The Condor 115(4):700–711

BIRD MORTALITY AT A WIND-ENERGY FACILITY NEAR A WETLAND OF INTERNATIONAL IMPORTANCE

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Abstract. Wind turbines provide a source of renewable energy to meet increasing human demand and offset the costs of fossil fuel usage and nuclear power generation. Birds are killed and displaced at wind facilities, so increased understanding of the drivers of mortality and displacement will assist planners considering the future placement and use of wind facilities. Our objectives were to assess the effect on birds of a wind facility in southeastern Wisconsin by (1) recording the species composition of recovered bird carcasses, (2) estimating mortality rates, and (3) identifying variables correlated with fatalities. We found 20 bird carcasses during scheduled searches. On this basis, we estimated that over two springs and two autumns of study from 2008 to 2010, 607 birds (0.026 per turbine per day, 0.017 per megawatt per day) were killed over 277 days of searching at this facility containing 86 turbines. Nocturnally migrating passerines accounted for 50% of the birds found killed. We found a significant negative relationship between bird fatalities and northward movement of birds through the wind facility. Despite the close proximity of Horicon Marsh National Wildlife Refuge, a wetland of international importance, we found no relationship between distance to Horicon Marsh and bird fatalities. Our study provides a timely assessment of fatal bird collisions with turbines at a wind facility in agricultural lands, uniquely located near a large wetland at which migrating birds stage.

Key words: *birds, mortality, national wildlife refuge, wind facility.*

Mortalidad de Aves en un Complejo de Energía Eólica cerca de un Humedal de Importancia Internacional

Resumen. Las turbinas de viento brindan una fuente de energía renovable que atienden la demanda humana creciente y compensan los costos del uso de los combustibles fósiles y de la generación de energía nuclear. Las aves mueren y son desplazadas en los complejos eólicos, por lo que un mayor entendimiento de las causas de mortalidad y desplazamiento ayudará a los planificadores a considerar el emplazamiento y uso de los complejos eólicos. Nuestros objetivos fueron evaluar el efecto sobre las aves de un complejo eólico en el sudeste de Wisconsin mediante (1) el registro de la composición de especies de los cadáveres encontrados de aves, (2) la estimación de las tasas de mortalidad y (3) la identificación de variables correlacionadas con las muertes. Encontramos 20 cadáveres de aves durante las búsquedas programadas. En base a esto, estimamos que a lo largo de dos primaveras y dos otoños de estudio desde 2008 a 2010, 607 aves (0.026 por turbina por día, 0.017 por megavatio por día) murieron a lo largo de 277 días de búsqueda en este complejo que contiene 86 turbinas. Las aves migratorias nocturnas representaron 50% de las aves muertas encontradas. Encontramos una relación negativa significativa entre las muertes de aves y el movimiento de las aves hacia el norte a través del complejo eólico. A pesar de la proximidad del Refugio Nacional de Vida Silvestre Horicon Marsh, un humedal de importancia internacional, no encontramos una relación entre la distancia a Horicon Marsh y las aves muertas. Nuestro estudio brinda una evaluación oportuna de las muertes de aves por colisión con turbinas en un complejo eólico en tierras agrícolas, localizado cerca de un gran humedal donde las aves migratorias hacen su parada.

INTRODUCTION

Avian population declines are attributed to a number of natural and anthropogenic causes, the latter of which may be mitigated. Identifying anthropogenic drivers of bird mortality can benefit conservation efforts if appropriate action is taken, whereas natural threats are less subject to control (Loss et al. 2012). Both terrestrial and offshore wind turbines are direct anthropogenic threats to birds, but they provide a source of renewable energy to meet the increasing energy demands of a growing human population and offset the high economic and environmental costs of consumption of finite fossil fuels and generation of nuclear power. Construction of wind facilities can result in significant bird fatalities (Osborn et al. 2000, Erickson et al. 2001, Mabee et al. 2006) and displacement (i.e., through disturbance and habitat loss; see Madders

Manuscript received 31 October 2012; accepted 30 April 2013.
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The Condor, Vol. 115, Number 4, pages 700–711. ISSN 0010-5422, electronic ISSN 1938-5129. DOI: 10.1525/cond.2013.120167

and Whitfield 2006, Garvin et al. 2011). Development of the global wind-energy industry is currently outpacing research on the effects of wind facilities on wildlife, namely, birds and bats. Though much effort has been dedicated to such investigations, many studies have not been peer-reviewed (e.g., technical reports), making them less accessible (deLucas et al. 2008, Garvin et al. 2011).

Bird fatalities at terrestrial wind facilities received increased attention after a study at the Altamont Pass Wind Resource Area, California (Orloff and Flannery 1992) revealed high rates of raptor mortality. Large soaring birds and/or birds with heavy wing loading, such as raptors, may be more susceptible to collision with wind turbines (Barrios and Rodriguez 2004, Garvin et al. 2011). Nocturnally migrating passerines, nominally protected under the Migratory Bird Treaty Act, account for most of the birds killed at wind facilities in the United States and Europe despite regional differences in habitat (Mabee et al. 2006, Kunz et al. 2007). Not surprisingly, the highest rates of avian mortality are often recorded during spring and fall migration (Richardson 1998). Wind facilities located on migration routes or near staging areas may kill greater numbers of birds (Erickson et al. 2005). In addition to the risk wind facilities pose to migratory birds, breeding summer residents also are susceptible to collision with wind turbines (Kuvlesky et al. 2007). The results of studies of the rate and species composition of bird mortality vary widely (Kuvlesky et al. 2007).

Wind turbines currently being constructed trend toward taller monopoles, longer blades, and slower blade-tip speeds, all of which have been shown to cause bird-mortality rates higher than those of older and shorter wind turbines (Morrison 2006, Barclay et al. 2007, Kuvlesky et al. 2007). Although wind facilities rank low among artificial structures that kill birds (e.g., communication towers, see Erickson et al. 2001), the large number of turbines in some wind facilities and the broad distribution of wind facilities along migration routes may affect entire populations, especially of threatened or endangered species (Dahl et al. 2012).

In many cases, bird species of conservation concern are less abundant and consequently may be less susceptible to fatalities in fragmented and converted environments such as agricultural lands (Fletcher et al. 2011). Fargione et al. (2012) found that in the northern Great Plains the areas where wind development had the least effect were agricultural. They emphasized both the benefit of locating wind turbines in existing agricultural land and the abundance of disturbed lands available for wind facilities. Our study expands on this knowledge base as we assess fatal bird collisions at a wind facility in an agricultural region of southeastern Wisconsin, a facility situated near an ecologically significant staging area for migratory birds that has been deemed a wetland of international importance: Horicon Marsh National Wildlife Refuge. Our objectives were to assess the effect of the facility on birds by (1) recording the species composition of recovered carcasses, (2) estimating mortality rates, and (3) identifying variables associated with fatalities. In addition, we discuss the conservation implications for birds in agricultural regions such as the midwestern United States and make suggestions for future research.

STUDY AREA

The western boundary of the study area was 3.2 km from the eastern edge of Horicon Marsh National Wildlife Refuge (Horicon Marsh), as a condition of the operating permit issued by the Wisconsin Public Service Commission (WPSC), with guidance from the Wisconsin Department of Natural Resources (WDNR) and U.S. Fish and Wildlife Service (USFWS) (Fig. 1). Horicon Marsh is listed as a Wetland of International Importance and both a global and state Important Bird Area; it is one of the United States' largest freshwater marshes and serves as a major staging area for migratory birds, including the Sandhill Crane (*Grus canadensis*), Canada Goose (*Branta canadensis*), and ducks. The study area was 68 km south of the Niagara Escarpment, which is the face of a 1046-km long sickle-shaped ridge of bedrock that runs from the northeastern United States, across portions of southeastern Canada, and then southward north and west of Lake Michigan to southeastern Wisconsin. In Wisconsin, the Niagara Escarpment extends for a distance of approximately 370 km and funnels wind along its extent, making the area beneficial to migrating birds and attractive to the wind industry. The remaining boundary lines encompassed all turbine locations at the Forward Energy Center (Energy Center; Fig. 1). The Energy Center is in northern Dodge and southern Fond du Lac counties in southeastern Wisconsin and covers 13 110 ha. It began commercial operation on 14 May 2008 and consists of 86 General Electric 1.5sle (1.5-MW) wind turbines 80 m high at the hub. The maximum height of the revolving blades is 118 m above ground level, and the blades sweep an area 77 m across (Fig. 2). Roughly 97% of the project area was agricultural land (primarily corn and soybeans, planted in rotation), and approximately 2% of the land area was deciduous woodland (i.e., fencerows, isolated woodlots). The Energy Center is approximately 56 km and 22 km west of Lake Michigan and Kettle Moraine State Forest, respectively, and 21 km south of Lake Winnebago (Fig. 1).

METHODS

We collected data during two seasons per year over two years for a total of four study periods. Most fatalities occur during birds' peak migration periods, so we concentrated our searches around these times (Richardson 1998, Kuvlesky et al. 2007). In autumn we searched turbines from 15 July to 15 October 2008 and 2009, in spring from 15 April to 31 May

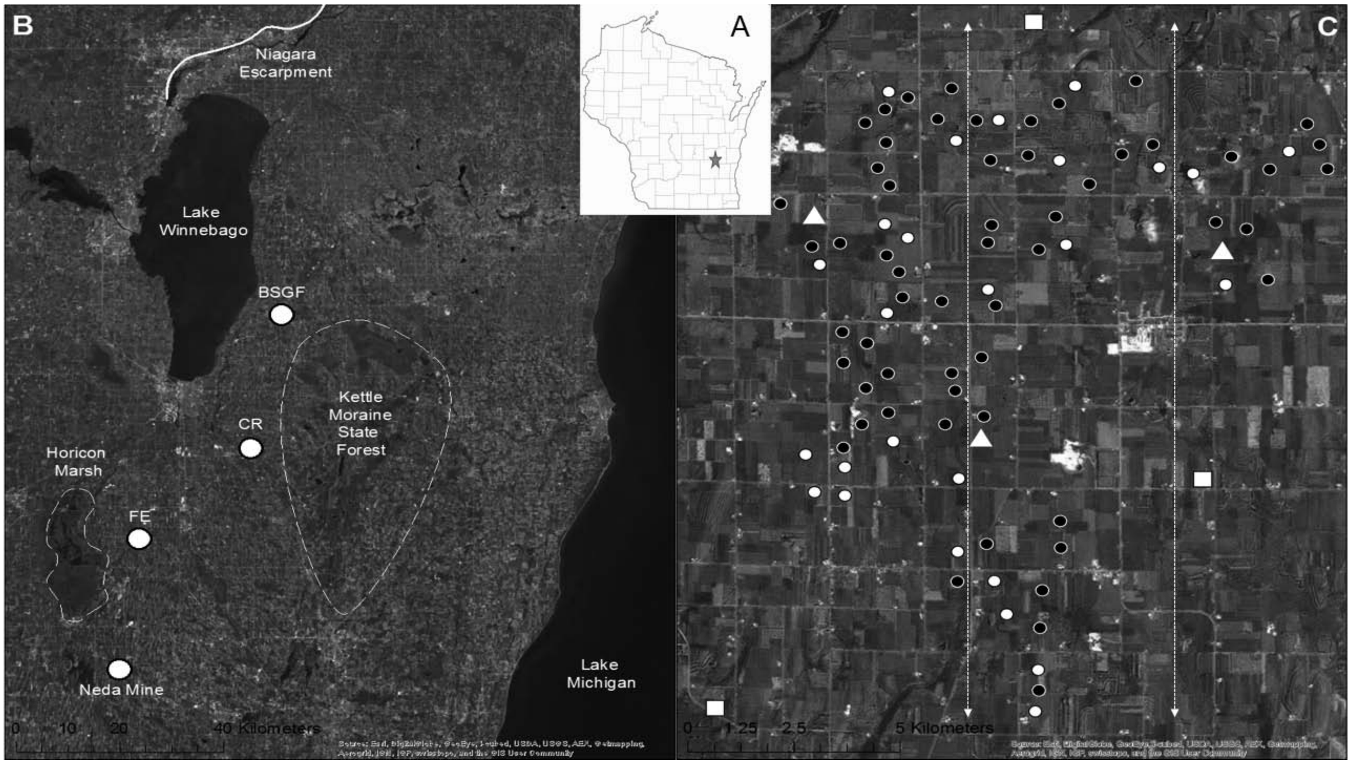

FIGURE 1. (A) Location of the Forward Energy Center in Wisconsin. (B) Map of Forward Energy Center (FE), Cedar Ridge (CR), and Blue Sky Green Field (BSGF) wind-energy facilities and neighboring ecologically significant landscape features; the dotted line indicates approximate boundaries, and the solid line indicates approximate location. (C) Locations of wind turbines within the Forward Energy Center. White dots, searched turbines; black dots, unsearched turbines; squares, control plots; triangles, turbines for which the entire searchable area was monitored; dotted lines, divisions between sections oriented north–south. Horicon Marsh is at the lower left.

2009 and 2010. Additionally, we searched for carcasses of late migrants such as the Sandhill Crane from 15 October to 15 November 2008. We discontinued these searches in autumn 2009 because we did not find any carcasses during searches in autumn 2008 and had limited resources to extend our sampling period in 2009.

STUDY DESIGN

We used an experimental design adapted from previous studies of bird and bat mortality in areas ecologically similar to our study area (Jain et al. 2007, Kerlinger et al. 2007). Our sampling methods were approved by the USFWS, WDNR, and WPSC.

We randomly selected 29 of 86 (34%) wind turbines at which to search for bird carcasses for the duration of the study. We divided the Energy Center into three sections oriented north–south, each approximately 3.22 km wide, which allowed establishment of an impact gradient as distance east of Horicon Marsh increased (see Fig. 1). The number of selected turbines in each section was proportional to the total number of turbines in each section. Because the western, central, and eastern strata contained 48%, 38%, and 14% of the total number of turbines at the Energy Center, respectively, we searched 14, 11, and 4 turbines within each respective section.

STUDY PLOTS

We defined total search area identically for all 29 study plots, with each plot consisting of a square 160 m on a side (2.5 ha) centered on the wind turbine. At 26 of the 29 searched turbines, we monitored only 19% (0.5 ha) of the total searchable area to minimize disturbance of crops because the Energy Center is situated in private agricultural land. At each of these 26 turbines, we randomly selected five parallel transects of 160 m × 5 m from a grid superimposed upon the total searchable area. The five parallel transects were perpendicular to the turbine's access road. The access road itself plus an extension and the pad of the turbine served as a sixth search transect.

At the remaining three turbines, we monitored the entire searchable area, which allowed us to estimate the number of carcasses potentially missed within plots where we searched only a subset of the total searchable area. Additionally, we searched three 0.5-ha control sites to measure background mortality rates. Control plots replicated search plots in terms of land use and cover to the extent possible. One control site and one fully cleared study plot were located within each of the three north–south-oriented sections of the study area, but each control site lay outside of the Energy Center's boundaries (Fig. 1).

All of the turbines monitored during our study were located in active agricultural fields; the searchable areas of study plots passed primarily through fields of corn and soybeans. Other crops included alfalfa, wheat, timothy grass, and hay, in addition to habitat set aside through the Conservation Reserve Program. We marked transects with posts and flagging for the duration of our 2-year study. A hired crew cleared every search transect of vegetation by mowing it with a tractor, ensuring adequate visibility (i.e., low, uniform vegetation or bare soil; Fig. 2). We captured variation in visibility by crop type in trials of searchers' efficiency (see Searcher Efficiency below).

CARCASS SEARCHES

Searches were consistent across all study plots. We searched the 0.5-ha plots by walking up one side of a transect then down the other side. We searched the 2.5-ha plots by walking parallel transects 5 m apart in a zigzag pattern and visually scanned approximately 2.5 m to each side of the search line. At all 29 study plots, we also searched the entire gravel and cement areas of the turbine pad. Prior to searches, we recorded weather conditions and vegetation height. We cleared all plots of any carcasses prior to beginning the first search of each study period.

We assigned each carcass found a unique carcass identification number that included the turbine number and date, placed it in a re-sealable bag, and scored it for level of decomposition on the following scale: freshly killed—unaltered by scavenging animals, no signs of fly larva infestation (on ground ~1–2 days); partially scavenged—signs of insect infestation, partially degraded and/or scavenged (on ground ~2–5 days); or decomposed—severely decomposed and/or scavenged (on ground >5 days).

We estimated the distance of the carcass from the base of the turbine by the same grid system from which we randomly chose the search transects. We recorded additional information on the appearance of the carcass and its location (e.g., cover type in which it was found), and photographed the carcass. Grodsky aged carcasses and identified them to species (in hand). We saved three raptor carcasses for sexing by

FIGURE 2. Example of mowed search transects searched for bird carcasses at the Forward Energy Center, Wisconsin, 2008–2010. Photo by Tom Underwood.

examination of reproductive organs and pathological analysis of causes of death, including radiographs and necropsy (see Garvin et al. 2011).

We considered bird carcasses found outside of designated searchable areas or discovered at turbines outside of the study area (e.g., reported by Energy Center technicians) as incidentals. We obtained required collection and salvage permits for the transport and possession of bird carcasses from the WDNR and the USFWS. Our research was exempt from approval by the University of Wisconsin-Madison's Animal Care Use Committee.

SEARCH INTERVALS

To minimize the potential for carcass removal by diurnal scavenging animals, we began searches approximately 30 min before sunrise and generally concluded them by 12:00. We randomly selected searched turbines for one of three search schedules: 11 (38%) turbines were searched every day, 9 (31%) were searched every 3 days, and 9 (31%) were searched every 5 days. We randomly assigned these search intervals to turbines throughout the three study sections. We searched one each of the three fully cleared sites and control sites every day, every 3 days, and every 5 days. We randomized the order in which turbines were searched during the day to prevent bias from effects of time of day.

SEARCHER EFFICIENCY

We ran searcher-efficiency trials to estimate the percentage of carcasses seen and recovered by individual searchers (i.e., detection probability). We calculated a searcher's efficiency as the percentage of trial bird carcasses found and recorded by the searcher relative to the total number of carcasses placed within the search area for that particular searcher. Trials were interspersed with searches throughout each study period. Before the day of a trial, we placed bird carcasses (from 1 to 4 per trial) at randomly selected locations within the search area. We recorded the crop the carcass was placed in (e.g., corn, soy) during all study periods except spring 2010. The timing and placement of carcasses was unknown to the searchers, and, like searches, trials began 30 min before sunrise. We did not physically mark the trial carcasses but mapped them on a grid and noted identifying attributes (e.g., appearance, condition of carcass) to distinguish the trial carcasses from actual fatalities. A technician returned after searches were completed for the day to determine whether searchers had successfully located trial carcasses. The trials were spread over every searched turbine over the duration of each study period. We set out approximately 100 birds during each study period to test for searcher efficiency. Because bird carcasses found during searches were few in relation to the number of searcher-efficiency trials required for our study, we only used Brown-headed Cowbirds (*Molothrus ater*) provided by the Wisconsin office of Wildlife Services, United States Department of Agriculture, for trial carcasses. We spread searcher-efficiency trials throughout each study period to account for any temporal variation in searcher efficiency. We averaged each searcher's ($\bar{x}$ = 5.5 searchers per study period) efficiency on the basis of approximately 18 trials per searcher per study period and adjusted estimated mortality by these rates.

SCAVENGER REMOVAL

We designed scavenger-removal trials to account for removal of carcasses by scavenging animals before searchers encountered them. As in searcher-efficiency trials, we used Brown-headed Cowbirds exclusively as trial carcasses for scavenger-removal trials. We used 1–3 birds for each trial and performed approximately 100 trials during each study period. As in searcher-efficiency trials, we distributed the scavenger-removal trials evenly throughout the study period to account for temporal variation in scavenger abundance and composition. We randomly selected the turbine, date, and placement of trial carcasses and mapped each carcass by the same methods described for searcher-efficiency trials. We checked trial carcasses every day to determine whether they had been scavenged, but the duration of scavenger-removal trials matched the search interval for the selected turbine (i.e., 1 day, 3 days, or 5 days). We set out all carcasses for scavenger-removal trials prior to 12:00. In contrast to searcher-efficiency trials, each searcher and field technician had a copy of the mapped location of each carcass placed for scavenger removal at each study plot to prevent searchers from removing them before the trial concluded. We incorporated estimated site-specific proportions of scavenger removals into the corrected estimate of mortality.

STATISTICAL ANALYSES

We obtained post-construction weather data, including hourly records of temperature, relative humidity, precipitation, and wind speed from the National Oceanic and Atmospheric Administration station at the Fond du Lac airport, located 17 km from the project area. We obtained hourly power (MW) data from Invenergy, LLC, via a General Electric data-logger. We averaged all of the hourly data over a 12-hr period from 19:00 to 07:00 each night, which encompassed times of peak activity for nocturnally migrating birds. Using spatial analyst tools in ArcMap, we measured distances of each study plot from Horicon Marsh and Neda Mine, which represent movement to the east (away from Horicon Marsh toward the Energy Center) and north (away from Neda Mine toward the Energy Center). Neda Mine is a bat hibernaculum and has no clear ecological relevance to birds but served as an unambiguous anchor point from which we assessed the effect of mortality along a north–south gradient representative of bird migration.

We analyzed bird fatalities recorded at the Energy Center with respect to selected covariates of landscape, weather, and turbine status. For all statistical analyses we used SAS software (version 9.2; SAS Institute, Inc., Cary, NC). We evaluated a generalized linear mixed model, which allowed for fixed and random effects. We used proc GLIMMIX to construct a predictive model evaluating the relationship between covariates and a response variable: bird fatalities. The unit of analysis was the observed occurrence (1 = carcass present; 0 = no carcass present) of a bird carcass per turbine per search day. We did not model fatalities of migratory and nonmigratory birds independently or fatalities by guild because the numbers were too small. We evaluated covariates for co-linearity with Pearson's correlation coefficients, and when variables were correlated ($r \geq 0.5$ or $r < -0.5$ and $P \leq 0.10$), we randomly excluded one from further consideration in our model. We accounted for spatial and temporal variation by including the natural log of the time spent searching a given site, which is a proxy for the area searched (e.g., 0.5 ha vs. 2.5 ha), as an offset in our model. In the generalized linear mixed model, random effects included searcher nested within turbine and season. We used a logit link for the response variable to analyze differences in the odds of a fatality occurring as a function of selected covariates. Degrees of freedom were derived by the approximation of Kenward and Roger (1997). We estimated parameters by the restricted-maximum subject-specific pseudo-likelihood approach, which Molenberghs and Verbeke (2006) showed correctly accounts for random effects in the estimation of parameters and their uncertainty in mixed-effects models.

Mortality estimation. We estimated mortality rates in the study area from data collected over all four periods (summer–autumn 2008 and 2009, and spring 2009 and 2010). Because searches did not occur throughout the year, we conditioned the results on sampling periods, which primarily coincided with periods of bird migration. We used a modified version of a mortality estimator proposed by Huso (2010), which accounts for searcher efficiency, scavenger removal, search interval, density-weighted area searched, and visibility within search transects. The estimator we used was

$$\hat{F} = \sum_{i=1}^{n} \frac{1}{\pi_i} \sum_{j=1}^{s} \sum_{k=1}^{K} \frac{c_{ijk}}{\hat{r}_{ijk}\hat{p}_{ijk}}$$

where

$\hat{F}$ = estimated number of birds killed at a given wind facility over the period sampled

π_i = product of the proportion of searchable area sampled at turbine *i* and the probability of turbine *i* being included in the sample set

c_{ijk} = bird fatalities observed at turbine *i* in search interval *j* in class *k* (carcasses or vegetation classes in which carcass-detection probability is homogeneous)

$\hat{r}_{ijk}$ = estimated probability that a bird killed at turbine *i* in interval *j* in class *k* remains unscavenged and observable, i.e., 1 – Pr(scavenger removal).

$\hat{p}_{ijk}$ = estimated probability of detecting a carcass at turbine *i* in interval *j* in class *k*, given it is observable and unscavenged (i.e., searcher efficiency).

Our estimator differs from that of Huso (2010) mainly in how we incorporate carcass removal (our trials were based on fixed intervals of 1, 3, and 5 days) and the proportion of searchable area in a given sample plot. Our estimates, along with 95% confidence intervals, were based on 3000 bootstrap samples with replacement from the original data and calculated in a SAS (version 9.2; SAS Institute Inc., Cary, NC) program developed for the purposes of this study.

None of the incidental mortalities or carcasses found away from search plots were included in mortality estimates. We estimated bird fatalities per turbine and fatalities per megawatt (see Arnett et al. 2008) for each study period and the entire study (i.e., all search days in four study periods). We assumed delayed lethal effects or bias from crippling to be low and did not account for them in our mortality estimates. However, Grodsky et al. (2011) and Rollins et al. (2012) both found evidence for potential delayed lethal effects in bats struck by wind turbines, so it is plausible that birds may similarly be at risk.

RESULTS

CARCASS SEARCHES

We searched study area plots for 277 days: 93 days for autumn in both 2008 and 2009 and 47 and 44 days for spring in 2009 and 2010, respectively. We completed 3763 searches over the duration of our 2-year study. At turbines searched daily, we conducted 2562 searches (per turbine, $\bar{x}$ = 232.91 ± 13.15 [SD]), at turbines searched every 3 days, 724 searches ($\bar{x}$ = 80.44 ± 2.13) and at turbines searched every 5 days, 477 searches ($\bar{x}$ = 53 ± 5.38). We completed 135, 43, and 29 searches at the control sites searched daily, every 3 days, and every 5 days, respectively, for a total of 207 searches at all control sites.

BIRD FATALITIES

We found 20 bird carcasses during scheduled searches. Additionally, we found 1 Tree Swallow and 3 Red-tailed Hawks as incidentals. Most bird carcasses were fresh (55%), 20% were partially scavenged, and 25% were decomposed (excludes incidentals). We found carcasses of 15 species (Table 1); the Red-tailed Hawk (n = 5; 21%), Tree Swallow (n = 3; 13%), Ruby-crowned Kinglet, Black-and-white Warbler, and Red-eyed Vireo (n = 2; 8% each) were the only species found more than once. All other species, including incidentals, were represented by one carcass. Most bird fatalities were of the orders Passeriformes (includes incidentals; n = 17; 71%)

TABLE 1. Summary of bird species found during searches for carcasses at the Forward Energy Center, Wisconsin, 2008–2010.

Species	Autumn 2008		Spring 2009		Autumn 2009		Spring 2010		Grand total	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%
Red-tailed Hawk (*Buteo jamaicensis*)	2*	28.6	2*	14.3	1*	50	0	0	5	20.8
Tree Swallow (*Tachycineta bicolor*)	2	28.6	1*	7.1	0	0	0	0	3	12.5
Black-and-white Warbler (*Mniotilta varia*)	0	0	2	14.3	0	0	0	0	2	8.3
Red-eyed Vireo (*Vireo olivaceus*)	0	0	2	14.3	0	0	0	0	2	8.3
Ruby-crowned Kinglet (*Regulus calendula*)	0	0	2	14.3	0	0	0	0	2	8.3
American Redstart (*Setophaga ruticilla*)	0	0	1	7.1	0	0	0	0	1	4.2
Barn Swallow (*Hirundo rustica*)	1	14.3	0	0	0	0	0	0	1	4.2
Black-billed Cuckoo (*Coccyzus erythropthalmus*)	0	0	1	7.1	0	0	0	0	1	4.2
Blackpoll Warbler (*Setophaga striata*)	0	0	0	0	1	50	0	0	1	4.2
Bobolink (*Dolichonyx oryzivorus*)	0	0	1	7.1	0	0	0	0	1	4.2
Cliff Swallow (*Petrochelidon pyrrhonota*)	1	14.3	0	0	0	0	0	0	1	4.2
European Starling (*Sturnus vulgaris*)	0	0	1	7.1	0	0	0	0	1	4.2
Killdeer (*Charadrius vociferus*)	1	14.3	0	0	0	0	0	0	1	4.2
Mallard (*Anas platyrhynchos*)	0	0	0	0	0	0	1	100	1	4.2
Savannah Sparrow (*Passerculus sandwichensis*)	0	0	1	7.1	0	0	0	0	1	4.2
Total	7	100	14	100	2	100	1	100	24	100

*One incidental Red-tailed Hawk carcass found in autumn 2008, spring 2009, and autumn 2009, respectively; one incidental Tree Swallow carcass found in spring 2009.

and Accipitriformes (includes incidentals; $n = 5$; 21%), with comparatively little representation from other orders. None of the birds found during searches is listed as a threatened or endangered species by federal or state agencies. However, the Black-billed Cuckoo, Bobolink, and Ruby-crowned Kinglet are considered species of concern in Wisconsin. We found no bird carcasses at control sites or during the extended autumn 2008 study period (15 October–15 November 2008).

Most carcasses found were of adults (includes incidentals; $n = 20$; 83%); few were of juveniles (includes incidentals; $n = 4$; 17%). All three necropsied Red-tailed Hawks were females with ovaries in nonreproductive condition. Radiology results for these individuals are highlighted in Garvin et al. (2011). On the basis of visual inspection, most bird carcasses were intact with few lacerations. Bird fatalities were evenly distributed between the western and central sections of our study site, and we recorded no fatalities in the eastern section. The 2.5-ha plots accounted for 45% of the total number of bird fatalities. Bird carcasses were evenly distributed across distances ranging up to 90 m from the base of the turbine, with the highest percentages of carcasses being found between 30 and 40 m and between 70 and 80 m (excludes incidentals; Table 2). The spatial orientations of bird carcasses (excluding incidentals) within the defined search area were 30% to the north and east ($n = 6$ each), 20% to the west ($n = 4$), 15% to the south ($n = 3$), and 5% ($n = 1$) in the middle of the plot (i.e., turbine pad).

Our model results suggested that distance to Neda Mine ($F = 0.48$, $P = 0.0270$) was the only covariate significantly associated with the odds of a carcass being encountered. For each unit increase in distance north through the Energy Center, the odds of observing a carcass decreased by ~20%, other factors in the model controlled for (odds ratio = 0.803; 95% CI = 0.655 – 0.974). No other covariate influenced the number of bird fatalities in our model, though there is a suggestion of a moderate positive effect of temperature (Table 3).

Temporal distribution. In autumn, bird fatalities apparently peaked near 18 August 2008 and 16 September 2009

TABLE 2. Summary of the distances bird carcasses were found from searched turbines at the Forward Energy Center, Wisconsin, 2008–2010. Excludes carcasses found incidentally.

Distance range[a] (m)	% Bird carcasses found: Autumn 2008	Spring 2009	Autumn 2009	Spring 2010	Total %
0–10	17	0	0	0	5.0
10–20	33	0	0	0	10.0
20–30	17	8	0	0	10.0
30–40	0	25	0	100	20.0
40–50	0	8	0	0	5.0
50–60	17	17	0	0	15.0
60–70	17	0	0	0	5.0
70–80	0	25	100	0	20.0
80–90	0	17	0	0	10.0

[a]The proportion of carcasses found in each distance interval is conditional on searcher-specific detection probability and the limits of our search area.

TABLE 3. Evaluation of fixed effects from a generalized linear mixed model of bird mortality at the Forward Energy Center, Wisconsin, 2008–2010.

Model effects	β (SE)	df Numerator	df Denominator	*F*	*P*	Odds ratio 95% CI
Power	0.002 (0.001)	1	3317	1.91	0.17	0.999–1.004
Temperature	0.06 (0.03)	1	3317	3.04	0.08	0.993–1.127
Relative humidity	–0.03 (0.03)	1	3317	1.21	0.27	0.922–1.023
Wind speed	–0.12 (0.11)	1	3317	1.03	0.31	0.709–1.115
Precipitation	0.07 (1.51)	1	3317	0	0.96	0.055–20.793
Distance to Neda Mine	–0.22 (0.10)	1	155.1	4.99	0.03	0.655–0.974
Distance to Horicon Marsh	–0.15 (0.21)	1	220.6	0.48	0.49	0.572–1.306

(excludes incidentals). Apparent bird fatalities peaked three different times (near 25 April, 10 May, and 20 May) during spring 2009 and once, near 25 May, during spring 2010.

Estimates. We estimated that bird mortality in autumn 2008 was 0.025 birds per turbine per day and 0.017 birds per MW per day. We estimated bird mortality in spring 2009 was 0.0695 birds per turbine per day and 0.046 birds per MW per day. We estimated bird mortality in autumn 2009 was 0.0037 birds per turbine per day and 0.025 birds per MW per day. We estimated bird mortality in spring 2010 was 0.014 birds per turbine per day and 0.0090 birds per MW per day. Averaged over all study periods, estimated total bird mortality was 0.026 birds per turbine per day and 0.017 birds per MW per day. We extrapolated an average of 607 bird fatalities during the two spring and two autumn study periods or 277 search days.

SEARCHER EFFICIENCY AND SCAVENGER REMOVAL

We used 392 trial bird carcasses to assess searchers' efficiency. Over the entire study, searchers detected 63% of the trial carcasses. Their efficiency was lower in the spring 2010 than during the first three study periods (Table 4). By crop, the rate of detection of trial carcasses was 76% in corn, 75% in soy, 62% in alfalfa, and 61% in fallow fields, hay fields, and habitat set aside through the Conservation Reserve Program. Searchers' efficiency ranged from 12.5% to 100% by turbine and from 30% to 100% by individual searcher.

We used 402 trial bird carcasses to assess scavenger removal. Over the entire study, 40% of the trial carcasses were removed from study plots. Removal rates were highest in fall 2008 and during the first day of our 5-day trials (Table 5).

DISCUSSION

We detected a significant negative relationship between the northward movement of birds through the Energy Center and the odds of encountering a bird fatality. Neotropical migrants constituted most bird fatalities at the Energy Center, and nearly all were killed in spring. Hence this effect may not only be correlated with the northward movement of migratory birds in spring, it may indicate the odds of a fatality are greater when a migrating bird first encounters the periphery of a wind facility. At the landscape level, the Energy Center is the first wind facility birds encounter in southeastern Wisconsin if they migrate west of the Great Lakes along the Niagara Escarpment. In combination with other studies, our results suggest possible landscape-level relationships between migration and bird mortality at wind facilities, which warrant further investigation.

Despite the Energy Center's proximity to Horicon Marsh, we did not find evidence of a statistically significant relationship between the odds of a bird fatality and distance to Horicon Marsh. Given the low heterogeneity in distances from Horicon Marsh to a potential bird fatality at the Energy

TABLE 4. Summary of searcher-efficiency trials at the Forward Energy Center, Wisconsin, 2008–2010.

Study period	Number of trial carcasses	% Detected
Autumn 2008	104	76.9
Spring 2009	95	71.6
Autumn 2009	98	64.3
Spring 2010	99	34.3
Total	392	62.6

TABLE 5. Summary of scavenger removal trials at the Forward Energy Center, Wisconsin, 2008–2010.

Study period	*n*	No. scavenged Day 1	Day 2	Day 3	Day 4	Day 5	Total count
Autumn 2008	100	33	17	8	5	0	63
Spring 2009	100	17	5	8	2	1	33
Autumn 2009	102	20	6	8	2	0	36
Spring 2010	100	11	3	7	4	3	28
Total	402	81	31	31	13	4	160

Center (due to the short east–west dimensions of the Energy Center, relative to the marsh), a distance effect from the marsh might not have been detectable at the spatial scale (i.e., one wind facility) we considered. Although large numbers of Sandhill Cranes and Canada Geese use Horicon Marsh as a staging area and for roosting and feeding, we did not observe fatalities of either species. Though federally endangered Whooping Cranes (*Grus americana*) were present in our study area, albeit in very small numbers, we did not record any fatalities. Ducks also use Horicon Marsh extensively, yet we found only one Mallard carcass and no other ducks during our 2-year study. We assumed the probability of our detecting a bird as large as a crane, goose, or duck, provided it was available (not scavenged), approached unity. Thus we believe there was a low probability of crane or waterfowl death (despite one detected Mallard fatality) at the surveyed turbines during our study. Grodsky observed both Sandhill Cranes and Canada Geese feeding under and maneuvering in flight among wind turbines in agricultural fields, but we did not study birds' rates of avoidance (but see Garvin et al. 2011). Our data and observations lead us to infer that large-bodied water birds associated with Horicon Marsh (e.g., cranes and geese) are unlikely to collide with wind turbines at the Energy Center during short-distance flights from roost to feeding areas. However, since we did not quantify the number of these birds, the time at risk of collision, or migratory status, we cannot make definitive conclusions.

Passerines migrating at night (i.e., neotropical migrants) constituted half of the observed fatalities at the Energy Center, which is consistent with general trends at wind facilities elsewhere in the United States and in Europe (Mabee et al. 2006, Kuvlesky et al. 2007, Bay et al. 2010). In some cases, we found more than one nocturnally migrating passerine on the same date and, less frequently, at the same turbine. We observed a qualitative association between bird fatalities and nights with fog and/or rain, which may have resulted from birds migrating at lower altitudes and within range of turbine blades. However, we did not find a significant relationship between bird fatalities and precipitation. Peaks in bird fatalities at the Energy Center coincided with peak migration periods for most neotropical migrants, and there was no suitable breeding or stopover habitat for most bird species at the Energy Center. Therefore, most bird fatalities at the Energy Center were likely associated with migration, as found in most studies of bird (Richardson 1998) and bat mortality (Arnett et al. 2008, Grodsky et al. 2012) at wind facilities in North America and Europe.

The Red-tailed Hawk was the most commonly killed bird species and the only raptor found during our searches. A concurrent study by Garvin et al. (2011) examined displacement of raptors following construction at the Energy Center and found decreased abundance as well as decreased species diversity. Since the Red-tailed Hawk was the only raptor found killed at the Energy Center despite the decreased abundance reported by Garvin et al. (2011), its behavior or flight characteristics may increase its susceptibility to collisions with turbines. Indeed, de Lucas et al. (2008) found that abundance of birds might not be related to mortality rates, and Ferrer et al. (2011) reported a weak relationship between many risk-assessment studies and actual death data. Such evidence suggests unknown mechanisms responsible for species-specific collision risk. Nevertheless, because of raptors' low reproductive potential and long lifespan, mortality from wind turbines may affect the population dynamics of raptors more than that of passerines (Kuvlesky et al. 2007). While there is concern for declining raptor species such as the Golden Eagle (*Aquila chrysaetos*), which is subject to additive mortality from wind turbines in both the western and eastern sections of its North American range (Katzner et al. 2012), agricultural regions have comparatively few raptor species of conservation concern.

Our estimates of average bird mortality for the Energy Center, transformed to match reporting standards from other studies, were 7.06 bird fatalities per turbine over the entire study period, 3.5 bird fatalities per turbine per year, and 4.7 bird fatalities per megawatt over the entire study period. A previous study in agricultural and woodland cover types in Wisconsin estimated bird mortality was 1.3 bird fatalities per turbine per year (Howe et al. 2002). Although methods differ, studies of wind facilities at Blue Sky Green Field (Gruver et al. 2009) and Cedar Ridge (BHE Environmental 2010), both located near the Energy Center, are most comparable to ours in design, land use, cover types, and especially timing of study and searches. Gruver et al. (2009) estimated approximately 7.0 bird fatalities per MW per year, excluding incidentals, and BHE Environmental (2010) estimated 10.8 bird fatalities per turbine over the entire study, excluding incidentals (per MW not provided). Our mortality estimate (4.7 bird fatalities per megawatt per study period) falls within the upper range of estimates compiled by Bay et al. (2010; 0.08 to over 7.0 bird fatalities per megawatt per study period) from 43 publicly available studies of wind facilities in the United States and Canada and are similar to those of Blue Sky Green Field (34 km northeast of Horicon Marsh) and Cedar Ridge (24 km northeast of Horicon Marsh). Although at 5 km the Energy Center is much closer to Horicon Marsh than are Blue Sky Green Field and Cedar Ridge, estimated mortality at both was higher, indicating other influential factors. For example, the proximity of those sites to Lake Michigan, which may focus bird migration, may contribute to mortality there being greater than at the Energy Center, which is farther from Lake Michigan. Similarly, Blue Sky Green Field and Cedar Ridge are both closer than the Energy Center to Kettle Moraine State Forest, a large tract of woodland that migratory birds may use as a stopover site.

Comparisons of mortality estimates between studies of human stressors on birds are difficult to make because of differences in reporting standards and underdeveloped methods (Loss et al. 2012, Piorkowski et al. 2012). For example, Gruver et al. (2009) counted "feather spots" (i.e., evidence of a bird's death) in addition to actual bird carcasses in their estimate of mortality, while we counted bird carcasses only. Similarly, most studies vary in effort and thus detectability of carcasses. Many studies report mortality per year, though searches may take place for only a portion of the year; such studies assume mortality rates during sampled and unsampled periods are homogeneous. For more accurate comparisons between studies, we advocate conditioning mortality on the number of search days and reporting per megawatt, which can easily be converted to kilowatt-hours for comparison of bird (or bat) mortality due to differing energy sources (Arnett et al. 2008, Sovacool 2009, Grodsky et al. 2012). However, comparisons of studies may not be valid if sampling did not coincide seasonally, and possibly in latitude.

Our number of searcher-efficiency trials was larger than in most other studies. Searchers' efficiency varied by crop type, being higher in corn and soy. Corn and soy did not grow back in our mowed transects, while alfalfa and hay grew back vigorously after mowing and consequently decreased visibility in transects. These results emphasize the importance of diligent maintenance of study transects and accounting for visibility when bird fatalities are sampled in agricultural environments. Searchers' efficiency for birds and bats was lowest in spring 2010 (Grodsky et al. 2012). The reasons for this are unclear but were likely correlated with the crop rotation typical of the area and/or the mowing regime for spring 2010. Searcher-efficiency trials ran concurrently with fatality searches, which began 30 min before sunrise. Therefore, searchers' efficiency may have been lower before sunrise because of the low light. However, trials were randomly assigned to searchers searching under randomly assigned turbines, and multiple turbines were searched each day. Thus the ratio of pre-dawn trials to trials in full daylight was probably low.

In contrast to most other studies, we used far more carcasses to test removal by scavengers, in trials shorter in duration. In most studies, scavenger-removal trials last until the carcass is actually removed. However, we removed trial carcasses from a plot if a scavenger didn't remove them by day 5. By placing only one to four carcasses per turbine for trials of no more than 5 days over an entire study period, we avoided swamping plots with carcasses for scavengers, which might bias fatality estimates low (Smallwood et al. 2010). Most of our trial carcasses were removed on day 1 of our 5-day trials, which indicates 5-day trials sufficiently captured most scavenging. Additionally, Huso (2010) defined the effective interval of a trial as "the length of time beyond which the probability of a carcass persisting is less than or equal to 1%." Our average rate of removal by scavengers indicated that 81% of all birds were scavenged by the end of day 5. Extrapolating those rates implies that the probability of a carcass persisting would drop below 1% by day 10 at the latest.

Heavily fragmented landscapes with high densities of anthropogenic structures typical of agricultural settings provide habitat for mesopredators that may scavenge dead or dying birds struck by wind turbines. Furthermore, many agricultural landscapes have high densities of feral and/or outdoor cats that probably are frequent scavengers under wind turbines. Beyond scavenging animals, our scavenger-removal trials also accounted for agricultural practices such as tilling or manure spreading that may reduce the number of dead birds found by searchers. This is particularly relevant where wind turbines are located in active agricultural fields. However, most carcass removal we observed was due to actual scavenging.

CONSERVATION IMPLICATIONS

Our estimates of bird mortality at the Energy Center were low despite the proximity of Horicon Marsh, an ecologically significant and extensive area used by migratory birds, although the risk may be elevated during northward migration. Fargione et al. (2012) modeled wind-development scenarios and reported vast space is available for wind-energy development in the northern Great Plains, where disturbed cover types such as agricultural lands (assumed to have low value for wildlife) can accommodate wind development, while minimizing adverse effects on wildlife. Given the heterogeneity in reported estimates of bird mortality just among wind facilities near the Energy Center, we caution against generalizing across agricultural areas in this region. Also, we cannot consider the risk of mortality to birds only, since bat mortality due to collision with wind turbines in agricultural landscapes (including those surrounding the Energy Center) is a growing conservation concern as well (see Grodsky et al. 2012). Bird mortality at wind facilities is orders of magnitude less than most other anthropogenic causes of bird fatalities, including window strikes, communication towers, and the fossil fuel cycle (Erickson et al. 2001, Sovacool 2012). However, commercial wind development is still an emerging industry, and it is important that the potential cumulative effects of these facilities on bird populations be considered (and formally evaluated). There is heterogeneity in the threat that wind facilities pose to birds, which is driven by complex interactions of factors at landscape and site-specific scales. While major migratory routes are clearly important to consider in the placement of wind facilities, it may be useful to explore the dynamics of fatality (and possible mitigation features) in relation to the peripheries of wind facilities, where migrants first encounter this potential threat. We encourage further study of the effects of wind-energy development on bird mortality at the levels of the landscape and specific facility, particularly in relation to migration, unique landscape features, and cumulative effects from clusters of wind facilities.

We advocate consideration of not only birds but also other potentially affected taxa such as bats when the placement and use of wind turbines is considered.

ACKNOWLEDGMENTS

A special thanks is given to the searchers involved in data collection for this study. We also thank Forward Energy staff members K. Drake, G. Otkin, A. Pearson, and L. Miner of Invenergy, LLC, for their cooperation. USFWS staff at Horicon Marsh National Wildlife Refuge provided assistance with data collection. Graduate students in the Department of Forest and Wildlife Ecology at the University of Wisconsin–Madison provided useful feedback and support for this paper. Invenergy, LLC, and a grant from Wisconsin Focus on Energy provided funding for this project.

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