUR	PESUR
Power (kW)	180	150	100	150
Blades	3	3	3	3
Rotor diameter (m)	23	20	10 or 18	20
Tower height (m)	28	28	18 or 36	21–28
Tower type	Tubular	Tubular	Lattice	Tubular
Rotor velocity (r.p.m.)	43	51	72	46
Speed (m s^{-1})	4–28	4–25	5–20	5–25
No.	16	50	156	34

turbines, when properly planned, should have minimal impact in comparison with other factors (Fielding, Whitfield & McLeod 2006). For many bird species, turbine collision is not as serious a source of mortality as other factors, such as highways (Fajardo *et al*. 1998), power lines (Ferrer, de la Riva & Castroviejo 1991; Janss & Ferrer 1998), radio/television towers (Stahlecker 1979; Smith 1985), glass windows (Klem 1990), and due to human activities such as poisoning (Harmata *et al*. 1999) and illegal shooting (Villafuerte, Viñuela & Blanco 1998). Nevertheless, the potential for wind farms to cause problems for bird populations should not be underestimated (Hunt 2002; Madders & Whitfield 2006), and the coexistence of birds and wind farms would be enhanced by a more detailed understanding of the factors involved in influencing collision fatality (Barrios & Rodríguez 2004).

A major difficulty in assessing the mortality impact of wind farms on bird populations is the apparent paucity of information from long-term studies at operational wind farms. Despite the existence of numerous studies in the 'grey' literature (Orloff & Flannery 1992, 1993; Hunt *et al*. 1995; Howell 1997; Hunt 1998; Morrison *et al*. 1998; Erickson *et al*. 2001; Kerlinger 2002), relatively little material on wind-farm impacts has been published in the peer-reviewed literature (Musters, Noordervliet & Terkeus 1996; Osborn *et al*. 2000; Johnson *et al*. 2002, 2004; Barrios & Rodríguez 2004; Garthe & Hüppop 2004; Lucas, Janss & Ferrer 2004, 2005; Chamberlain *et al*. 2006; Larsen & Guillemette 2007). Furthermore, study methods vary greatly, as do their results, and although more than 1 year of data may be needed to obtain robust estimates of fatality rates (Smallwood & Thelander 2004), long-term studies are extremely rare. Here we examine long-term avian fatalities in wind farms. We analyse 10 years of bird fatality sampling at two wind farms in Tarifa (Cadiz, Spain) in relation to bird abundance, and test several factors which have been hypothesized to be associated with bird mortality.

Materials and methods

STUDY AREA

The study wind farms, called EEE and PESUR, were located in Tarifa, Campo de Gibraltar area, Andalusia region, southern Spain (30STF590000–30STE610950) (see also Barrios & Rodríguez 2004). The study area consists of a series of mountain ranges [maximum altitude 820 m above sea level (a.s.l.)] running north–south and reaching the northern shore of the Strait of Gibraltar. The vegetation is characterized by brushwood and scattered trees (*Quercus suber*, *Q. rotundifolia*) on the mountain ridges, and pasture land used for cattle grazing predominating in the lower areas. Easterly winds prevail.

The EEE wind farm is situated along the Sierra de Enmedio mountain ridge (550–650 m a.s.l.) (Fig. 1). During our study, it comprised 66 wind turbines of two models and all rotors were oriented windward (Table 1). Two new rows of turbines were constructed in 1998 and were not included in our study.

The PESUR wind farm is situated in the Dehesa de los Zorrillos, on hills with maximum peaks of 250 m a.s.l. (Fig. 2). It comprises 190 wind turbines with three different designs, and all rotors are orientated leeward to the wind (Table 1). The AWP models (see Table 1) make up a 'wind wall' configuration (Orloff & Flannery 1992) consisting of wind turbines closely aligned with each other but with alternating tower heights.

We used the distance D, defined as 2·5 times the turbine rotor diameter, between a turbine and the nearest other turbine, to distinguish between different rows within each wind farm (if a turbine was > D away from its neighbour, it was classed as being in a different row or 'string'). D is the optimal distance to maximize wind energy capture as used by computation research into wind energy (Grady, Hussaini & Abdullah 2005). On this basis, two different turbine rows were distinguished in EEE (called North and South), whereas PESUR consisted of seven rows: Castro (26 turbines), Alba (14 turbines), Poblana (21 turbines), Piedracana (30 turbines), Tesoro (33 turbines), Bujo (42 turbines) and Zorrillos (24 turbines). All rows were orientated north to south except the Zorrillos row, which was orientated north-west to south-east.

Cliff-nesting species such as griffon vultures *Gyps fulvus*, common kestrels *Falco tinnunculus*, Bonelli's eagles *Hieraaetus fasciatus*, peregrine falcons *Falco peregrinus*, Eurasian eagle owls *Bubo bubo*, as well as a forest species, short-toed snake eagle *Circaetus gallicus*, are characteristic breeding or resident birds of prey in the study area with Bonelli's eagle and peregrine falcon classed as endangered in Spain (Madroño, González & Atienza 2004). Besides supporting an important breeding and resident bird community, the Strait of Gibraltar is one of the most important migration routes for Paleartic birds (Bernis 1980; Finlayson 1992; Bildstein & Zalles 2000). During migration, thousands of soaring species pass through the study area, including European honey buzzards *Pernis apivorus*, booted eagles *Hieraaetus pennatus*, black kites *Milvus migrans*, white storks *Ciconia ciconia* and short-toed snake eagles (bird names follow Gill & Wright 2006).

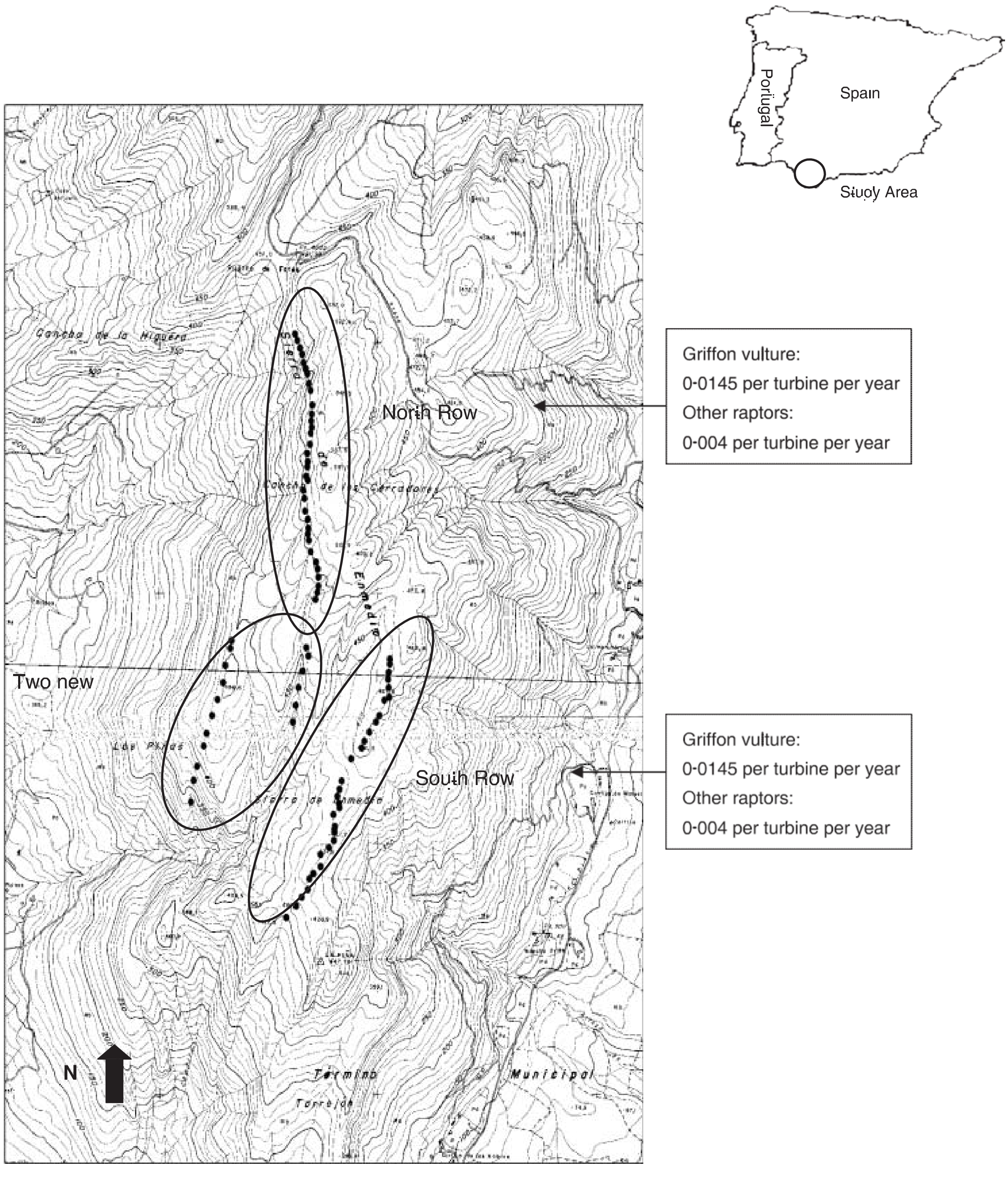

Fig. 1. EEE wind-farm map (scale 1:10 000) with the North and the South rows and the two new rows (not included in this study) with mortality rates for both griffon vultures and other raptors in each row. Small map of Spain show the study area at a national scale.

FIELD METHODS AND ANALYTICAL APPROACH

We used avian fatality data collected between November 1993 and June 2003 by the Department of Cadiz of the Andalusian Environmental Ministry in the wind resource areas, comprising records of dead birds collected during research studies and by maintenance personnel at the farms. The searches for collision victims were not standardized during the study period, but occurred approximately once per week. Gauthreaux (1996) suggested that searches for bird fatalities should cover a circular area around each turbine, but because all turbines in our study area were arranged in strings, the most efficient search method was to walk transects or drive unpaved roads along the strings (see also Smallwood & Thelander 2004).

For reasons beyond our control, the search of all turbine strings was not carried out at standardized intervals throughout the study period. However, nearly all data on dead birds were recorded on a standard data sheet including date, species, turbine identity, etc., (Morrison & Sinclair 1998). Each recorded fatality was associated with a carcass that was clearly attributable to a turbine collision rather than any other cause, and that did not share a body part with

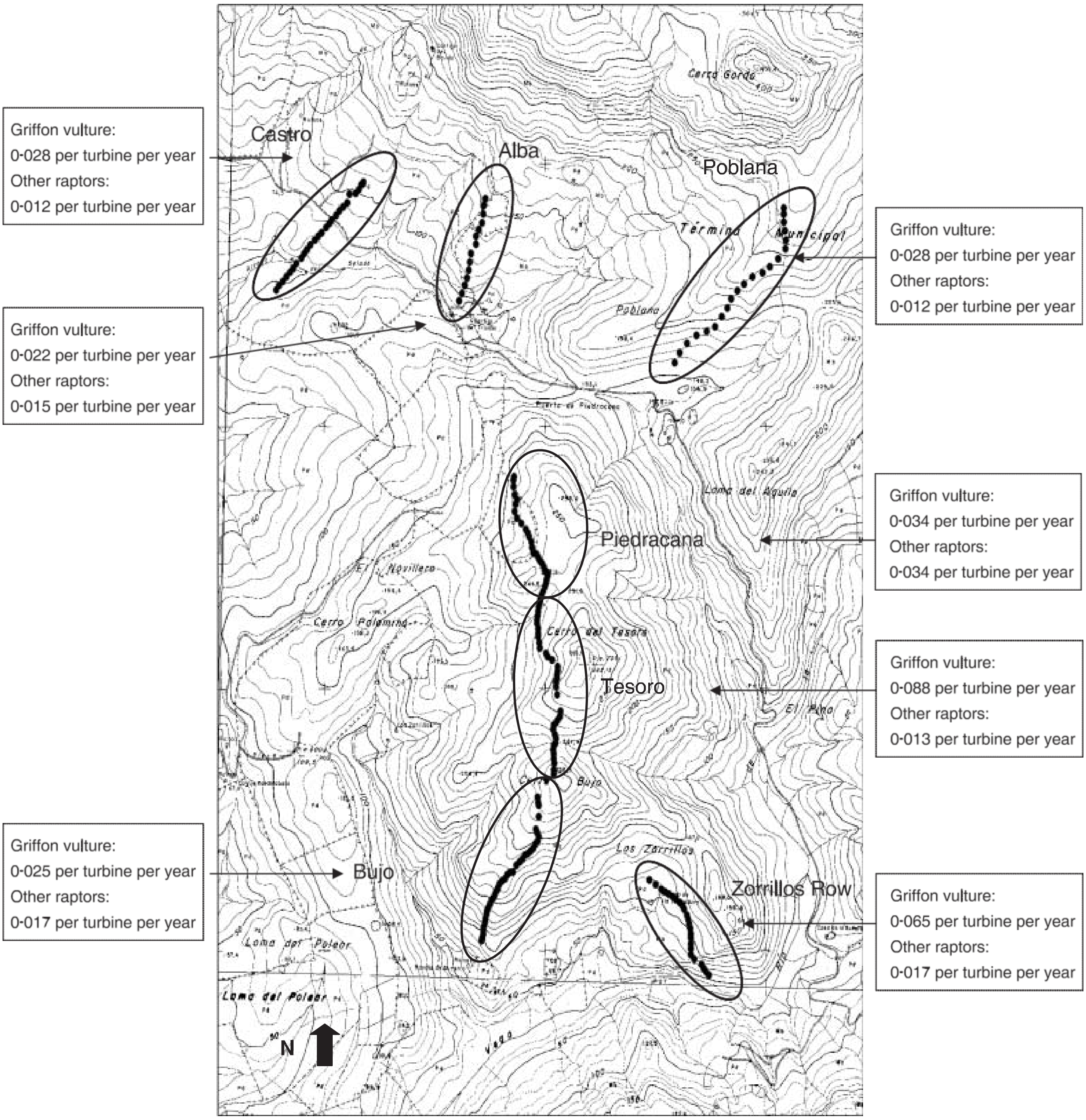

Fig. 2. PESUR wind-farm map (scale 1:10 000) with mortality rates for both griffon vultures and other raptors in each row.

contemporaneous remains. From our previous experience and other evidence at our study sites (Barrios & Rodríguez 2004), we assumed that all dead birds the size of black kite or larger were found. The carcasses of such large birds were not lost to scavengers before searches, and were readily detected by human observers. Although decomposition occurred over time, remains were still present for months to years: a period much longer than any inter-search interval. Smaller species were not included in our study (see Results), and therefore, it was not necessary to apply corrections to account for search biases on mortality (Gauthreaux 1996). We were confident that search protocols produced no spatial biases, due to similar search regimes between and within wind farms and to the longevity of carcass presence. Potential temporal biases were minimized by classing fatality events in broad seasonal or annual categories and by failure time analysis (see below).

To determine the abundance and composition of the local bird community, bird observation surveys were conducted at EEE (2000–2001) and PESUR (2000–2002) during four periods of the year: pre-breeding (mid-January to mid-April), breeding (mid-April to mid-July), post-breeding (mid-July to mid-October) and winter (mid-October to mid-January). At EEE, counts were made over 150 h, and at PESUR wind farm over 250 h. Observations were made from fixed points within 200 m of turbines and during each survey, the number of each species of bird that crossed the rows within 250 m of a turbine was recorded. Each observation lasted 1 h. Survey effort was not equal across seasons; therefore, bird abundance was averaged per season and the mean values used to give the relative abundance of each species in a year.

Failure time analysis measures the length of time from an arbitrary starting point until the first observed ‘event’ and compares the distributions of the time intervals for each event occurrence (Muenchow 1986): in our analysis an event was the collision of a bird at a wind farm. Failure time analysis accommodates 'censored' data in which an event was not observed, perhaps because the study ended before the event happened. For these censored data points, the actual time of occurrence of the event is unknown, for example, when no fatalities are recorded at a turbine (Muenchow 1986).

Several authors have proposed that features of turbine design or location may increase collision risk (e.g. Orloff & Flannery 1992, 1993; Hunt 2002; Percival 2003; Smallwood & Thelander 2004). Therefore, we recorded: (i) tower design (tubular or lattice steel tower), (iii) turbine hub height, (iii) row, (iv) turbine position within the row (end or mid-row), and (v) elevation above sea level based on topographic maps.

STATISTICAL METHODS

We used non-parametric statistics for those variables that did not fit a normal distribution. Post-hoc power analysis was used to determine whether it was appropriate to pool bird mortality data from wind farms. A given alpha value (0·05), sample sizes and effect size were used to obtain a power value higher than 0·8 (Thomas 1997).

We used bird fatality events to assess the factors associated with collisions, so that survival time in failure time analysis was calculated as the time taken for a bird collision (event) to occur and was used as an explanatory variable in a proportional hazard (Cox) regression. The Cox regression for censored data was tested for effects of turbine characteristics (height, tower model, elevation above sea level, row identity, and the effects of turbine position within the row) and for differences in collision rates between griffon vultures and all other species combined. This analysis was stratified by the two types of turbine (lattice and tubular).

Statistica 6·0 and SPSS 13 were used to perform all statistical procedures and we used an alpha value of $P = 0{\cdot}05$ to assess significance of results. GPower 3·0·8 was used to perform power analysis (Faul *et al*. 2007).

Results

BIRD MORTALITY

In the EEE wind farm, a total of 26 dead birds of four raptor species were found during the study period (Table 2). Griffon vulture mortality rate was 0·03 dead birds per turbine per year. The total raptor mortality rate was 2·69 dead birds per year or 0·04 dead birds per turbine per year.

In the PESUR wind farm a total of 125 dead birds from eight raptor species was recorded across the study period (Table 2). Griffon vulture mortality rate was 0·05 dead birds per turbine per year and for all raptors the mortality rate was 12·93 dead birds per year or 0·07 dead birds per turbine per year.

No statistical differences in the number of dead birds per turbine per year were detected between the two wind farms for griffon vultures (Mann-Whitney test, $Z = -1{\cdot}043$, $n = 10$, $P = 0{\cdot}297$) or for other raptor species combined (Mann–Whitney test, $Z = -1{\cdot}650$, $n = 10$, $P = 0{\cdot}099$). The power of the test was high for griffon vultures ($\alpha = 0{\cdot}05$, power = 0·95, effect size = 0·898), indicating that it was appropriate to combine results from wind farms. The power of the test for other raptors was lower ($\alpha = 0{\cdot}05$, power = 0·7, effect size = 0·97), but to avoid further weakening any subsequent within-site tests, we chose to combine mortality data from EEE and PESUR in subsequent analyses.

Statistically significant differences in the number of dead griffon vultures per day were detected between seasons (Kruskal–Wallis test, $\chi^2 = 34{\cdot}272$, d.f. = 3, $P < 0{\cdot}001$), due to a greater number of dead vultures in winter than in other periods (Mann–Whitney tests, $n = 10$, $Z \le -3{\cdot}088$, $P \le 0{\cdot}002$ for all three comparisons; Fig. 3). No significant differences in vulture mortality were evident between years (Kruskal–Wallis Test, $\chi^2 = 12{\cdot}220$, d.f. = 9, $P = 0{\cdot}271$). Significant differences in the number of dead raptors other than griffons were detected between seasons (Kruskal–Wallis Test, $\chi^2 = 12{\cdot}718$, d.f. = 3, $P = 0{\cdot}005$) with more dead birds found in winter than during other periods (Mann–Whitney tests, $n = 10$, $Z \le -2{\cdot}694$, $P \le 0{\cdot}007$ for all three comparisons; Fig. 3).

RAPTOR ABUNDANCE

A total of 1314 raptors crossed the two wind farms during the observation periods (Table 3). Statistically significant differences

Table 2. Number and species of dead birds in EEE and in PESUR wind farms during the study period (9·67 years), species mortality rates (n° dead birds/turbine/year) and species' relative abundance. – = no data as a nocturnal species

	EEE wind farm			PESUR wind farm		
Species	No. of dead birds	Mortality rate	Relative abundance (%)	No. of dead birds	Mortality rate	Relative abundance (%)
Gyps fulvus	20	0·0313	89·73	91	0·0495	57·17
Circaetus gallicus	3	0·0047	0·81	4	0·0022	4·64
Bubo bubo	2	0·0031	–	5	0·0027	–
Neophron percnopterus	1	0·0016	1·08	0	0	0·63
Falco tinnunculus	0	0	3·78	19	0·0103	3·77
Falco naumanni	0	0	0	3	0·0016	0
Pernis apivorus	0	0	0	1	0·0005	8·44
Hieraaetus pennatus	0	0	0·81	1	0·0005	2·21
Milvus migrans	0	0	3·78	1	0·0005	14·66
Ciconia ciconia	0	0	0	0	0	10·55
Total	26	0·0407	100	125	0·0680	100

Table 3. Abundance (number of birds per hour) of birds recorded in the two wind farms. Number of birds are given in brackets. Number of 1-h observations = 90, 102, 101 and 102 for winter, pre-breeding, breeding and post-breeding periods, respectively

Season	EEE wind farm		PESUR wind farm	
	Bird abundance	Griffon vulture abundance	Bird abundance	Griffon vulture abundance
Winter	0·43 (17)	0·43 (17)	2·28 (118)	1·30 (69)
Pre-breeding	6·52 (215)	5·67 (187)	8·06 (548)	3·99 (271)
Breeding	0·67 (24)	0·56 (19)	1·88 (120)	0·42 (27)
Post-breeding	3·45 (115)	3·27 (108)	2·38 (162)	1·30 (157)
Overall	2·61 (371)	2·34 (331)	3·78 (948)	2·08 (524)

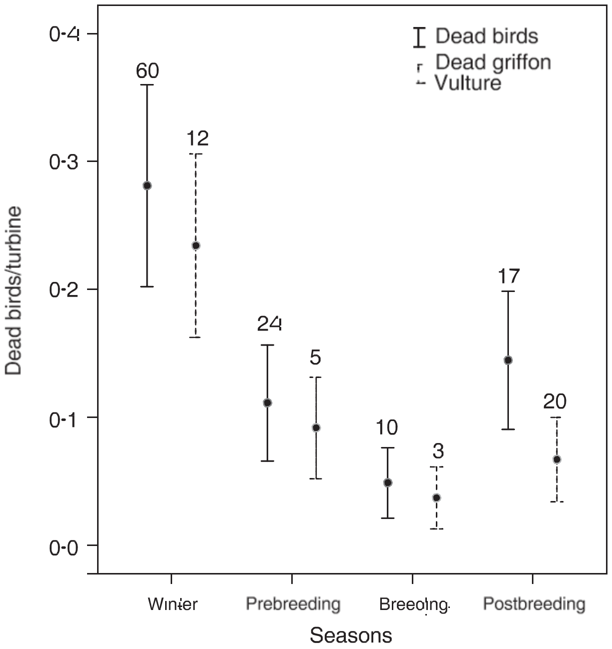

Fig. 3. Mean (± standard error bars) number of dead birds per turbine and dead griffon vultures per turbine according to season. Numbers above points give the number of fatalities for griffon vulture and other birds combined (151 total fatalities).

in the number of griffon vultures per observation were detected between seasons (Kruskal–Wallis Test, $\chi^2 = 61{\cdot}108$, d.f. = 3, $P < 0{\cdot}001$), due to a higher abundance pre-breeding than in other periods (Mann–Whitney tests, $Z \leq -4{\cdot}569$, $P < 0{\cdot}001$ for all three comparisons). The same seasonal differences were detected in the number of raptors other than griffon vultures (Kruskal–Wallis Test, $\chi^2 = 67{\cdot}007$, d.f. = 3, $P < 0{\cdot}001$), again due to a higher abundance during the pre-breeding period than in other periods (Mann-Whitney tests, $Z \leq -4{\cdot}655$, $P < 0{\cdot}001$ for all three comparisons).

Taking species as replicates, and excluding Eurasian eagle owl because it is largely nocturnal and *Falco* species because of their small size, there was no correlation between a species' mortality and its abundance at EEE (Spearman's $\rho = 0{\cdot}342$, $n = 5$, $P = 0{\cdot}573$) or PESUR (Spearman's $\rho = 0{\cdot}449$, $n = 7$, $P = 0{\cdot}312$) (Table 2). Including *Falco* species made no substantive difference to the results (EEE: Spearman's $\rho = 0{\cdot}188$, $n = 6$, $P = 0{\cdot}722$; PESUR: Spearman's $\rho = 0{\cdot}179$, $n = 9$, $P = 0{\cdot}645$).

SPATIAL MORTALITY DISTRIBUTION

No significant differences in mortality rates were detected between the two rows at the EEE wind farm for griffon vultures ($\chi^2 = 0{\cdot}018$, d.f. = 1, $P = 0{\cdot}892$) or for all other raptors combined ($\chi^2 = 0{\cdot}023$, d.f. = 1, $P = 0{\cdot}877$). In contrast, significant differences were detected among the seven rows at the PESUR wind farm for both griffon vultures ($\chi^2 = 23{\cdot}866$, d.f. = 6, $P < 0{\cdot}001$) and for other raptors combined ($\chi^2 = 17{\cdot}867$, d.f. = 6, $P = 0{\cdot}006$). These mortality differences were largely due to most dead birds being detected in Piedracana (28 total dead birds: 20 griffon vultures, 8 others raptors) and Tesoro (32 dead birds: 22 griffon vultures, 10 others raptors) rows.

A stratified proportional hazard (Cox) regression for censored data was conducted to analyse the effect of turbine characteristics on bird collisions. The model ($n = 231$, uncensored data 53·25%, log-likelihood of final solution = –512·236, null model = –577·539, $\chi^2 = 130{\cdot}605$, d.f. = 5, $P < 0{\cdot}001$) included species (B = 2·23, $P < 0{\cdot}001$, with griffon vulture the most likely to collide), turbine height (B = 0·420, $P = 0{\cdot}039$) and elevation above sea level (B = 0·005, $P = 0{\cdot}011$). The taller the height of the turbines and the higher their elevation above sea level, the shorter the time to a bird collision.

Discussion

Avian mortality rates have been presented for several wind farms around the world (Orloff & Flannery 1993; Dirksen, Winden & Spaans 1998; Barrios & Rodríguez 2004). Like most studies (Erickson *et al*. 2001; Percival 2003; Drewitt & Langston 2006), our mortality rates per turbine were relatively low. However, historical data have not been considered previously and, to our knowledge, our study is the first to analyse long-term samples of bird mortality. A weakness of this study is that it lacked a single protocol for carcass searches, and achieving better consistency in sampling should be an important goal for future work. Nonetheless, the apparently low scavenging rate and the consequent persistence of carcasses around wind farms, coupled with the long timeframe over which carcass searches were conducted, yielded important insights into the effects of wind farms on birds. These fall into three groups: (i) the validity of mortality estimates derived from short-term studies; (ii) the common assumption that more bird activity in the environs of a wind farm will result in more mortality; and (iii) the suggestion that physical characteristics of turbines and their location with respect to other turbines affects the collision risk that they pose to birds.

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 the wind farms (e.g. habituation) (see also Stewart, Pullin & Coles 2004; Hötker, Thomsen & Köster 2006).

Bird mortality and bird abundance varied markedly between seasons. Although numbers of dead birds, and especially dead griffon vultures, were higher during winter, bird abundance, and especially griffon vulture abundance, was higher during the pre-breeding season. This is not consistent with the proposal of Barrios & Rodríguez (2004) that bird mortality increases with bird density but supports the results reported by Fernley, Lowther & Whitfield (2006) and Whitfield & Madders (2006) of no relationship between collision mortality and abundance. It is frequently assumed that collision mortality should increase with bird abundance because more birds are 'available' to collide (e.g. Langston & Pullan 2003; Smallwood & Thelander 2004), but our study adds to mounting evidence that such an assumption may be too simplistic. This result has important implications when attempting to predict the impacts of wind- farm proposals. For example, a direct positive relationship between mortality and abundance is an implicit assumption of predictive collision risk models (CRMs) (e.g. Band, Madders & Whitfield 2007). If this assumption is wrong, the utility of current CRMs as predictive tools is severely weakened.

We suggest that others factors, related to species-specific flight behaviour, weather, and topography around the wind farm, might be equally or more important in explaining differences in mortality rates. The different vulnerability of species to collision with turbines is well known and has been linked to species-specific flight behaviour (Orloff & Flannery 1993; Thelander, Smallwood & Rugge 2003; Barrios & Rodríguez 2004; Drewitt & Langston 2006).

High wing loading is associated with low manoeuvrability in flight and a low capability for powered flight is typical of some soaring birds like griffon vultures (Tucker 1971). This relationship has been linked with an elevated risk of collision with objects other than turbine blades (Pennycuick 1975; Janss 2000). With only weak-powered flight, griffon vultures rely heavily on wind for flying (Pennycuick 1975) and to lift them above turbines, whereas other species can use powered flight to avoid collisions with turbine blades. This increases their risk of collision with turbine blades compared with species that have a greater capability for powered flight. Winds that provide lift and assist griffon vultures in cross-country soaring flights will come from two main sources: declivity updrafts from wind deflected upwards by ground slopes, and thermals (Pennycuick 1998). We expect, therefore, that collisions will be more likely when uplift winds are weaker. Several lines of evidence from Tarifa support this idea.

All else being equal, more lift is required by a griffon vulture to fly over a taller turbine at a higher elevation and we found that such turbines killed more vultures compared to shorter turbines at lower elevations. Vulture mortality was also greatest in winter, when thermal updrafts are less common due to lower soil temperatures and lower insolation. Updrafts from gentle slopes are weaker than those from steeper slopes, and so turbines situated on the top of gentle slopes should pose a greater risk to vultures than those atop steep slopes. Piedracana and Tesoro are long turbine rows situated on the gentlest slopes within PESUR (see Fig. 2) and griffon vulture mortality rates were higher here than at other rows in PESUR. Moreover, the slopes surrounding EEE were steeper than those at PESUR and vulture mortality was 1·6 times greater at PESUR than EEE. Declivity updrafts will also be weaker when the speed of the deflected wind is lower and Barrios & Rodríguez (2004) recorded more griffon vulture deaths when winds were light ($< 8\ m\ s^{-1}$).

Failure time analyses are not commonly used with ecological data (Muenchow 1986; Pyke & Thompson 1986) but the incorporation of censored data in this type of analysis adds more information when addressing ecological questions. Our failure time analysis model enabled us to assess the influence of different factors on the probability of bird collisions. Orloff & Flannery (1992, 1993; although see Smallwood & Thelander 2004) considered lattice towers more dangerous to raptors, but we found no evidence to support this supposition. The effect of a turbine's position in a row on collision has also been the subject of several investigations (e.g. Smallwood & Thelander 2004), but we found that this factor was not influential at Tarifa.

SYNTHESIS AND APPLICATIONS

Mortality rates per turbine were relatively low in this study, and we found no indication of a change in mortality rates across the study period. Griffon vulture was the species most affected by collision mortality. However, collision mortality did not simply increase with abundance, either between raptor species or between seasons for griffon vultures. Therefore, when attempting to predict the impacts of a wind-farm proposal, it is inadequate to assume that collision mortality will increase with bird abundance. Rather, we propose that differences in mortality are equally or more likely to be related to species-specific flight behaviour and morphology, weather and topography around the wind farm. Several features of griffon vulture mortality at Tarifa were consistent with this hypothesis.

It is difficult to make general recommendations for measures to minimize collision with wind turbines. However, repowering of older wind farms, such as those at Tarifa, could provide an opportunity to study such mitigation measures. Reducing the number of turbines and avoiding locations on the top of hills with gentle slopes should decrease rates of bird mortality, but the collision problem will not be eliminated by these measures (Janss 2000). A greater understanding of the mechanisms involved in influencing collision risk for different species, especially the interaction between bird flight behaviour, topography and weather, is essential if the situation is to be managed effectively. As the number of wind farms proliferates, the need for effective mitigation measures becomes increasingly important.

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