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Abstract.—In 1994 a major wind power development project was initiated in southwest Minnesota that may eventually produce 425 megawatts (MW) of electricity. The wind plant currently consists of 3 phases that total 354 turbines capable of generating 236 MW. During a study conducted from 1996–1999 to assess effects of wind power development on wildlife, 184 bat collision fatalities were documented within the wind plant. Hoary bats (*Lasiurus cinereus*) and eastern red bats (*L. borealis*) comprised most of the fatalities. After correcting bat fatality estimates for searcher efficiency and scavenger removal rates, we estimated that the number of bat fatalities per turbine ranged from 0.07 per y at the Phase 1 wind plant to 2.04 per y at the Phase 3 wind plant. The timing of mortalities, and other factors, suggest that most mortality involves migrant rather than resident breeding bats.

Introduction

Wind has been used to commercially produce energy in North America since the early 1970s [American Wind Energy Association (AWEA), 1995]. Recent advances in wind turbine technologies have reduced costs associated with wind power production (Hansen *et al.*, 1992), and wind power produced in the United States in 2001 was comparable in price to conventional power produced using natural gas [American Wind Energy Association (AWEA), 2001]. Commercial wind plants have been constructed in 26 states (Anderson *et al.*, 1999; AWEA, 2002). Although generally considered environmentally friendly, wind power has been associated with the deaths of birds colliding with turbines and other wind plant structures, especially in California. As a result of these concerns, state and federal agencies require monitoring of many new wind development areas to assess the extent of and potential for avian mortality from collision with turbines.

In 1999 development of a 354-turbine wind plant was completed on Buffalo Ridge in southwestern Minnesota (Fig. 1). Avian monitoring studies were initiated during completion of the first 73 turbine phase of the facility in 1994. An unexpected outcome of these monitoring studies was the discovery of 13 bat fatalities near turbines during the first 2 y of operation (Osborn *et al.*, 1996). We conducted additional monitoring studies at the expanded wind plant from 1996–1999. Although our study was designed primarily to assess effects of wind power development on birds, data collected during fatality searches also allowed us to address wind power impacts on bats. Our objectives were to estimate the number of bat mortalities attributable to collisions with wind turbines for the entire Buffalo

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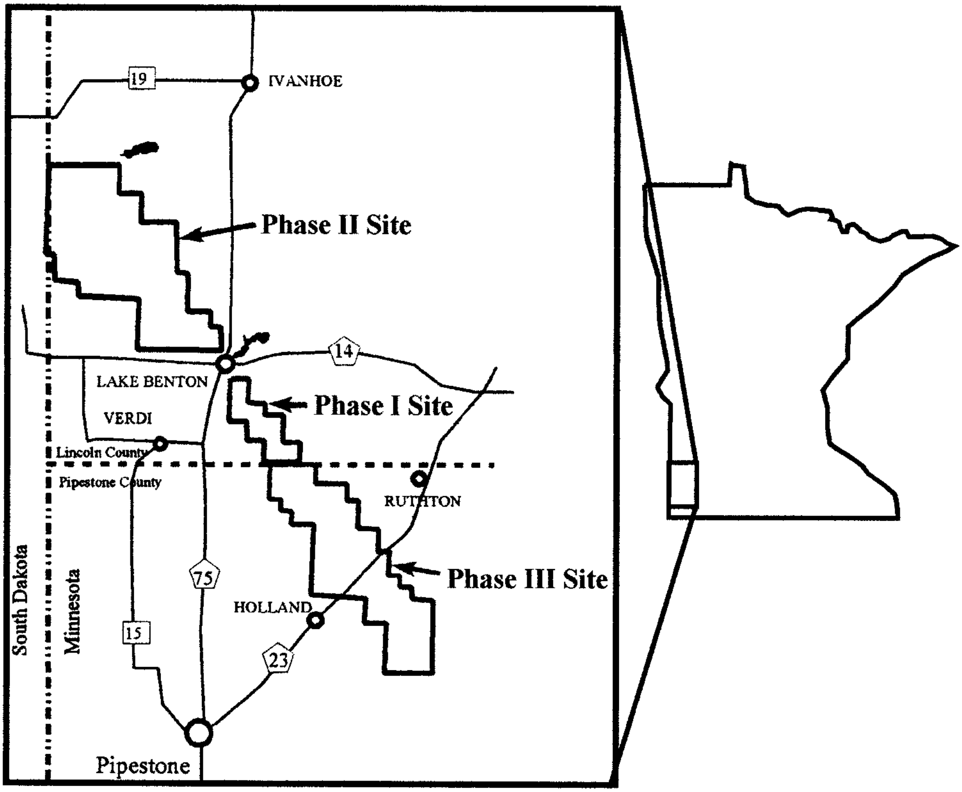

FIG. 1.—Location of the Buffalo Ridge Wind Development Area in Minnesota

Ridge wind plant, to determine the species and groups at highest risk and to determine what factors might be related to the collision mortality.

STUDY AREA

The study area was comprised of a large portion of Buffalo Ridge, a 100-km-long segment of the Bemis Moraine located in southwest Minnesota and northeast South Dakota (Fig. 1). Buffalo Ridge is located in the Coteau des Prairies, a major physiographic landform consisting of terminal moraines and stream-dissected lands (Coffin and Pfannmuller, 1988). The ridge runs diagonally from southeast to northwest and separates the Missouri and Mississippi river watersheds. Elevations range from 546 m to 610 m above sea level. Vegetation types consist primarily of corn, soybeans, small grains and hay; pasture; and Conservation Reserve Program (CRP) grasslands. Less prevalent vegetation types include deciduous woodlots associated with farmsteads, wooded ravines and wetlands. Vegetation, including vertical density and vegetation height, has previously been described for cropland, pasture and CRP habitats in the Buffalo Ridge study area (Leddy, 1996).

The wind plant currently consists of three major phases of development (Fig. 1). Phase 1, constructed in 1994, consists of 73 turbines and related facilities, including distribution lines, meteorological towers, communication systems, transformers, substations, roads and operations and maintenance facilities. Turbines in Phase 1 are arranged in 10 strings with 3–20 turbines spaced from 91 m to 183 m apart per string. Phase 1 turbines are installed on top of 36-m tubular towers and have blade diameters of 33 m. The rotor-swept height of Phase 1 turbines is 19.5 m to 52.5 m and the rotor-swept area is 855 m^2. Phase 2, consisting of 143 newer-generation 750 kilowatt (KW) turbines, was completed in July 1998. Phase 2 consists of 26 strings of turbines, with 2 to 12 turbines per string spaced at intervals from approximately 100 m to 200 m. Phase 2 turbines are installed on top of 50-m tubular towers and blade diameters are 46 m and 48 m. Therefore, the rotor-swept height of the Phase 2 turbines is either 26 m to 74 m or 27 m to 73 m and the rotor-swept area is either 1661 m^2 or 1809 m^2. Phase 3 is comprised of 138 of the same turbines used for Phase 2 and was completed in June 1999. Phase 3 consists of 36 strings of turbines, with 2 to 13 turbines per string spaced at intervals ranging from approximately 250 m to 500 m. None of the turbines at the Phase 1 wind plant are lighted. At the Phase 2 wind plant, 6 of the 143 turbines are lighted (3 at each end of the wind plant). Half of the turbines (every other one) within the Phase 3 wind plant are lighted due to their proximity to the Pipestone, Minnesota airport. Gravel access roads service all turbine strings and each turbine is placed on a gravel pad that averaged approximately 14 m in diameter at Phase 1 turbine sites, 24 m in diameter at Phase 2 turbine sites and 36 m in diameter at Phase 3 turbine sites.

METHODS

Fatality searches.—Fatality searches were conducted at 21 of the 73 turbines within the Phase 1 study area, 40 of the 143 turbines within the Phase 2 study area and 30 of the 138 turbines within the Phase 3 study area. Turbines were numbered consecutively in each phase, and we selected turbines for searching using a systematic design with a random start for the first turbine. Searches were conducted from 1996 through 1999 at Phase 1, in 1998 and 1999 at Phase 2 and in 1999 at Phase 3. Each turbine was searched every 14 d from 15 March to 15 November each study year. A 100 m × 100 m (1.0 ha) square plot was centered around each turbine to ensure all areas within 50 m of the turbine were searched (Anderson *et al.*, 1999). We used a square plot, rather than a circular one, to facilitate marking search boundaries and conducting the search. Transects were initially set at 6 m apart in the area to be searched, and the searcher initially walked at a rate of approximately 30–45 m/min along each transect searching both sides out to 3 m for fatalities (Johnson *et al.*, 1993). Transect width and search speed were adjusted based on visibility within each habitat type. On average, approximately 30 to 45 min were spent searching each plot.

Bat fatalities found incidentally at turbines not selected for searching also were recorded. For each bat fatality found we recorded species, date and time, location, distance to nearest turbine and condition (*i.e.,* intact, scavenged, dismembered). Injuries observed were recorded during a cursory field necropsy. A subset of fresh intact bat carcasses was aged and sexed. The mean number of fatalities per turbine and associated variance were calculated using standard formulas.

Fatality search biases.—Two primary sources of bias must be accounted for to improve the accuracy of fatality estimates; these include the proportion of carcasses removed by scavengers between search intervals and the proportion of carcasses present in the search plot but not detected by the observer. We conducted carcass removal trials to estimate the length of time bat fatalities remained in the search area. The trials were conducted at randomly-selected turbine locations but not within the same turbine plots where fatality searches occurred. Four trials were conducted, each with 10 fresh hoary bat (*Lasiurus cinereus*) carcasses found during the study.

To simulate bats that were both killed or wounded by turbine collision, carcasses were placed so that they were completely exposed, hidden or partially hidden. We monitored carcasses daily for 14 d (the interval between searches for carcasses on each plot) to determine scavenger removal rates. We used estimates of carcass removal to adjust fatality counts for removal bias. The mean length of time a carcass remained in the study area before it was removed and associated variance were calculated using standard formulas. Because several bat carcasses remained at the end of 14 d, the mean length of stay was estimated using statistical methods appropriate for censored data (Shumway *et al.*, 1989). We estimated carcass removal statistics as a function of major habitat type (*e.g.*, crop field, CRP grassland, gravel pad around turbines) within each of the three wind development areas.

We conducted searcher efficiency trials in the same areas in which fatality searches occurred to estimate the percentage of bat fatalities found by searchers. Carcasses used to represent the size and color of bats during searcher efficiency trials included juvenile (<7-d old) mallards (*Anas platyrhynchos*), juvenile (7 to 14 d old) northern bobwhites (*Colinus virginianus*) and adult house sparrows (*Passer domesticus*) and European starlings (*Sturnus vulgaris*). We did not conduct searcher efficiency trials with bats due to a shortage of suitable bat carcasses and because searcher efficiency data collected at another wind plant indicated that detectability of bats was very similar to that of small birds.

Personnel conducting searches did not know the location of searcher efficiency carcasses. We placed carcasses at random locations within areas being searched for fatalities before the search on the same day. Searcher efficiency trials were spread over the entire study period to incorporate effects of varying weather and vegetation growth. We placed carcasses in a variety of exposures to simulate a range of conditions as was described for carcass removal trials. The mean proportion of placed carcasses found by searchers and associated variance were calculated using standard formulas. We used results of searcher efficiency trials to evaluate effectiveness of the fatality search effort and to make adjustments for the final estimate of the total number of fatalities. A separate searcher efficiency rate was estimated for each major habitat.

Estimating the total number of fatalities.—The proportion of each major habitat type in each turbine plot was recorded and averaged for all plots. Because virtually all bat fatalities were found within 30 m of turbines, the habitat proportions for each turbine plot were estimated based on a 120 × 120 m search plot rather than the 150 × 150 m search plot actually used. To calculate the total number of bat fatalities, we weighted values used for searcher efficiency and scavenger removal rates based on the relative proportion of each habitat type in the search plots. The estimated total number of fatalities for the wind plant, m, was calculated by:

$$m = \frac{NxIxC}{kx\bar{t}xp}$$

where N is the total number of turbines, I is the interval between searches in days, C is the total number of fatalities found during the study, k is the number of turbines sampled, $\bar{t}$ is the mean length of time fatalities remain in the study area before being removed and p is the searcher efficiency.

The variance was calculated using the variance of a product formula (Goodman, 1960) and the variance of a ratio formula (Cochran, 1977). The variance of the product t and p is:

$$V(\bar{t}xp) = \bar{t}^2 xV(p) + p^2 xV(\bar{t}) - V(\bar{t})xV(p).$$

TABLE 1.—Number and total proportion of bat carcasses found associated with turbines at Buffalo Ridge, Minnesota, in 1998 and 1999

Species	Number of carcasses	Percent of identified fatalities
Hoary Bat (*Lasiurus cinereus*)	108	66
Red Bat (*Lasiurus borealis*)	37	23
Silver-haired Bat (*Lasionycteris noctivagans*)	6	4
Eastern Pipistrelle (*Pipistrellus subflavus*)	6	4
Little Brown Bat (*Myotis lucifugus*)	5	3
Big Brown Bat (*Eptesicus fuscus*)	1	0.6
Unidentified	21	NA
Total	184	

From this, the variance of m is:

$$V(m) = \frac{N^2}{k^2} x I^2 x m^2 x \left[\frac{V(\bar{t}xp)}{\bar{t}^2 x \bar{p}^2} + \frac{V(\overline{C})}{\overline{C}^2} \right].$$

Lights on structures have shown to increase collision mortality of nocturnal avian migrants (Manville, 2001). In addition, bats often forage at artificial lights (Wilson, 1965; Barclay, 1985; Geggie and Fenton, 1985; Furlonger *et al.*, 1987) where insect numbers are highest (Hickey and Fenton, 1990). To evaluate whether lights on turbines increased the probability of bat collisions, we tested the hypothesis that bat mortality at lighted turbines was higher than at unlit turbines using a *z*-test for equality of proportions.

RESULTS

Although 13 bat fatalities were documented in the Phase 1 wind plant in 1994 and 1995 (Osborn *et al.*, 1996), we did not document any further bat mortality at this site in 1996 and 1997. In 1998, however, we found 2 dead bats in the Phase 1 study area and 76 dead bats in the Phase 2 study area which became operational in the summer of 1998. In 1999 we found 106 bat fatalities, including five in the Phase 1 wind plant, 57 in the Phase 2 wind plant and 44 in the Phase 3 wind plant that became operational in the summer of 1999.

Twenty-one of the 184 bats found during the study were too decomposed to allow for positive identification. Of the 163 bats that could be identified, hoary bats comprised 66% and eastern red bats (*Lasiurus borealis*) comprised 23% of the fatalities. The remaining fatalities were comprised of small numbers of silver-haired bats (*Lasionycteris noctivagans*), eastern pipistrelles (*Pipistrellus subflavus*), little brown bats (*Myotis lucifugus*) and big brown bats (*Eptesicus fuscus*) (Table 1).

In 1998, 37 bats collected during the study were sexed, but age data were not collected. In 1999, 21 bats were both sexed and aged following criteria in Kunz (1988). Both the hoary and eastern red bat samples were comprised primarily of males. Two of the 8 hoary and 7 of the 11 eastern red bats in the sample were juveniles (Table 2). Bat fatalities were found during the period from 20 May to 19 October; however, 177 (97%) were found from 15 July to 15 September (Table 3).

All bat casualties were found associated with turbines and appeared related to turbine collisions. Injuries sustained by bats included fractured wings, legs and necks; head wounds; abrasions and abdominal injuries. Seventy of the bats (38%) were intact, 111 (60%) were scavenged, 1 (0.5%) was dismembered and 2 (1%) were observed with injuries, but not captured.

TABLE 2.—Sex and age composition of a subsample of bat carcasses found associated with turbines at Buffalo Ridge, Minnesota, during 1998 and 1999

1998

Species	n	% male	% female	% juvenile
Hoary Bat (*Lasiurus cinereus*)	27	63	37	unknown
Eastern Red Bat (*Lasiurus borealis*)	7	57	43	unknown

1999

Species	n	% adult male	% adult female	% juvenile
Hoary Bat (*Lasiurus cinereus*)	8	63	12	25
Eastern Red Bat (*Lasiurus borealis*)	11	27	9	64

Bat fatalities were fairly widespread throughout the study area. From 1998 to 1999 dead bats were found at 33 of the 40 turbine plots randomly selected for fatality searches in the Phase 2 study area, and fatalities were found incidentally at an additional 31 turbines. In the Phase 3 wind plant, bat fatalities were found at 20 of the 30 turbines randomly selected for sampling in 1999 and at an additional eight turbines during other study activities. The largest number of bats found at any one turbine was eight at a turbine in the Phase 2 study area; these bats were found over a 1-mo period (31 July to 31 August 1998). The largest number of bats found at one time was 5 at a single turbine on 13 August 1999. Fifty-four percent of all bat carcasses were found $\leq$10 m from a turbine, 43% were found from 10 m to 20 m, 3% were found from 20 m to 30 m and one (0.5%) was found >30 m from a turbine (34.8 m). Based on distribution of bat fatalities surrounding turbines, the 100 m × 100 m search plot was more than adequate to detect all bat fatalities associated with turbines (Gauthreaux, 1996). Lighted turbines comprised 22% of all turbines in the wind plant and 18% of the bat fatalities were found at lighted turbines. The mean number of bat mortalities

TABLE 3.—Timing of bat collision fatalities at the Buffalo Ridge, Minnesota Wind Resource Area. Data from 1998 and 1999 are pooled

Time period	Number of bat fatalities found
15–31 March	0
1–15 April	0
16–30 April	0
1–15 May	0
16–31 May	1
1–15 June	0
16–30 June	0
1–15 July	1
16–31 July	45
1–15 August	57
16–31 August	39
1–15 September	36
16–30 September	2
1–15 October	1
16–31 October	2
1–15 November	0

TABLE 4.—Estimates of turbine-related bat mortality for the Buffalo Ridge, Minnesota wind development area, March through November 1996–1998

Year	No. turbines searched	No. fatalities found	Total mortality estimate[a]	90% CI	No. fatalities per turbine per year	90% CI
Phase 1 Wind plant—73 turbines						
1996	21	0	0	na[b]	0	na
1997	21	0	0	na	0	na
1998	21	2	0[c]	na	0	na
1999	21	5	19	4–33	0.26	0.06–0.46
Mean	21	2	5	1–8	0.07	0–0.49
Phase 2 Wind plant—143 turbines						
1998	40	76	231	172–290	1.62	1.21–2.03
1999	40	57	277	219–335	1.94	1.53–2.35
Mean	40	67	254	213–295	1.78	1.61–1.95
Phase 3 Wind plant—138 turbines						
1999	30	44	282	199–365	2.04	1.46–2.62

[a] Mortality estimate calculated by extrapolating the number of fatalities found at a sample of turbines to all turbines in the wind plant, and then adjusting this number upwards to take into consideration the proportion of fatalities removed by scavengers prior to the search or not detected by the searchers

[b] na = not applicable

[c] The mortality estimate was 0 because no fatalities were found on the 21 randomly-selected study plots; 2 fatalities were found at non study plots in the wind development area

at lighted turbines was not significantly higher than the mean number of fatalities at unlit turbines ($z = -1.3$, $P = 0.9$).

During the study, 306 small birds were placed for searcher efficiency trials, 29.4% (SE = 0.04) of them were detected by searchers. The 40 bat carcasses used to measure scavenger removal rates lasted an average of 10.4 d (SE = 2.6) during the summer and fall seasons. Virtually all scavenging of bat carcasses was done by insects.

One hundred fifteen (63%) of the 184 bat casualties found in 1998 and 1999 were located during scheduled fatality searches; the remainder were found during other study activities. We used only fatalities found during scheduled fatality searches to estimate mean number of fatalities per turbine and total wind plant mortality. An estimate of total bat mortality in the Phase 1 study area could not be made in 1998 because neither of the two dead bats found were located on fatality search plots. In 1999 we found three bats during scheduled fatality searches in the Phase 1 study area. For all 4 study years combined, we estimated mean annual bat mortality at the Phase 1 wind plant to be 5, which is equivalent to a mean of 0.07 collisions per turbine per year (Table 4). We estimated bat mortality in the Phase 2 wind plant to average 254 per y in 1998 and 1999, which equates to 1.78 fatalities per turbine. The estimated total bat mortality in the Phase 3 study area in 1999 was 282, which equates to a mean of 2.04 bats killed per turbine (Table 4). For all three wind plants combined, we estimate that 541 bat collision fatalities occur each year.

DISCUSSION

Bat collision mortality is not unique to wind plants or to Buffalo Ridge. Previous studies have documented bats colliding with other man-made structures. The first report was that by

Saunders (1930), who reported that five bats of three species were killed at a lighthouse in Ontario, Canada. Five eastern red bats were reported killed by colliding with a television tower in Kansas (Van Gelder, 1956). Small numbers (≤ 5) of eastern red bat collision victims have also been reported at communication towers in Missouri (Anonymous, 1961), North Dakota (Avery and Clement, 1972), Tennessee (Ganier, 1962) and Saskatchewan, Canada (Gollop, 1965). One yellow bat (*Lasiurus intermedius*) collision victim was found at a Florida TV tower (Taylor and Anderson, 1973). During 25 y of monitoring a television tower in Florida, Crawford and Baker (1981) found 54 bat collision victims representing seven species. Over an 8-y period, 50 eastern red, 27 silver-haired, 1 hoary and 1 little brown bat collision victims were found underneath large windows at a convention center in Chicago, Illinois (Timm, 1989). Bats have also been documented colliding with powerlines (Dedon *et al.*, 1989) and fences (Iwen, 1958; Denys, 1972; Wisely, 1978).

Mortality at wind plants was first documented in Australia, where 22 white-striped mastiff-bats (*Tadarida australis*) were found at the base of turbines over 4-y (Hall and Richards, 1972). In 1999, 45 dead bats were found at a wind plant in Carbon County, Wyoming, 10 dead bats were found at a wind plant in Umatilla County, Oregon, and 34 dead bats were found within a 31-turbine wind plant in Wisconsin (Keeley *et al.*, 2001). Small numbers of dead bats have also been found at wind plants in California (Orloff and Flannery, 1992; Howell, 1997; Anderson *et al.*, 2000; Thelander and Rugge, 2000) and Colorado (R. Ryder, Colorado State University, pers. comm.). Most bat mortality documented at other wind plants occurred in late summer and early fall and involved tree bats, with hoary bats being the most prevalent fatality.

The near absence of collision mortality in June and early July when resident bats are breeding in Minnesota (Hazard, 1982) indicates that resident populations are not being impacted by the wind plant. Based on the timing of fall migration of hoary, red and silver-haired bats (Findley and Jones, 1964; LaVal and LaVal, 1979; Izor, 1979; Koehler and Barclay, 2000) as well as fall dispersal of eastern pipistrelles, little brown bats and big brown bats (Barbour and Davis, 1969; Humphrey and Cope, 1976), most of the collision mortality apparently involves migrant or dispersing bats. The presence of lighting on turbines did not increase the number of bat collision fatalities at the Buffalo Ridge wind plant.

Data collected by Koehler and Barclay (2000) in Manitoba indicate that hoary bats should be migrating through the Buffalo Ridge area in mid to late May if they follow similar routes in the spring and fall, yet we found only 1 fatality in May. Plots of museum occurrence records of hoary bats indicate extremely low densities of this species in Minnesota in May, with much higher densities in July and August. A similar pattern occurs for eastern red bat, whereas silver-haired bat abundance is fairly similar from mid May through mid September (P. Cryan, University of New Mexico, pers. comm.) These data indicate that hoary and red bats may use different migration corridors in the spring and fall, as do some species of birds (*e.g.,* Richardson, 1974, 1976). Behavioral differences between migrating hoary bats in the spring and fall also may be related to mortality patterns. Such differences have been reported; in Florida, autumn migration of hoary bats occurred in waves whereas the spring migration appeared to be far more scattered and less organized (Zinn and Baker, 1979).

The cause of bat collisions with wind turbines or other man-made structures is not well understood (Osborn *et al.*, 1996). According to Van Gelder (1956), most bat collisions at other man-made structures occur during migration and are normally associated with inclement weather and avian collision mortalities. However, at a communication tower in Florida, bat fatalities were found largely in the absence of associated avian mortalities (Crawford and Baker, 1981), and at Buffalo Ridge, we found very few avian fatalities during the time frame that most bat fatalities occurred. Migrating bats may navigate without use of echolocation (Crawford and Baker, 1981). Bats have good visual acuity (Suthers, 1966, 1970) and evidence indicates that bats depend on vision, rather than echolocation, for long-distance orientation (Mueller, 1968; Williams and Williams, 1970). If bats are flying through wind plants on Buffalo Ridge by sight only, then causes of bat mortality could be similar to causes of avian collision mortality at wind plants.

Potential population effects of wind power-related mortality cannot be quantified with available data. Based on the bat mortality documented at Buffalo Ridge, as well as at other wind plants in the United States, the potential for wind plants to impact bat populations should be addressed when siting new facilities, especially in areas where threatened or endangered bat species may occur. The wind power and utility industries are currently funding studies to examine bat mortality at wind plants. Future research should concentrate on determining the causes of collisions, potential population effects and development of mitigation strategies to avoid or minimize bat mortality at wind plants.

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