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Response of raptors to a windfarm

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Summary

1. The global growth of wind energy has outpaced our assessment of possible impacts on wildlife. There is a pressing need for studies with pre- and post-construction data to determine whether wind facilities will have detrimental effects on susceptible avian groups such as raptors.

2. A pre- and post-construction study was conducted to determine the impact of a windfarm on the abundance and behaviour of raptors in Wisconsin, USA. Variation in abundance and behaviour was examined both within and among years and relative to selected spatial, temporal and weather covariates. Raptor avoidance rates and indices of collision risk were calculated.

3. Raptor abundance post-construction was reduced by 47% compared to pre-construction levels. Flight behaviour varied by species, but most individuals remained at a distance of at least 100 m from turbines and above the height of the rotor zone.

4. Turkey vultures *Cathartes aura* and red-tailed hawks *Buteo jamaicensis* displayed high-risk flight behaviours more often than all other raptor species, but also showed signs of avoidance. Red-tailed hawks were the only raptor species found dead beneath turbines during mortality searches. There were few observed mortalities and corrected mortality estimates were comparable to those from other windfarm studies.

5. *Synthesis and applications*. The decline in raptor abundance post-construction together with other lines of evidence suggests some displacement from the windfarm project area. While certain species may be at risk, flight behaviour data and mortality estimates indicate that the majority of raptors may not be directly affected by the presence of turbines. The avoidance rates recorded in this study should be used to improve collision risk models, and both current and future windfarms should investigate avoidance behaviour post-construction.

Key-words: avoidance rates, birds, collision risk, displacement, flight behaviour, wildlife, wind turbines

Introduction

The growth of the global wind energy industry has outpaced our understanding of the possible impacts on wildlife, specifically birds and bats which may be most affected. Of those studies which have been completed, most lack pre-construction data, thereby providing no context in which to place post-construction findings. Additionally, current efforts to model collision risk suffer from a dearth of information about avian avoidance rates that can bias estimates (Chamberlain *et al.* 2006). Lastly, much of the research on wildlife-impacts is restricted to 'grey' literature (de Lucas *et al.* 2008), and the availability of current information is often restricted by developers and utilities in order to protect their interests within a competitive industry.

Studies indicate that raptors are especially susceptible to negative impacts by windfarms (Rugge 2001; Howe, Evans & Wolf 2002; Barrios & Rodriguez 2004; Hoover & Morrison 2005; Percival 2005; Stewart, Pullin & Coles 2007; Kikuchi 2008; de Lucas *et al.* 2008; Smallwood, Rugge & Morrison 2009). Raptors are more likely to collide with turbine blades than many other avian species due to their morphology and foraging behaviour (e.g. heavy wing loading, focus on distant prey; Janss 2000; Kikuchi 2008). Furthermore, research has shown that raptors forage, perch and fly within 50 m of wind turbines disproportionately more often than expected by chance alone, with individuals often perching on turbine towers (Orloff & Flannery 1992; Barrios & Rodriguez 2004; Smallwood & Thelander 2004). Compounding the problem, raptors occur at relatively low densities and most are long-lived with low reproductive output, making them especially susceptible to additive mortality (Kikuchi 2008).

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There are three main threats to birds posed by windfarms: risk of collision, disturbance and habitat loss (reviewed in Langston & Pullan 2003; Percival 2005). While most research has focused on collision risk, disturbance due to windfarm construction, and habitat loss and fragmentation caused by turbine access roads may lead to displacement of resident raptors, as well as other species (Madders & Whitfield 2006). Such displacement may be driven by reductions in the availability of nest-sites or areas for foraging and other activities (Madders & Whitfield 2006). While there is equivocal evidence of windfarm-induced displacement of raptors [e.g. golden eagle *Aquila chrysaetos* and northern harrier *Circus cyaneus* (also known as hen harrier), see Pearce-Higgins *et al*. 2009], a lack of standardized protocols makes comparison between species and studies difficult (reviewed in both Drewitt & Langston 2006; Madders & Whitfield 2006).

We conducted a pre- and post-construction study to evaluate potential impacts of a 129-MW windfarm in southeast Wisconsin, USA on the abundance (used as an index of raptor activity) and behaviour of raptors within the project area. While each wind facility is somewhat unique, the agricultural setting of this windfarm made it widely applicable to many current and planned windfarms in the USA and around the world, especially as developers are pressured to avoid building in areas with high densities of sensitive species. We recorded behavioural observations to improve collective knowledge about how raptors in flight respond to turbines (e.g. avoidance or attraction), as well as to generate observed avoidance rates. A concurrent mortality study provided information on collision rates, and, subsequently, estimation of avoidance rates (extrapolated from rates of mortality or non-avoidance). We accounted for important covariates that are often neglected, such as weather conditions which modulate collision risk (reviewed in Drewitt & Langston 2008), detectability (Robbins 1981) and flight height (Shamoun-Baranes *et al*. 2006).

This study is uniquely capable of assessing displacement, avoidance and mortality rates. As such, the specific aims of our study were to determine (i) whether raptors were being displaced from within the windfarm, and if so, which species were most vulnerable; (ii) the proportion of raptors displaying avoidance behaviours as they approached a turbine; (iii) the relative risk of collision for all raptors as a group and for individual raptor species; and (iv) potential correlations with observed mortality and estimated avoidance rates.

The location of the windfarm within a predominantly agricultural area with little suitable habitat made it unlikely to have the high densities of raptor activity seen at windfarms in California, USA and Tarifa, Spain, and served as an ideal site with minimal threat to raptors. Furthermore, the results of similar studies in the vicinity (Howe & Atwater 1999; Howe, Evans & Wolf 2002) and pre-construction assessments at this windfarm suggest there will be no difference in abundance between years or between reference and windfarm project areas. Based on previous studies of avoidance behaviour and collision risk (Howe, Evans & Wolf 2002; reviewed in Langston & Pullan 2003), we expected to see species-specific differences, with the particular flight behaviour and hunting ecology of American kestrels *Falco sparverius*, red-tailed hawks *Buteo jamaicensis* and turkey vultures *Cathartes aura* causing them to fly more often than other species within 100 m of turbines and to have the highest risk of collision, and northern harriers, which typically course low over the ground and rarely collide with turbines (Whitfield & Madders 2006), having the highest rates of avoidance. Although all these species have been observed to fly within the rotor zone near turbines at windfarms in Wisconsin, we expected our results to be similar to comparable windfarm studies in the region and around the world which found few raptor mortalities and high avoidance rates, probably due to effective siting measures and risk-recognition by raptors in flight (Howe, Evans & Wolf 2002; reviewed in Madders & Whitfield 2006; Gruver *et al*. 2009).

We present one year of pre-construction and two years of post-construction data, their management implications, and suggestions for future avenues of research.

Materials and methods

STUDY AREA

The study windfarm, the Forward Wind Energy Centre, encompasses approximately 13 110 hectares in southeastern Wisconsin (88°27–34′N, 43°32–39′W; Fig. 1 inset). Approximately 97% of the project area is agricultural land, and 2% is deciduous woodland. The landscape within the project area is mostly flat with an elevational gradient of less than 90 m. The windfarm consists of 86 General Electric 1·5sle wind turbines for a combined maximum capacity of 129 MW of energy annually. These turbines have a single tubular tower configuration that measures 80 m high at the hub, and reaches 118 m at the rotor-tip. Adopting terminology from Smallwood, Rugge & Morrison (2009), the rotor plane (area swept by the rotor blades) measures 77 m across, covers 4657 m^2 and is characterized by a rotor zone spanning 41–118 m aboveground. Turbines are clustered and typically spaced at least 500 m apart. The windfarm became commercially operational on 14 May, 2008.

FIELD METHODS AND ANALYTICAL APPROACH

As part of a larger study, we compared pre- and post-construction measures of raptor abundance and flight behaviour. Pre-construction data collection by the consulting firm Curry and Kerlinger, LLC, was not done within reference areas, preventing the use of the standard Before-After-Control-Impact design. However, data were collected from reference areas post-construction, allowing evaluation of windfarm effects on avian use metrics in both spatial and temporal dimensions. Thus our study was more robust than a pre- or post-construction-only study, or a simple comparison of impact and reference areas.

Four flight transects oriented in a north-south direction were established parallel to the geographical boundaries of the Horicon National Wildlife Refuge at distances extending 1, 3, 6 and 10 km east from the refuge (Fig. 1). Raptor survey stations were established at the intersections of these flight transects with three east–west transects for a total of 12 survey stations (Fig. 1). The use of this grid system, combined with high visibility at the selected sites, allowed for nearly full visual coverage of the entire project area. Eight survey stations were established in a similar manner exterior to the windfarm project area in June of 2009 to serve as reference stations for

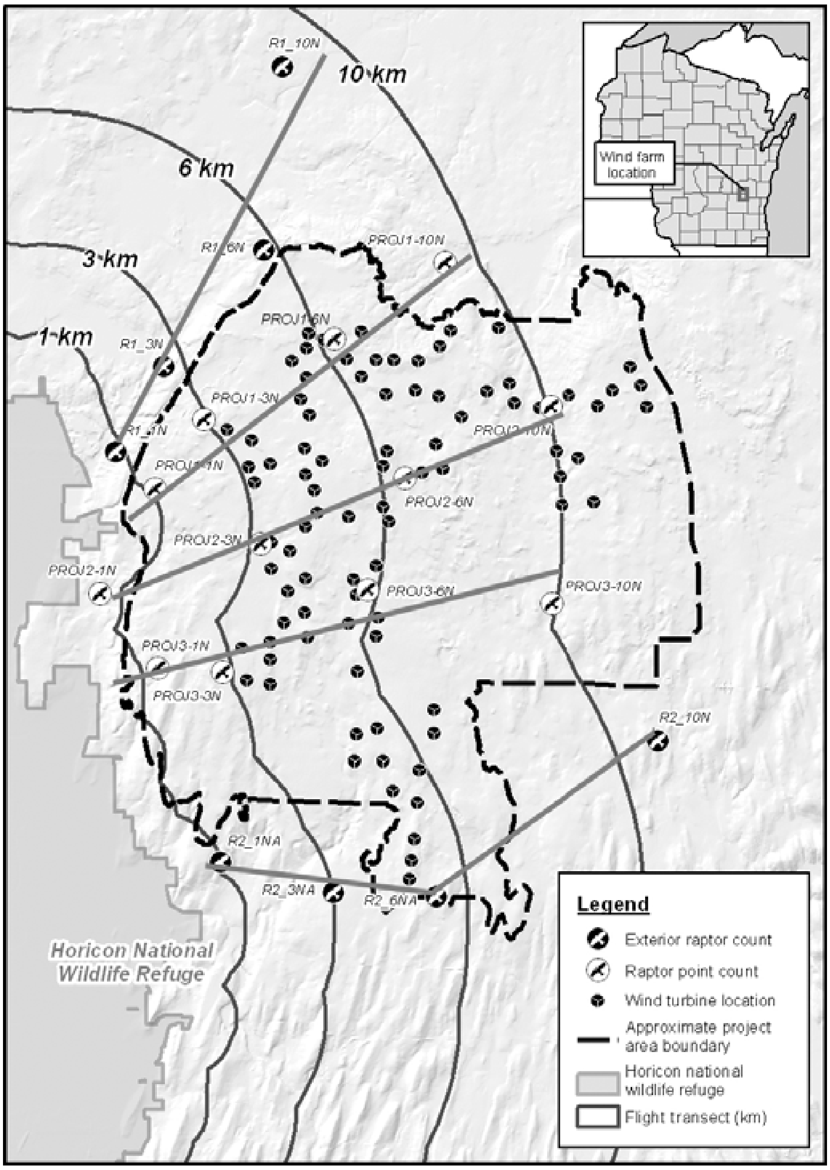

Fig. 1. Windfarm project area, Wisconsin, USA. Heavy grey lines indicate east–west study transects. Inset depicts location of the windfarm within the state of Wisconsin.

comparison with project (interior) stations (Fig. 1). Data analysis using reference stations was restricted to the summer of 2009 in order to keep comparisons valid among years. Therefore, unless otherwise noted, all results exclude data from reference stations.

Raptor survey methodology was adapted from standardized count methodologies (Fuller & Mosher 1981; Bibby *et al.* 2000), and was designed in conjunction with state and federal agencies. The circular plot survey method was used with no distance cut-off. We conducted surveys between 08:30 and 15:00, with each survey lasting 60 min, and the order of sites determined via randomization without replacement. Observations were primarily restricted to resident raptor species (accipiters, buteos, eagles, falcons, harriers, osprey, owls and vultures) that were detectable using binoculars of 10× magnification. A field scope (25–75 × 82) mounted on a tripod was used to supplement identification with binoculars. For each raptor observed, we recorded date, time, species, number of individuals in same-species groups, behaviour (e.g. flying or perched), flight height with respect to the rotor zone (below = 0–40 m, within = 41–118 m, above = 119 m or higher above ground level) and direction. Initial flight height category was recorded, as well as any subsequent changes in flight height during the survey. Flight paths were not mapped because there were often too many individuals to monitor within the visual area. Behavioural response when within 100 m of turbines was also recorded, categorized as avoidance, no response or high-risk. Avoidance was defined as changes in flight height category or flight direction that deviated away from turbines or turbine blades, regardless of distance to turbines (i.e. small-scale and last-second avoidance, Blew *et al.* 2008). High-risk behaviours were defined as flights directly toward a turbine without signs of avoidance, circling around a turbine and within the rotor plane. We used the number of birds flying through the rotor zone at any time during the survey while within 500 m of a turbine array as an additional index of collision risk. To reduce double-counting within a single observation period, we excluded subsequent counts of individuals suspected to have been previously recorded (e.g. same species in the same general area), but included any changes in flight height, behaviour and response to turbines with the first observation for that individual.

Pre-construction raptor surveys were conducted by a biologist working for Curry and Kerlinger, LLC, and occurred year-round from 4 April 2005 to 31 March 2006. Post-construction raptor surveys were conducted by J.C.G. from 12 June 2008 to 31 August 2008, and by J.C.G. and her field assistant C. Kowalchuk (C.K.) from 15 April 2009 to 31 August 2009. Stations were visited approximately five times each between April and May and four times between June and August. We restricted pre-construction data to 15 April 2005–31 August 2005 for comparison with post-construction data.

Bird mortality data were obtained from a complementary study conducted by S.M.G. as part of a larger study of this windfarm (Drake *et al.* 2010; see Appendix S1 in Supporting Information for methodology). Data were also used from US Breeding Bird Surveys, both state-wide and restricted to the region near the windfarm (USGS 2010), to investigate annual trends in raptor abundance.

Scientific and common names for birds are derived from the 7th edition of the Check-list of North American Birds, produced by the American Ornithologists' Union. Individuals could not always be identified to the species level, and thus taxonomic groupings such as buteo and accipiter were used when appropriate. The research described in this paper was approved by the University of Wisconsin-Madison's animal care and use committee and assigned protocol number A01354-0-06-08.

HABITAT DATA

We quantified the habitat occurring within a 3-km radius around each survey station using GIS data derived from the US 2001 National Land Cover Database, which is the most current land cover database available for this region. We calculated the percentage of each circular plot that was covered in each land cover category. In order to determine the amount of natural habitat, defined here as areas largely unmodified by humans, we excluded categories that included pasture, crop, barren or developed land. We then combined the remaining cover categories (e.g. wetland, forest, grassland) into the broader category of natural habitat.

WEATHER DATA

During pre-construction surveys cloud cover, temperature and average wind speed data were collected on-site at the time of each raptor survey. We collected post-construction data on-site for cloud cover, while 10-min incremental wind speed data were obtained from a turbine anemometer in the centre of the study area. Post-construction hourly temperature data were obtained from the National Weather Service station at the Fond Du Lac, Wisconsin airport, located 17 km from the centre of the project area. Variation among years was investigated using daily averages, but there was no systematic variation in any weather variables that might influence the outcome of the results based on our modelling.

STATISTICAL ANALYSES

The abundance of raptors within the windfarm (number of birds per survey) was analysed with respect to selected temporal, spatial and environmental covariates. All statistical analyses were conducted using SAS software (Version 9.2, SAS Institute Inc., Cary, NC, USA) to evaluate generalized linear mixed models (GLMM) which allow the incorporation of both fixed and random effects.

We used PROC GLIMMIX to construct a separate predictive model for seven raptor count response variables. The unit of analysis was the count of raptors within a 60-min survey on a given visit. We modelled turkey vultures with a Poisson distribution, while all raptors combined, red-tailed hawks and all raptors from summer 2009 only were modelled with a negative binomial distribution. Due to the small numbers of accipiter, American kestrel and northern harrier (average < 1 per survey), we performed a logistic regression with PROC GLIMMIX (logit link) to analyse differences in the odds of observing these species as a function of selected covariates. Other raptor species were observed too infrequently to analyse. Degrees of freedom were calculated using the approximation of Kenward & Roger (1997). Parameter estimation was performed using Restricted Maximum Subject-Specific Pseudo-Likelihood (RSPL), which effectively accounts for random effects (Molenberghs & Verbeke 2006). We conducted post hoc analyses on least-square means using a Bonferroni adjustment to evaluate between-year differences.

We used a single predictive model which included the primary sources of variation for each response variable to evaluate the effect of windfarm construction on raptor abundance. This avoided multiple model comparisons with pseudo-AIC criteria. We considered year as a fixed effect to distinguish between pre- and post-construction. Environmental and temporal fixed effects included percentage cloud cover, temperature, wind speed, percentage of natural habitat and time of day modelled as a quadratic effect. This latter effect accounted for declining activity of raptors as the survey day progressed. Inferences regarding environmental variables were limited to the ranges observed during the study (range: cloud cover = 0–100%, temperature = 38–90 °F, wind speed = 0–33 mph, natural habitat = 3–35%). We used Pearson's correlation coefficients (r) calculated with the SAS procedure PROC CORR to evaluate and limit collinear environmental variables before inclusion in the model. Given that there were unequal time intervals between raptor survey visits, we accounted for non-independence of repeat counts at the same site by using a one-dimensional spatial power covariance structure appropriate for accounting for temporal covariance among visits (with the exception of accipiters and American kestrels, in which limited data precluded its use). Both survey station and visit nested within survey station and year were modelled as random effects.

Avoidance rates, defined here as the probability of a bird taking avoidance action when encountering a turbine (Chamberlain *et al.* 2006), were estimated as: 1 – [(corrected estimate of actual mortality per carcass search period)/(total number of birds at risk during carcass search period)] (Madders & Whitfield 2006). We calculated the number of birds at risk (per species) as the number of birds flying through the rotor zone (at any time during a survey) within 500 m of turbine arrays. Observations were restricted to this focal area to improve estimate accuracy by (i) limiting them to birds that actually flew within turbine arrays, and (ii) decreasing the error caused by estimating flight heights long distances away from turbines. We then divided by the hours of observation to generate the mean passage rate, and subsequently multiplied by the average day length during the study period (14·5 h). This daily rate was then multiplied by the number of days of mortality searches to generate the number of birds passing through the windfarm within the rotor zone during carcass searches. Observed small-scale avoidance rates were derived from the proportion of individuals flying within 100 m of turbines that showed avoidance behaviours.

Estimates of raptor mortality were corrected for searcher efficiency and scavenger removal, and calculated using the Huso estimator (Huso 2010). Full details of the calculations of mortality estimates can be found in Appendix S1 Supporting Information.

Results

ABUNDANCE – VARIATION AMONG YEARS

A total of 93, 48 and 108 surveys were conducted in 2005, 2008 and 2009, respectively, with abundance of species and groups varying among years (Table 1). The most abundant species were the same in all years: turkey vulture, red-tailed hawk, northern harrier and American kestrel (Table 1). Overall raptor abundance was on average 47% lower post-construction (Tables 2a and 3a). The abundances of all five species/groups examined were affected by year, and were lower post-construction compared to pre-construction (Tables 2–4). Abundance of red-tailed hawks was on average 51% lower post-construction (Tables 2b and 3b), while turkey vulture abundance did not differ between 2005 and 2008, but decreased by 50% in 2009, and was marginally lower in 2009 compared to 2008 (Table 3c). American kestrels, northern harriers and accipiters all had slightly lower chances of being observed in 2008 compared to 2005 (although confidence intervals included 1·0), but significantly lower chances of being observed in 2009 compared to 2005 (Table 4). Environmental and temporal variables affected the abundances of species/groups differently, except for the presence of natural habitat which universally had no effect (Table 2). Of the species/groups examined, only the northern harrier was a species of special concern in Wisconsin.

US Breeding Bird Survey data collected state-wide from 2005, 2008 and 2009 showed no difference among years in raptor abundance using matched-pairs *t*-tests on the number of birds per count for each species (2005–2008: $t_9 = 1{\cdot}35$, $P = 0{\cdot}210$, 2005–2009: $t_9 = 1{\cdot}16$, $P = 0{\cdot}275$, 2008–2009: $t_9 = 1{\cdot}07$, $P = 0{\cdot}311$). Survey data collected within the region of the windfarm (Wisconsin routes 59, 60 and 61) from 2005 to 2009 yielded similar results. Because data were far sparser, a one-way ANOVA of the effect of year on ln-transformed number per count by species was used ($F_{4,15} = 1{\cdot}66$, $P = 0{\cdot}211$).

ABUNDANCE – VARIATION BETWEEN REFERENCE AND PROJECT STATIONS

We examined the overall abundance of raptors restricted to June–August 2009 in a GLMM which included station type (reference or project) as an additional fixed effect. Overall raptor abundance was on average 61% greater at reference stations (mean raptors per survey: Reference = 9·75 ± 1·70; Project = 6·07 ± 0·67) and varied with environmental effects (Table 2g).

FLIGHT HEIGHT

Despite training to ensure continuity between observers, observations by C.K. were significantly different to observations by other observers (flight height frequency by observer Pearson test: $\chi^2 = 60{\cdot}8$, $P < 0{\cdot}001$). Thus flight height results from 2009 exclude observations by C.K. unless noted differently.

Greater numbers of raptors flew above the rotor zone relative to below or within it during both pre- and post-construction (initial flight heights used; Fig. 2). We compared the relative frequencies of birds flying within each flight height category (frequencies of initial flight heights per survey) between pre- and post-construction and found no difference (Wilcoxon test, chi-square approximation below RZ: $\chi^2_1 = 0{\cdot}960$, $P = 0{\cdot}327$; within RZ: $\chi^2_1 = 0{\cdot}041$, $P = 0{\cdot}839$; above RZ: $\chi^2_1 = 0{\cdot}384$, $P = 0{\cdot}535$). We did not attempt to examine whether flight heights exterior from the windfarm were different because the relevant surveys had biased flight heights (see above). Species-specific flight behaviours did not appear to change greatly between pre- and post-construction for those species with enough numbers to compare.

RISK OF COLLISION

Of the 1480 raptors observed post-construction (includes observations by C.K.), 1455 (98%) were in flight at some point during the survey. Of those in flight, 913 (63%) flew within 500 m of turbine arrays, and nearly half of these individuals (49%, $N = 445$) flew within the rotor zone at some point during the survey. This is a conservative estimate because

Table 1. Annual abundance (number of raptors per survey) observed by species/group

Species	Status	2005 abundance	2008 abundance	2009 abundance
Accipiter		0·333 (31)	0·083 (4)	0·065 (7)
American kestrel		0·376 (35)	0·104 (5)	0·028 (3)
Bald eagle	SC	0·022 (2)	0	0
Broad-winged hawk		0·086 (8)	0	0·019 (2)
Buteo		0·011 (1)	0	0·123 (14)
Great horned owl		0	0	0·009 (1)
Northern harrier	SC	0·688 (64)	0·229 (11)	0·296 (32)
Osprey*	ST	0·022 (2)	0	0
Peregrine falcon	SE	0·022 (2)	0·021 (1)	0
Red-shouldered hawk	ST	0·011 (1)	0	0·019 (2)
Red-tailed hawk		4·591 (427)	2·063 (99)	2·324 (251)
Turkey vulture		6·075 (565)	6·354 (305)	3·500 (378)
Unidentified raptor		0·602 (56)	0·042 (2)	0·250 (27)
Total		12·839 (1194)	8·896 (427)	6·639 (717)

Numbers of birds are given in brackets. Conservation status of each species/group is denoted. SE = State Endangered, ST = State Threatened, SC = Species of Concern in Wisconsin, *currently in the process of being de-listed.

Table 2. Evaluation of fixed effects from generalized linear mixed model of abundance (a) all raptors, (b) red-tailed hawk, (c) turkey vulture, (d) American kestrel, (e) northern harrier, (f) accipiter and (g) all raptors for summer 2009 only

Model effects	Estimate (SE)	df	t	*P*
(a) All raptors combined				
Int	−8·552 (3·059)	201	−2·80	0·006
Year 2005	0·711 (0·127)	34	5·61	< 0·001
Year 2008	0·241 (0·150)	53	1·61	0·114
Wind speed	−0·023 (0·007)	229	−3·04	0·003
Temperature	−0·000 (0·005)	176	−0·03	0·977
Cloud cover	−0·005 (0·001)	223	−4·66	< 0·001
Time of day	0·029 (0·009)	201	3·38	0·001
Time of day^2	−0·000 (0·000)	200	−3·19	0·002
Natural habitat	0·681 (0·602)	35	1·13	0·266
(b) Red-tailed hawk				
Int	−4·959 (3·772)	191	−1·31	0·190
Year 2005	0·687 (0·142)	27	4·84	< 0·001
Year 2008	−0·038 (0·191)	59	−0·20	0·844
Wind speed	−0·032 (0·009)	221	−3·43	< 0·001
Temperature	−0·021 (0·006)	191	−3·61	< 0·001
Cloud cover	−0·008 (0·001)	219	−5·44	< 0·001
Time of day	0·021 (0·011)	195	1·96	0·051
Time of day^2	−0·000 (0·000)	197	−1·83	0·069
Natural habitat	0·505 (0·694)	27	0·73	0·473
(c) Turkey vulture				
Int	−15·23 (5·250)	207	−2·90	0·004
Year 2005	0·702 (0·160)	153	4·38	< 0·001
Year 2008	0·466 (0·192)	121	2·43	0·017
Wind speed	−0·032 (0·013)	222	−2·56	0·011
Temperature	0·012 (0·008)	209	2·64	0·009
Cloud cover	−0·005 (0·002)	208	−2·68	0·008
Time of day	0·041 (0·015)	207	2·79	0·006
Time of day^2	−0·000 (0·000)	204	−2·64	0·009
Natural habitat	0·517 (0·737)	127	0·70	0·484
(d) American kestrel				
Int	−2·330 (15·109)	237	−0·15	0·878
Year 2005	2·781 (0·689)	237	4·03	< 0·001
Year 2008	1·464 (0·814)	237	1·80	0·074
Wind speed	0·048 (0·043)	237	1·11	0·269
Temperature	0·018 (0·023)	237	0·76	0·446
Cloud cover	0·010 (0·006)	237	1·66	0·099
Time of day	−0·012 (0·043)	237	−0·27	0·787
Time of day^2	0·000 (0·000)	237	0·28	0·782
Natural habitat	0·732 (3·716)	12	0·20	0·847
(e) Northern harrier				
Int	−9·646 (11·849)	237	−0·81	0·416
Year 2005	1·356 (0·357)	129	3·79	< 0·001
Year 2008	0·292 (0·493)	177	0·59	0·554
Wind speed	0·017 (0·029)	237	0·57	0·566
Temperature	−0·014 (0·017)	213	−0·82	0·412
Cloud cover	0·005 (0·004)	237	1·07	0·284
Time of day	0·024 (0·034)	237	0·72	0·470
Time of day^2	−0·000 (0·000)	237	−0·73	0·464
Natural habitat	1·804 (1·623)	103	1·11	0·269
(f) Accipiter				
Int	−5·383 (14·362)	237	−0·37	0·708
Year 2005	1·740 (0·492)	237	3·54	< 0·001
Year 2008	0·261 (0·706)	237	0·37	0·712
Wind speed	−0·044 (0·039)	237	−1·13	0·259
Temperature	−0·013 (0·021)	237	−0·62	0·533
Cloud cover	−0·004 (0·005)	237	−0·76	0·449

Table 2. (Continued)

Model effects	Estimate (SE)	df	t	*P*
Time of day	0·008 (0·041)	237	0·20	0·838
Time of day^2	−0·000 (0·000)	237	−0·15	0·882
Natural habitat	3·796 (2·871)	8	1·32	0·222
(g) All raptors summer 2009 only				
Int	−9·354 (6·081)	125	−1·54	0·127
Station type	−0·474 (0·214)	21	−2·21	0·038
Wind speed	−0·014 (0·010)	126	−1·37	0·175
Temperature	0·000 (0·007)	112	0·00	0·999
Cloud cover	−0·005 (0·002)	132	−2·54	0·012
Time of day	0·033 (0·017)	126	1·96	0·052
Time of day^2	−0·000 (0·000)	126	−1·90	0·060
Natural habitat	−0·690 (1·020)	16	−0·68	0·509

observations by C.K. tended to be biased low (i.e. relatively more observations recorded within RZ and fewer recorded above RZ compared to other observers). Based on the proportion of a species flying through the rotor zone within 500 m of turbines, American kestrel (57%, 4 of 7), red-tailed hawk (56%, 151 of 270) and turkey vulture (48%, 269 of 564) had the highest collision risk, compared to accipiter (33%, 3 of 9) and northern harrier (10%, 3 of 29).

Only 11% of raptors flying within 500 m of turbines were observed flying within 100 m of a turbine. Most demonstrated especially high-risk behaviours, while the remainder displayed signs of small-scale avoidance (Table 5). The raptors with no response to turbines were typically individuals on a straight flight path passing through the windfarm. Red-tailed hawks and turkey vultures made up the majority of the birds that flew within 100 m of turbines (Table 5). Over half (57%) of the observations of raptors flying within 100 m of a turbine were seen at three of the survey stations, indicating a non-random distribution in space.

RATES OF MORTALITY

Two red-tailed hawks were found during searches beneath a subset of turbines ($N = 29$), one in August 2008 and the other in May 2009. Three red-tailed hawks were found near turbines outside of search transects or search schedules (incidental finds; see Table S1, Supporting Information). No other raptor mortalities were reported. Carcasses appeared to be randomly distributed throughout the windfarm. All carcasses showed injuries typical of collision with turbine blades as revealed by X-ray and necropsy (e.g. wing injuries/amputations, neck injuries, decapitation, Barrios & Rodriguez 2007).

The corrected estimates of mortality were: autumn 2008 = 0·003 red-tailed hawks turbine^{-1} day^{-1} (95% CI = 0, 0·009), spring 2009 = 0·005 red-tailed hawks turbine^{-1}day^{-1} (95% CI = 0, 0·017), and autumn 2009 = 0·000 (no raptors found). Assuming one raptor carcass had been found in autumn 2009, the estimate of mortality would have been at most 0·003 raptors turbine^{-1} day^{-1} (95% CI = 0, 0·009). Conservative annual rates of mortality based on the total number of days within the search period(s) per year were 0·363

Table 3. *Post hoc* comparison of year effects (a) total raptors, (b) red-tailed hawk and (c) turkey vulture

Year comparison	Estimate (SE)	df	t	Adj *P*	Year	Mean Count (SE)
(a) All raptors						
2005 vs. 2008	0·467 (0·155)	56	3·03	0·012	2005	12·64 (1·14)
2005 vs. 2009	0·711 (0·127)	34	5·61	< 0·001	2008	7·90 (0·97)
2008 vs. 2009	0·241 (0·145)	53	1·61	0·345	2009	6·21 (0·54)
(b) Red-tailed hawk						
2005 vs. 2008	0·725 (0·195)	58	3·72	0·002	2005	4·14 (0·41)
2005 vs. 2009	0·687 (0·142)	27	4·84	< 0·001	2008	2·01 (0·33)
2008 vs. 2009	−0·038 (0·191)	59	−0·20	1·000	2009	2·08 (0·21)
(c) Turkey vulture						
2005 vs. 2008	0·236 (0·203)	116	1·16	0·740	2005	4·97 (0·55)
2005 vs. 2009	0·702 (0·160)	153	4·38	< 0·001	2008	3·93 (0·63)
2008 vs. 2009	0·466 (0·192)	121	2·43	0·049	2009	2·47 (0·27)

Table 4. Post hoc comparison of year effects (a) American kestrel, (b) northern harrier, and (c) accipiter

Year comparison	Estimate (SE)	df	t	Adj *P*	OR	95% CI
(a) American kestrel						
2005 vs. 2008	1·317 (0·651)	237	2·02	0·133	3·73	0·78, 17·94
2005 vs. 2009	2·781 (0·689)	237	4·03	< 0·001	16·14	3·06, 85·08
2008 vs. 2009	1·464 (0·814)	237	1·80	0·220	4·32	0·61, 30·81
(b) Northern harrier						
2005 vs. 2008	1·064 (0·497)	154	2·14	0·102	2·90	0·87, 9·66
2005 vs. 2009	1·356 (0·357)	129	3·79	0·001	3·88	1·63, 9·22
2008 vs. 2009	0·292 (0·493)	177	0·59	1·000	1·34	0·41, 4·41
(c) Accipiter						
2005 vs. 2008	1·479 (0·654)	237	2·26	0·074	4·39	0·91, 21·21
2005 vs. 2009	1·740 (0·492)	237	3·54	0·002	5·70	1·74, 18·65
2008 vs. 2009	0·261 (0·706)	237	0·37	1·000	1·30	0·24, 7·12

Odds ratios (OR) with adjusted 95% confidence intervals are presented.

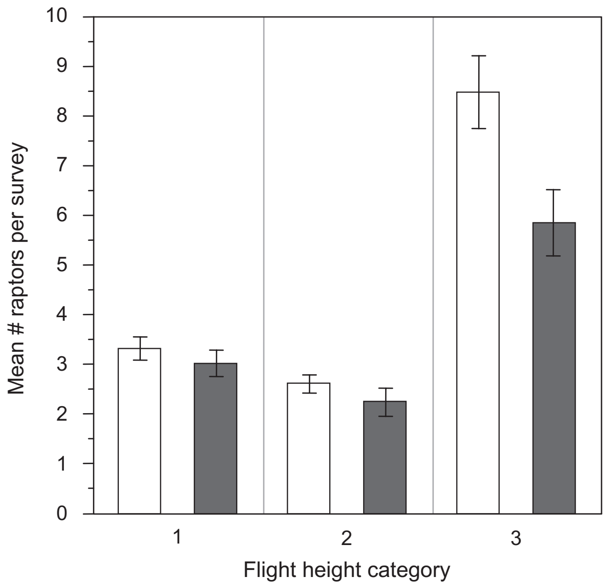

Fig. 2. Flight height frequency distributions pre- (open) and post-construction (filled). Flight height category 1 = below rotor zone, 2 = within rotor zone, 3 = above rotor zone.

Table 5. Behavioural response of all raptors that approached within 100 m of wind turbines

Response	A	N	R	Total
Accipiter		1		**1**
American kestrel			1	**1**
Buteo			2	**2**
Northern harrier	3			**3**
Red-tailed hawk	12	11	21	**44**
Turkey vulture	17	6	30	**53**
Total	**32**	**18**	**54**	**104**

Type of response to turbines is categorized as avoidance (A), no response (N) or high-risk (R).

red-tailed hawks turbine^{-1} year^{-1} (95% CI = 0, 1·128) for 2008, and 0·275 red-tailed hawks turbine^{-1} year^{-1} (95% CI = 0, 0·835) for 2009 (actual estimates from spring and autumn combined). Incidental carcasses were excluded from mortality calculations. Because no carcasses were found for other raptor species, one can assume that mortality estimates for these species would be less than the values provided above.

AVOIDANCE RATES

Avoidance rates were estimated for the five most abundant raptor species/groups (accipiter, American kestrel, northern harrier, red-tailed hawk and turkey vulture; Table 6). Observed small-scale avoidance was significantly lower compared to estimates of avoidance for nearly all species, with the exception of northern harrier (Table 6).

Discussion

ABUNDANCE

Although we predicted abundance would remain relatively constant, raptor abundance was lower post-construction compared to pre-construction levels. This index of raptor activity was also affected by spatial, temporal and weather covariates (similar to previous studies, e.g. Bunn, Klein & Bildstein 1995). Additionally, American kestrel, red-tailed hawk and turkey vulture appeared to decline more than other species.

The decline in raptor abundance post-construction may have been a result of general avoidance (displacement) of the windfarm. Raptors may have relocated to areas outside the windfarm, which was supported by our finding that abundance was higher at reference stations outside of the windfarm project area, although pre-construction baseline data were not collected at reference stations. Another study in Wisconsin (Howe, Evans & Wolf 2002) found that open-country raptors were more abundant in the reference area surrounding their windfarm than within the windfarm itself. Moreover, all five species/groups analysed at the windfarm were less abundant post-construction, providing further evidence of a possible displacement effect.

Displacement could have been caused by the disturbance of windfarm construction and the ongoing presence of turbines and maintenance machinery (reviewed in both Langston & Pullan 2003; Madders & Whitfield 2006). Habitat fragmentation or loss is unlikely to have caused this apparent displacement because the windfarm is located in a primarily agricultural setting with very little apparent, suitable raptor habitat (habitat effects reviewed in Langston & Pullan 2003), and the land use has been consistent since before 2005. On average, only 11% of the habitat assessed was considered natural habitat, and this variable did not influence abundance for any raptor species or group.

Whether this possible displacement effect will remain constant over time, become more pronounced (see Stewart, Pullin & Coles 2007) or decrease through gradual habituation as with pink-footed geese *Anser brachyrhynchus* (Madsen & Boertmann 2008), will require additional years of study. The abundance of accipiter, American kestrel, northern harrier and turkey vulture decreased significantly from 2005 to 2009, but not between 2005 and 2008, suggesting that for some species there may be a temporal lag in the possible displacement effect in response to windfarm construction. No raptor groups analysed in this study changed significantly in abundance from 2008 to 2009 (although it was marginally lower in 2009 for turkey vulture), suggesting that raptor activity did not rebound over the temporal scale considered, minimizing the possibility that post-construction declines were an artefact caused by annual variation or observer differences. This is further supported by analyses of annual state and regional breeding bird survey data which indicated that raptor numbers were not abnormally high in 2005, and thus our single year of pre-construction data should provide an unbiased comparison. While there may be slight differences between observers in technique, visual acuity and skill in species identification, using identical study protocols should aid in controlling for any inter-observer differences. Furthermore, observer identity (as a random variable) was investigated within statistical models, and only significantly impacted observations of flight height which were then adjusted accordingly. Therefore, the decrease in raptor abundance seems most likely to be caused by displacement of raptors in the vicinity of the windfarm.

COLLISION RISK, AVOIDANCE, AND MORTALITY RATES

Overall, birds flew least often within the rotor zone, indicating that risk of collision with turbines was minimal, similar to our predictions. This was further supported by the fact that although half of the individuals observed within turbine arrays flew within the rotor zone, few of these approached within 100 m of turbines. While observer bias may influence estimation of flight heights, especially during surveys lacking turbine height references, observations of birds within 100 m of turbines were likely to be accurate and of greatest relevance

Table 6. Estimated and observed avoidance rates

	2008				2009			
Species	E. Mortality	No. at Risk	E. Avoid.	O. Avoid.	E. Mortality	No. at Risk	E. Avoid.	O. Avoid.
Accipiter	0	42·81	100·0%	0%	0	36·58	100·0%	–
American kestrel	0	128·43	100·0%	0%	0	18·29	100·0%	–
Northern harrier	0	42·81	100·0%	–	0	36·58	100·0%	100%
Red-tailed hawk	31·22	1412·71	97·8%	20%	23·65	2158·02	98·9%	29%
Turkey vulture	0	2397·33	100·0%	20%	0	3895·41	100·0%	43%

The corrected estimate of mortality per year within the entire windfarm, number of birds at risk, estimates of avoidance and observed small-scale avoidance are presented for the most abundant species for each year post-construction.

when observing small-scale avoidance and predicting collision risk.

There were species-specific differences in both collision risk and avoidance rates. While American kestrels, red-tailed hawks and turkey vultures followed predictions by having the highest proportions of individuals at risk of collision, and similarly high proportions of birds displaying high-risk behaviours near turbines, these indices of collision risk did not correlate with observed mortalities. Observed small-scale avoidance rates were highest for northern harrier (all individuals avoided turbines), with the next highest values for turkey vulture, followed by red-tailed hawk and American kestrel. In comparison, estimated avoidance rates were 100% for all but red-tailed hawks. Thus, avoidance behaviour, at any scale, does appear to strongly affect collision risk, and through it, mortality. According to Orloff & Flannery (1992), turkey vultures have low risk of collision, while red-tailed hawks are at high-risk. In contrast, we found these species had similar flight behaviours within 100 m of turbines, similar to findings by Howe, Evans & Wolf (2002). Nonetheless, of all raptor species, we only recorded five red-tailed hawk mortality events (three as incidentals), suggesting that foraging strategies and other species-specific differences may also affect the level of collision risk (Orloff & Flannery 1992; de Lucas *et al.* 2008).

As expected, few mortalities were observed, and uncorrected numbers were similar to studies at comparable windfarms conducted within the same region and with similar methodology to our windfarm [one incidental raptor per year, Gruver *et al.* (2009); five raptors including three incidentals per year, BHE Environmental, Inc. 2010]. Our results were also similar to other studies in the Upper Midwestern USA (e.g. Howe, Evans & Wolf 2002; Johnson *et al.* 2002), as well as elsewhere in the USA and Europe, with the exceptions of Altamont Pass Wind Resource Area, California, USA and Tarifa, Spain which documented very high raptor mortality rates (reviewed in both Erickson *et al.* 2002; Drewitt & Langston 2006). While a long-term study by de Lucas *et al.* (2008) found that mortality is not correlated with abundance (a measure of avian use), Smallwood, Rugge & Morrison (2009) found that red-tailed hawk fatalities increased with both utilization rates and frequency of flights through turbine rows. Our results support the former findings as no carcasses were found of the most abundant species (turkey vulture), suggesting that mortality is influenced by more than abundance alone (see above). Mortality rates did not directly correlate with our index of collision risk or observations of small-scale avoidance. Although red-tailed hawks, the only species for which carcasses were found, ranked among the highest in terms of collision risk and high-risk behaviours, no carcasses were found for the other high-risk species (e.g. American kestrel, turkey vulture).

Avoidance behaviour varied by location within the windfarm, similar to studies where raptor mortalities were unequally distributed in space (Barrios & Rodriguez 2004). However, mortalities in our study appeared to be distributed randomly, and did not occur in the same areas as the majority of observations of birds within 100 m of turbines.

MANAGEMENT IMPLICATIONS

The northern (hen) harrier was the only species of concern (at the state level) which declined post-construction. Our study supports the notion that northern harriers appear to be at low risk of collision (reviewed in Whitfield & Madders 2006; Smallwood, Rugge & Morrison 2009). A recent study in the UK showed that northern harriers avoided flying within 250 m of turbines (Pearce-Higgins *et al.* 2009). However, Pearce-Higgins *et al.* predicted that this avoidance could result in a 53% reduction in flight activity within 500 m of turbine arrays. Our findings also support the presence of such indirect negative effects, and we encourage continued monitoring of harrier population levels near windfarms both in the USA and globally.

Our observations of avoidance flight behaviours and estimation of avoidance rates, although technically simple, based on small sample sizes and uncorrected for several factors (Madders & Whitfield 2006), still provide important information because avoidance rates of operational windfarms are extremely rare and have a strong influence on estimated collision risk. Indeed, collision risk modelling, an important tool used in windfarm development, has been limited by the lack of species- and state-specific avoidance data (Chamberlain *et al.* 2006). Our reported avoidance rates will provide a reference useful for collision risk modelling of future windfarms. However, site-specific assessments of avoidance behaviour are strongly recommended, and we caution against calculating avoidance rates using estimates of mortality that are based on hypothetical data, since this may involve invalid assumptions.

Lastly, our results suggest that construction of the windfarm poses a minimal mortality risk for raptors, and may not be sufficient to cause population-wide effects. However, our windfarm is only one of four large (> 50 MW) windfarms within the region. While impacts (e.g. displacement) from each windfarm separately may be negligible to raptor populations, the cumulative effects may be biologically significant, as has been found for populations of the Egyptian vulture *Neophron percnopterus* in Spain by Carrete *et al.* (2009) (but see Smales & Muir 2005). Future research should consider raptor population dynamics across multiple windfarms in a broader spatial context in order to predict impacts at the population level.

Conclusions

Our study provides evidence for possible displacement and an increased collision risk for raptors (particularly turkey vultures and red-tailed hawks) near the windfarm. However, our observed and estimated avoidance rates, coupled with low mortality events, may indicate effective avoidance behaviours by individuals that remain within the windfarm project area. Determining whether resident species will habituate to the presence of the windfarm and return to their pre-construction levels will require additional years of study. Additionally, cumulative effects from the multiple windfarms in the area on local populations may be biologically significant and should be estimated. Lastly, providing empirically determined avoidance rates for several raptor species may aid in the advancement of collision risk modelling in general, and in the planning of future windfarms. Taken together, these findings may aid in reducing the negative impacts of windfarms on susceptible groups such as raptors, both in the USA and elsewhere.

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Supporting Information

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

Appendix S1. Raptor mortality methodology.

Table S1. Mortality search results.

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