Invited Paper

Patterns of Bat Fatalities at Wind Energy Facilities in North America

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ABSTRACT Wind has become one of the fastest growing sources of renewable energy worldwide, but widespread and often extensive fatalities of bats have increased concern regarding the impacts of wind energy development on bats and other wildlife. We synthesized available information on patterns of bat fatalities from a review of 21 postconstruction fatality studies conducted at 19 facilities in 5 United States regions and one Canadian province. Dominance of migratory, foliage- and tree-roosting lasiurine species (e.g., hoary bat [*Lasiurus cinereus*]) killed by turbines was consistent among studies. Bat fatalities, although highly variable and periodic, consistently peaked in late summer and fall, coinciding with migration of lasiurines and other species. A notable exception was documented fatalities of pregnant female Brazilian free-tailed bats (*Tadarida brasiliensis*) in May and June at a facility in Oklahoma, USA, and female silver-haired bats (*Lasionycteris noctivagans*) during spring in Tennessee, USA, and Alberta, Canada. Most studies reported that fatalities were distributed randomly across turbines at a site, although the highest number of fatalities was often found near the end of turbine strings. Two studies conducted simultaneously in the same region documented similar timing of fatalities between sites, which suggests broader patterns of collisions dictated by weather, prey abundance, or other factors. None of the studies found differences in bat fatalities between turbines equipped with lighting required by the Federal Aviation Administration and turbines that were unlit. All studies that addressed relationships between bat fatalities and weather patterns found that most bats were killed on nights with low wind speed (<6 m/sec) and that fatalities increased immediately before and after passage of storm fronts. Weather patterns may be predictors of bat activity and fatality; thus, mitigation efforts that focus on these high-risk periods could reduce bat fatality substantially. We caution that estimates of bat fatality are conditioned by length of study and search interval and that they are biased in relation to how searcher efficiency, scavenger removal, and habitat differences were or were not accounted for. Our review will assist managers, biologists, and decision-makers with understanding unifying and unique patterns of bat fatality, biases, and limitations of existing efforts, and it will aid in designing future research needed to develop mitigation strategies for minimizing or eliminating bat fatality at wind facilities. (JOURNAL OF WILDLIFE MANAGEMENT 72(1):61–78; 2008)

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As concerns about climate change (see review in Inkley et al. 2004) and increasing costs and long-term environmental impacts from the use of fossil fuels have heightened (McLeish 2002), wind has become an increasingly important sector of the energy industry and one of the fastest growing sources of renewable energy (Pasqualetti et al. 2004). Wind-generated electricity is renewable and generally considered environmentally clean, and recent technological advances and tax subsidies have allowed commercial wind generation to compete with energy produced from fossil fuels and nuclear power (Gipe 1995, Redlinger et al. 2002). Unfortunately, fatalities of bats have been recorded at wind facilities worldwide, including Australia (Hall and Richards 1972), North America (Johnson et al. 2003*a*, *b*, 2004; Fiedler 2004; Arnett 2005), and Europe (Ahlen 2002, Bach and Rahmel 2004, Dürr and Bach 2004, Brinkman 2006). Small numbers of bats were first recorded in the United States at wind energy projects in California, USA, during avian fatality searches (Orloff and Flannery 1992, Thelander and Rugge 2000). However, bat fatalities at wind energy facilities generally received little attention in North America until 2003 when an estimated 1,400–4,000 bats were killed at the Mountaineer Wind Energy Center in West Virginia, USA (Kerns and Kerlinger 2004). High bat fatalities continued at the Mountaineer facility in 2004, and large kills also have been reported at facilities in Pennsylva-

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nia, USA, and Tennessee, USA (Fiedler 2004, Arnett 2005). Although bats collide with other tall anthropogenic structures, the frequency and magnitude of fatalities is much lower than those observed at wind turbines (Arnett 2005, Cryan and Veilleux 2007). These fatalities raise concerns about potential impacts on bat populations at a time when many species of bats are known or suspected to be in decline and extensive planning and development of wind energy is increasing worldwide (Pierson 1998, Racey and Entwistle 2003, Winhold and Kurta 2006, Energy Information Administration 2007, Kunz et al. 2007).

Postconstruction fatality searches at wind facilities originally were designed to monitor annual or seasonal avian fatality rates, primarily for large raptors (Erickson et al. 2002). Since the recent discovery of high bat fatalities at wind facilities in the eastern United States, however, postconstruction monitoring has intensified, and most permitting agencies now require estimates of bat fatalities. Sampling designs and methods for conducting fatality searches are well established (Anderson et al. 1999, Morrison et al. 2001). Important sources of field sampling biases must be accounted for to correct estimates of fatality and include 1) fatalities that occur on a highly periodic basis, 2) carcass removal by scavengers, 3) searcher efficiency, 4) failure to account for the influence of site (e.g., vegetation) conditions in relation to carcass removal and searcher efficiency (Wobeser and Wobeser 1992, Philibert et al. 1993, Anderson et al. 1999, Morrison 2002), and 5) fatalities or injured bats that may land or move outside search plots.

Most estimators assume fatalities occur at uniformly distributed, independent random times between search days. However, if the distribution of fatalities is highly clustered, then estimates may be biased, especially if carcass removal rates are high. Searches, especially those conducted at the least frequent intervals (e.g., 14 days and 28 days), may result in highly biased estimates of fatalities if scavenging rates are high and poorly accounted for (Morrison 2002, Kerns et al. 2005). It also is well known that searcher efficiency or observer detection (i.e., the rate at which searchers detect carcasses) varies among individuals (Morrison et al. 2001). Searcher efficiency and carcass scavenging should be expected to vary considerably within and among different vegetation cover conditions (Wobeser and Wobeser 1992, Philibert et al. 1993, Anderson et al. 1999, Morrison 2002). Additional factors affecting the precision and accuracy of fatality estimates include search effort, including the number of turbines searched, intensity of searches within search plots, and the experience of observers (Anderson et al. 1999).

Documenting patterns of bat fatality is fundamental to understanding bat interactions with turbines, the timing and predictability of fatality, and in developing solutions to reduce or eliminate fatalities. Few postconstruction studies on bat fatalities had been conducted in North America before 2004 (Johnson 2005), and, unfortunately, the majority of empirical data from wind facilities around the world reside in unpublished reports. Synthesizing what little information exists on bat fatalities would be useful for identifying patterns and information gaps and for developing hypotheses for field testing. Dürr and Bach (2004) and Bach and Rahmel (2004) reviewed data from studies in Germany, and they concluded that knowledge of factors influencing bat fatality is unsatisfactory. Johnson (2005) reviewed 11 studies on bat fatalities at wind energy facilities in the United States and discussed patterns of species composition and seasonal timing of fatalities. Here, we synthesize available information on bat fatalities from 21 studies conducted at 19 wind energy facilities in 5 regions of the United States and one province in Canada. Our objective was to present unifying and unique patterns from these studies; discuss the scope, biases, and limitations of existing efforts; identify information gaps; and offer suggestions for future research needed to develop mitigation strategies for minimizing or eliminating bat fatality at wind facilities.

A REVIEW OF EXISTING LITERATURE

We synthesized information from existing wind facilities in North America with regard to characteristics of surrounding habitat; turbines used; duration of studies; methods used; how field sampling biases were accounted for; and patterns of fatality in relation to species, gender, temporal and spatial relationships, and weather (Appendix A). We only used data from studies published in scientific journals or unpublished reports that were publicly available through an agency or organization. We categorized studies by geographic region following Johnson (2005) and Kunz et al. (2007).

We present analytical results from individual studies, and we did not attempt to develop our own estimates of fatalities using data from these studies or perform statistical analyses of observed patterns using, for example, meta-analytic approaches. We only report estimates of fatalities where bias corrections (e.g., searcher efficiency and carcass removal) were quantified and used to adjust estimates (Erickson et al. 2001, Morrison 2002). However, we caution that studies had varying levels of effort, used different methods to quantify bias, sometimes had low sample sizes for both the numbers of trials and carcasses used, engaged birds as surrogates for bats, and rarely accounted for variation in searcher efficiency and carcass removal among habitat and visibility conditions (Appendices B, C). We reported estimated fatalities per turbine from each study and calculated estimates per megawatt (MW) by dividing the number of fatalities per turbine by the MW capacity of each type of turbine. Additionally, as another means of standardizing results among studies and turbine sizes, we report fatalities per 2,000 m^2 of rotor-swept area, which we calculated by multiplying the number of fatalities per turbine by 2,000 and dividing by the total rotor-swept area for each type of turbine. The last 2 metrics standardize results among different size and numbers of turbines, providing a more appropriate metric for comparison among facilities. We present patterns of fatalities in relation to species and sex composition, temporal and spatial relationships, influence of lighting, and weather for all studies reporting these data.

KEY FINDINGS FROM STUDIES IN NORTH AMERICA

Our review of 21 studies from 19 different wind energy facilities in 5 regions in the United States and one province in Canada (Appendix A) indicates that number, type and size of wind turbines, and habitats sampled varied considerably among facilities (Appendix B). The majority of facilities had one size and type of turbine, but 2 sites (Buffalo Mountain, TN, and Buffalo Ridge, MN, USA) had 2 types of turbines operating. Most (16 of 21; 76%) facilities were located within agricultural cropland or landscapes with mixed habitats that included cropland, grazed and ungrazed grasslands, pasture, woodlots, or habitats set aside by Conservation Reserve Program, and 2 facilities (10%) occurred exclusively in short grass prairie (Appendix B). Only 3 facilities (15%) were located in completely forested habitats on ridges, all of which were in the eastern United States in deciduous forest.

Characteristics of Studies and Factors Influencing Estimates of Bat Fatality

Twelve (57%) studies were conducted for <12 months and included either one spring or fall season or one of each, whereas 9 studies were conducted for ≥ 2 spring or fall seasons during ≥ 2 years (Appendix B). The 2 efforts of the longest duration occurred at Buffalo Mountain in Tennessee (36 months; Nicholson 2003, Fiedler 2004, Fielder et al. 2007) and Buffalo Ridge in Minnesota (48 months; Osborn et al. 1996; Johnson et al. 2003*a*, 2004). Ten (50%) studies used 14–28-day intervals between searches at each turbine, and 5 studies used ≥ 2 different intervals during the study (Appendix C). Daily searches were performed at half the turbines at each of 2 facilities, one each in Pennsylvania and West Virginia, but only covered a 6-week period from 31 July to 13 September (Kerns et al. 2005; Appendix C). Daily searches also were conducted at 10 of 120 turbines at one facility in New York, USA (10 of 120 turbines were searched on 3-day intervals, and 30 of 120 turbines were searched at 7-day intervals; Jain et al. 2007).

Only 8 studies used bat carcasses to quantify searcher bias and scavenger removal, and most other studies used previously frozen birds as surrogates for bats when performing the bias correction trials (Appendix C). Searcher efficiency ranged from 25% to 75%, and it was lowest in forested sites in the eastern United States (25–42%) and generally was highest in more open habitats in the western United States and Canada (42–75%). Bat carcasses lasted 1.9–12 days, on average, during removal trials; birds lasted as long as 23 days, on average (Appendix C).

Most studies calculated an overall bias correction factor for the entire study period and across different habitat conditions. Kerns et al. (2005) estimated searcher efficiency and carcass removal for each of 3 strata that corresponded to high-, moderate-, and low-visibility habitats and estimated the overall mean number of fatalities per turbine, summing individual estimates calculated for each stratum.

Table 1. Estimates of mean bat fatalities per turbine, per megawatt (MW) of energy produced per turbine, and per 2,000 m^2 of rotor-swept area for 21 studies at 19 wind facilities in North America, 1996–2006.

Study area location[a]	Estimated mean fatality/ turbine	Estimated mean fatality/MW	Estimated mean fatality/2,000-m^2 rotor-swept area
Canada			
CRAB	0.5	0.8	0.6
MLAB	0.5	0.7	0.5
SVAB	18.5	10.6	7.4
Eastern USA			
BMTN1[b]	20.8	31.5	24.0
BMTN2[b]	35.2	53.3	40.6
BMTN2[c]	69.6	38.7	27.7
MRNY1[d]	24.5	14.9	9.4
MYPA[d]	23.0	15.3	11.3
MTWV1	48.0	32.0	23.6
MTWV2[d]	38.0	25.3	18.7
Rocky Mountains, USA			
FRWY	1.3	2.0	1.9
Pacific Northwest, USA			
HWCA	3.4	1.9	1.4
KLOR	1.2	0.8	0.6
SLOR	1.1	1.7	1.3
VAOR	0.7	1.1	0.8
NCWA	3.2	2.5	2.1
Midwestern USA			
BRMN1[e]	0.1	0.2	0.2
BRMN2[f]	2.0	2.7	2.4
BRMN3[g]	2.1	2.7	2.3
LIWI	4.3	6.5	5.0
TOIA	7.8	8.7	7.4
South-central USA			
WOOK[h]	1.2	0.8	0.7

[a] See Appendix A for study area abbreviations.
[b] Estimated bats killed by 3 0.66-MW turbines.
[c] Estimated bats killed by 15 1.8-MW turbines.
[d] Estimated bats killed from daily searches conducted at these facilities.
[e] Estimated bats killed by 73 0.33-MW turbines based on 4 yr of data.
[f] Estimated bats killed by 143 0.75-MW turbines based on 4 yr of data.
[g] Estimated bats killed by 138 0.75-MW turbines based on 3 yr of data.
[h] Estimated mean over 8 surveys in 2 yr.

Estimates of Bat Fatalities

We again caution that patterns and estimates of fatalities we report are conditioned by length of study and search interval and that all were calculated differently and are biased in relation to how each study did or did not account for sources of field sampling bias (Appendix C). Estimates of bat fatalities were highest at wind energy facilities located on forested ridges in the eastern United States and lowest in the Rocky Mountain and Pacific Northwest regions (Table 1). Bat fatalities seemed more variable among sites in the upper midwestern United States, with estimates ranging from 0.2 bats to 8.7 bats/MW. In southwestern Alberta, Canada, 3 sites that had similar vegetation and topographic composition and that were in proximity to one another had dramatically different estimates of bat fatalities. Bat fatalities collected in 2005 at the Summerview facility were estimated to be 14.1 times greater, on average, than at the other 2 nearby facilities (Table 1), and high fatalities were again

Table 2. Percentage of species[a] composition of bat fatalities at wind facilities in North America, 1996–2006 (modified from Johnson 2005).

Study location[b]	EPFU	LABL	LABO	LACI	LANO	MYLU	MYSE	PISU	TABR	Other	Total no. bats found	% of total no. of species[c]
Canada												
CRAB				57.7	13.4	23.1				5.8	52	33
MLAB	1.9			87.0	1.9	9.2					54	44
SVAB	0.8		0.2	45.9	51.1	1.1				0.9	532	56
Eastern United States												
BMTN1	0.9		60.5	9.6	1.8			25.4		1.8[d]	114	40
BMTN2	0.4		60.9	13.0	7.6			17.2		0.8[d]	238	40
MRNY1	5.4		13.0	45.9	14.6	13.5				7.6	384	56
MYPA	6.9		27.5	45.4	5.7	2.7	0.7	8.0		0.5	262	78
MTWV1	0.4		42.1	18.5	5.9	12.6	1.3	18.3		0.8	475	54
MTWV2	2.5		24.1	33.7	4.8	9.8		24.6		0.5	398	54
Rocky Mountains, USA												
FRWY	1.5			88.1	3.7	4.4				2.2[e]	135	25
Pacific Northwest, USA												
HWCA		4.3		64.3					41.3		70	14
KLOR				50.0	16.7					33.3[e]	6	13
SLOR	1.6			46.1	50.0	0.8				1.6[e]	128	33
VAOR				50.0	30.0	10.0				10.0[e]	10	20
NCWA				44.0	56.0						27	13
Midwestern United States												
BRMN 1–3	3.6		17.4	65.0	4.8	1.9		1.7		5.7[e]	420	86
LIWI	1.4		38.9	34.7	16.7					8.3	72	57
TOIA	10.7		24.0	28.0	12.0	24.0		1.3			75	66
South-central United States												
WOOK	0.9		2.7	9.0	0.9			0.9	85.6	0.9	111	34

[a] EPFU = big brown bat; LABL = western red bat; LABO = eastern red bat; LACI = hoary bat; LANO = silver-haired bat; MYLU = little brown bat; MYSE = northern long-eared bat; PISU = eastern pipistrelle; TABR = Brazilian free-tailed bat.

[b] See Appendix A for study area abbreviations.

[c] % of the total no. of species known to occur in each state or province known to have been killed by wind turbines.

[d] At BMTN, 3 Seminole bats were killed (2 in Sep 2003 and 1 in Oct 2005).

[e] Unidentified species.

recorded at Summerview in 2006 (E. Baerwald and R. M. R. Barclay, University of Calgary, unpublished data). Estimates from the only study conducted in the south-central United States were <1 bat/MW, but only 2 searches were performed at each turbine in May and June for each of 2 years of study (Piorkowski 2006).

Composition of Bat Fatalities

Species composition.—Of the 45 species of bats that occur north of Mexico, 11 were reported killed at wind energy facilities (Johnson 2005, Kunz et al. 2007). On a state-by-state or provincial basis, the proportion of the number of species found killed at wind facilities ranged from 11% to 86% of the number of species known to occur in the state or province (Table 2). In most regions and individual studies, bat fatalities seemed heavily skewed to migratory foliage-roosting species that included the hoary bat (*Lasiurus cinereus*), eastern red bat (*Lasiurus borealis*), and migratory tree and cavity-roosting silver-haired bat (*Lasionycteris noctivagans*; Table 2). Hoary bats constituted high proportions of fatalities at most facilities (range = 9–88.1%; Table 2). Silver-haired bats were found more frequently in Canada, Iowa, USA, and the Pacific Northwest relative to the eastern United States, whereas eastern red bats were commonly found in eastern forested sites and in the midwestern United States. Eastern pipistrelles (*Pipistrelles subflavus*) constituted as much as 25.4% of fatalities at facilities in the eastern United States (Table 2). Fatalities of summer resident species, including little brown bats (*Myotis lucifugus*) and big brown bats (*Eptesicus fuscus*), usually were low (0–13.5%), except at one site each in Canada and Iowa, where little brown bats made up nearly 25% of the fatalities. The only 2 investigations at wind facilities within the range of the Brazilian free-tailed bat (*Tadarida brasiliensis*) reported high proportions of fatalities of that species (41.3% and 85.6% in CA and OK, respectively). The Brazilian free-tailed bat is a long-distant migrant that roosts colonially in caves. No studies were reported in Texas, USA, or New Mexico, USA, where large colonies of Mexican free-tailed bats (*Tadarida brasiliensis*) were known to reside, and several wind energy facilities were in operation (Kunz et al. 2007).

No study reported a species of bat listed as threatened or endangered under the Endangered Species Act killed at a wind facility. However, there were few facilities operating within the range of threatened and endangered species such as the Indiana bat (*Myotis sodalis*). In Canada, 3 of the species (hoary, silver-haired, and eastern red bats) found killed at wind facilities were considered to be of special management concern provincially.

Age and sex.—Few studies reported age and sex composition of bat carcasses found at wind facilities, and many carcasses could not be identified to age or sex due to

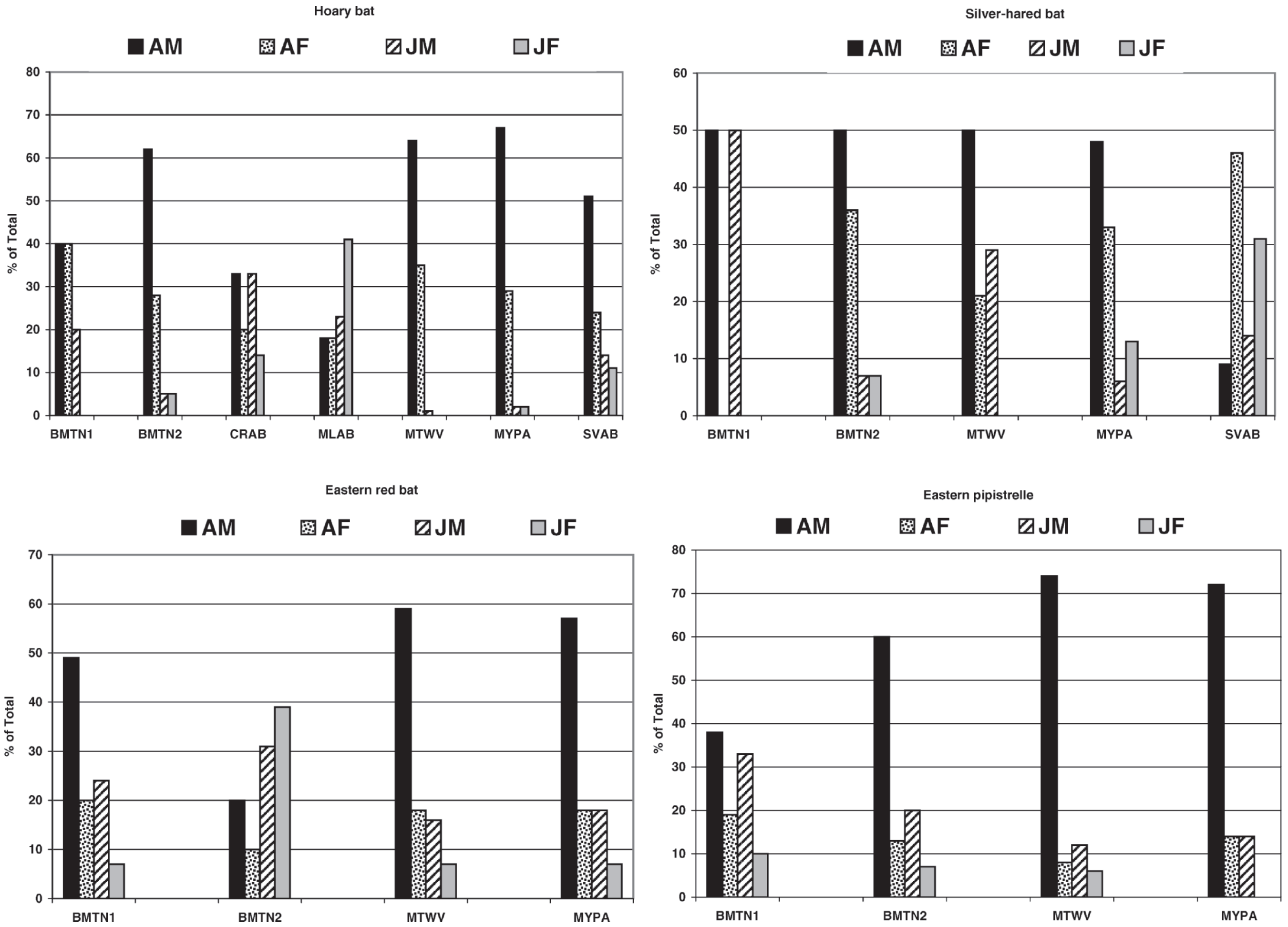

Figure 1. Percentage of adult male (AM), juvenile male (JM), adult female (AF), and juvenile female (JF) bat fatalities for hoary bats, eastern red bats, silver-haired bats, and eastern pipistrelle found at wind energy facilities (see Appendix A) in North America, 1996–2006.

decomposition and scavenging by insects. Fatalities were skewed toward males of the 4 most commonly killed species at most facilities (Fig. 1). However, preliminary data suggest the converse may be true in Oklahoma with Mexican free-tailed bats (Piorkowski 2006). In Canada, female silver-haired bats were killed more frequently than males, whereas the opposite was true for hoary bats. Although it is intuitive that inexperienced juveniles could be more susceptible to collisions with wind turbines, data generally do not support this hypothesis. Theoretically, there should at least be an equal number of young versus adult males in lasiurine populations, assuming sex ratios at birth are equal in hoary bats, silver-haired bats, and eastern pipistrelles that have litter sizes of 2 bats (Kunz 1982, Shump and Shump 1982*b*, Barclay and Harder 2003). Because red bats produce an average litter of 4 bats (Kunz 1982, Shump and Shump 1982*a*, Ford et al. 2001), there should be twice as many young red bats as adult red bats. Thus, it seems more likely that there could be differential probability of attraction to or collision with turbines between adults and juveniles, especially male lasiurines. An exception was Buffalo Mountain in Tennessee in 2005 where juveniles often were killed at equal or higher rates than adults for red bats, silver-haired bats, and eastern pipistrelles (Fig. 1; Fiedler et al. 2007).

Temporal Patterns of Bat Fatalities

Seasonal timing of fatality.—The highest bat fatalities at wind energy facilities were consistently reported during late summer and early fall (Johnson 2005, Kunz et al. 2007), although few studies spanned the entire season when bats are active (generally Apr–Nov). In Iowa, the temporal distribution of fatalities peaked in August, with substantial numbers in July and September. At all 3 facilities in Alberta, numbers of bat fatalities increased in early August, peaked in late August, and ended in early October. At Buffalo Mountain in Tennessee, 75% of bat fatalities occurred between 1 August and 15 September. In 2005, the peak was very pronounced, with 61% of fatalities occurring between 15 and 30 August, whereas fatalities were more dispersed during 2000–2003, with 96% occurring during an 88-day period centered on 22–23 August (Fiedler et al. 2007). Trends in bat activity during 2002 and 2003 in Tennessee, as measured by acoustic detectors, supported seasonal patterns of fatality; bat activity levels quadrupled by mid-August, after beginning to increase in mid-July to early August, and then decreased to previous levels by early to

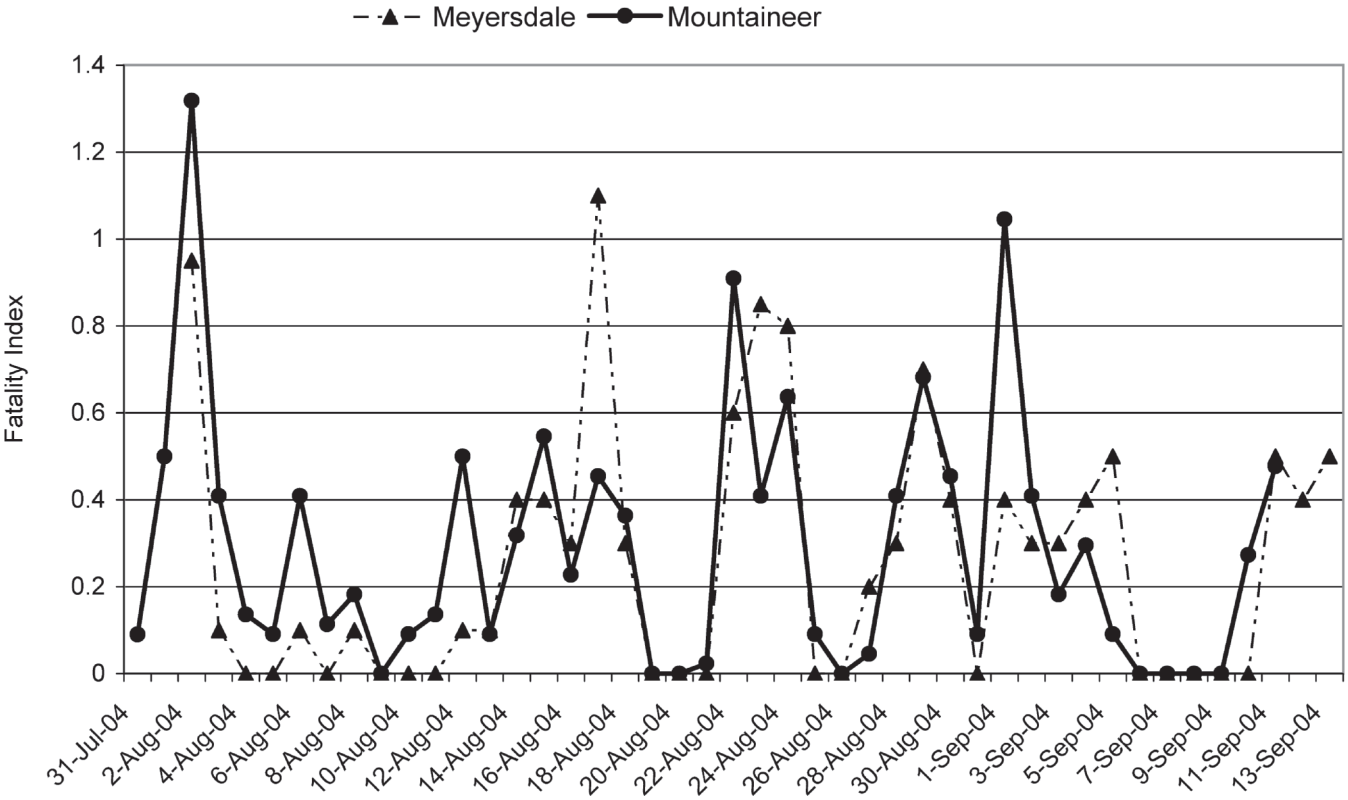

Figure 2. Daily bat fatalities (no. of fresh bat fatalities/no. of turbines searched) from the Mountaineer Wind Energy Center in West Virginia, USA (31 Jul–11 Sep 2004) and the Meyersdale Wind Energy Center in Pennsylvania, USA (2 Aug–13 Sep 2004; Kerns et al. 2005). Fatality index is the total number of fresh bats found on a given day divided by the number of turbines searched that day.

mid-September (Fiedler 2004). In New York, Jain et al. (2007) found that bat fatalities were low in the mid-June, peaked from mid-July to mid-August, and then declined precipitously through mid-November. Studies from Germany also supported this pattern of seasonal fatality during the fall migration period (Dürr and Bach 2004, Brinkmann 2006).

Of 272 silver-haired bat fatalities at Summerview in Alberta, 16 (6%) occurred in May and June, suggesting spring migratory fatalities occurred, at least in this region. In Tennessee, 16 of 19 (84%) silver-haired bats killed were found between mid-April and early June, supporting similar findings in Alberta and the contention that fatalities at wind facilities can be anticipated during spring migration, at least for silver-haired bats.

Timing of fatalities between sites.—Only one study to date conducted fatality searches simultaneously at multiple sites within a region to evaluate temporal patterns between sites. In 2004, Kerns et al. (2005) conducted daily fatality searches from 1 August to 13 September at the Mountaineer and Meyersdale Wind Energy Center in West Virginia and Pennsylvania, respectively. Although fatalities were highly variable and periodic throughout the study, the timing of all bat fatalities at the 2 sites was highly correlated (Fig. 2; Kerns et al. 2005). Additionally, the timing of hoary and eastern red bat fatalities was positively correlated at Mountaineer and Meyersdale (Fig. 3; Kerns et al. 2005).

Spatial Patterns of Bat Fatality

Identifying spatial patterns of bat fatalities among turbines within a facility is important for developing mitigation strategies to reduce or eliminate fatalities. For example, if fatalities are concentrated at specific turbines, then turbine-specific mitigation strategies, such as curtailment, removal, or relocating the turbine, may reduce bat fatalities; however, if fatalities are broadly distributed, then facility-wide mitigation strategies must be considered. Very few studies reported information on patterns of fatalities among turbines. At the Mountaineer and Meyersdale facilities, bat fatalities were distributed across all turbines, although higher than average numbers of bats generally were found at turbines located near an end or center of the array at both sites (Kerns et al. 2005). Fiedler (2004) found that all 3 turbines studied at Buffalo Mountain in Tennessee killed the same number of bats. In a follow-up study, Fiedler et al. (2007) found that bat fatalities were again equally distributed among the 3 0.66-MW turbines originally studied and among 15 newer 1.8-MW turbines installed at the Buffalo Mountain site. Fielder et al. (2007) did observe a general north-south trend of bat fatalities. Mean number of estimated bat fatalities at 10 1.8-MW turbines on the northern ridge ($\bar{x} = 29.0$) was greater than at 2 of these same turbines on the southernmost ridge ($\bar{x} = 11.6$) and slightly greater than at the 3 on the middle ridge ($\bar{x} = 23.4$), although the differences were not statistically significant (Fiedler et al. 2007). In Alberta, Brown and

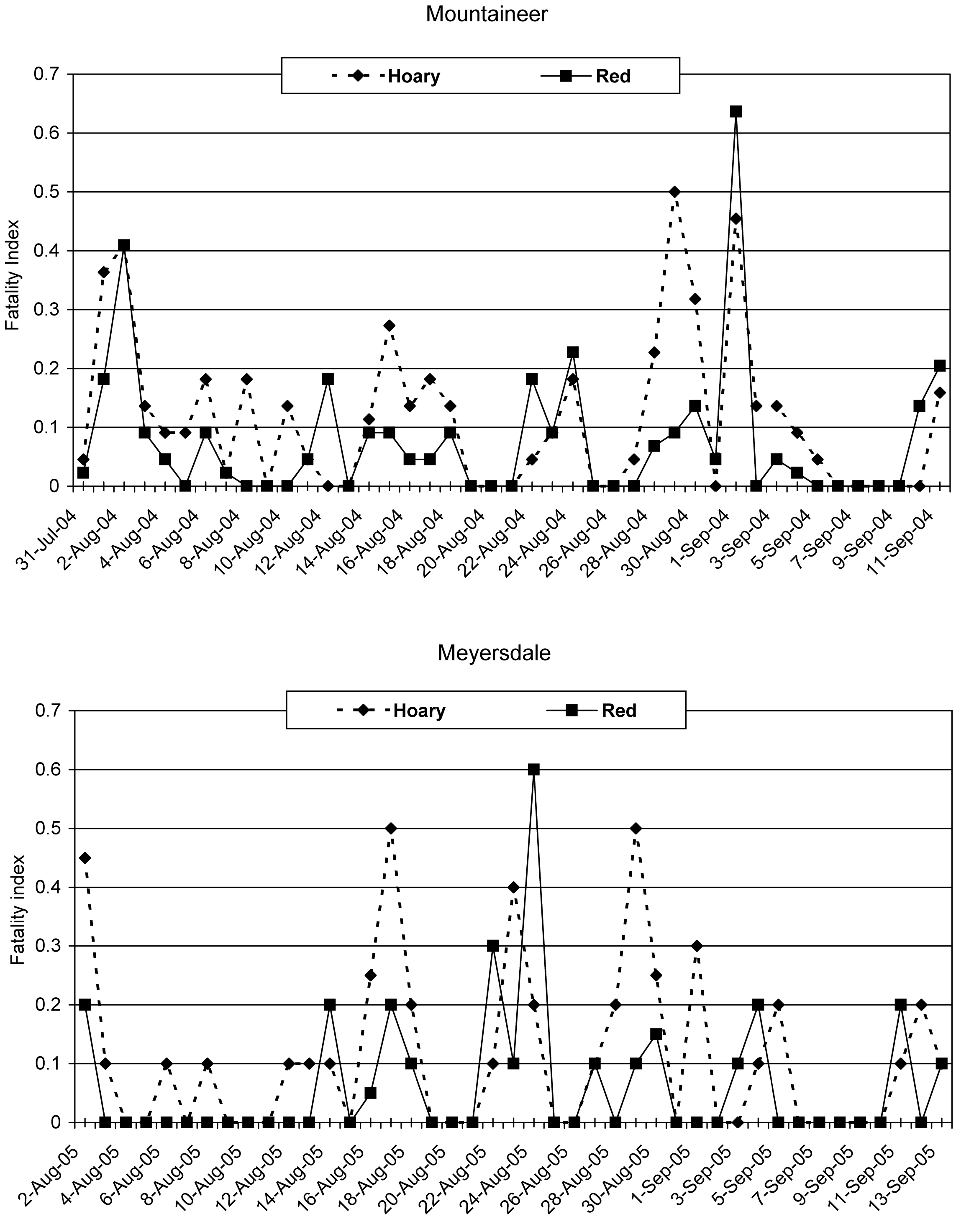

Figure 3. Daily bat fatalities (no. of fresh bat fatalities/no. of turbines searched) of hoary and eastern red bats from the Mountaineer Wind Energy Center in West Virginia, USA (31 Jul–11 Sep 2004) and the Meyersdale Wind Energy Center in Pennsylvania, USA (2 Aug–13 Sep 2004; Kerns et al. 2005). Fatality index is the total number of fresh bats found on a given day divided by the number of turbines searched that day.

Hamilton (2002, 2006*a*, *b*) found no discernible patterns of collisions at any of the wind facilities studied, and fatalities were not significantly greater at end-row or mid-row turbines, although preliminary findings from a new study at Summerview suggest a possible north-south trend in fatalities (R. M. R. Barclay and E. Baerwald, personal communication).

If fatalities are related to habitat or topographic characteristics, then understanding these relationships may help in developing mitigation strategies (e.g., avoiding placement of turbines near open water sources or a known cave roost). Many wind energy facilities occur in settings with too little habitat or topographic variation among turbines to allow an evaluation of landscape relationships with bat fatalities, but some facilities did allow such examination. In Minnesota, Johnson et al. (2004) did not find a significant relationship between the number of bat fatalities and any of the 10 cover types within 100 m of turbines. Moreover, Johnson et al. (2004) found no relationship between fatalities and distance to nearest wetland or woodlot. In Oklahoma, USA, Piorkowski (2006) found that fatalities of Brazilian free-tail bats were closely associated with wooded ravines in May and June 2004, but he did not observe this pattern in 2005. Jain et al. (2007) examined the relationship between the number of bat fatalities and distance to wetlands, and they found no significant relationship from daily and 3-day carcass searches, but they did find a significant negative relationship between number of fatalities and distance to wetlands for 7-day searches, thus offering some support for the suggestion that turbines located closer to wetlands may kill more bats. No other studies we reviewed reported associations with landscape or topographic features. In Germany, Brinkmann (2006) did not find relationships between bat fatalities and location of turbines in different habitats or altitudes.

Relationships Between Turbine Size and Bat Fatality

The height and dimensions of the rotor-swept area of turbines seemed to have some influence on bat fatality. During the second phase of study at Buffalo Mountain in Tennessee, 0.66-MW turbines that had 65-m-tall towers and 1,735-m^2 rotor-swept area killed fewer bats per turbine but more bats per MW than adjacent 1.8-MW turbines with 78-m towers and nearly 3 times the total rotor-swept area (Table 1). At the Buffalo Ridge site in Minnesota, taller turbines with greater rotor-swept areas killed more bats per turbine and per MW compared with smaller turbines. In Alberta, estimated fatalities were 14.1 times fewer, on average, at 2 facilities with 0.66-MW turbines with 50-m-tall towers and 1,735-m^2 rotor-swept area, compared with one facility with 1.8-MW turbines with 65-m towers and 5,027-m^2 rotor-swept area (Table 1). However, these sites were not sampled simultaneously during the same years, and this difference could have resulted from annual variation or some other factor. Interestingly, the 0.66-MW turbines used in Canada were mounted on 50-m monopoles, compared with 65-m-tall turbines used on the same type of turbine at Buffalo Mountain, Tennessee, where considerably higher numbers of fatalities were observed, which offers some support for the hypothesis that taller turbines may kill more bats (Barclay et al. 2007).

Relationships Among Turbine Operation, Weather, and Bat Fatality

Of the 64 turbines studied at the Mountaineer and Meyersdale facilities, one (turbine 11 at Mountaineer) was nonoperational throughout the study period, and it was the only turbine where no fatalities were observed in 2004 (Kerns et al. 2005). Searches at this same turbine with Labrador retrievers trained to find dead bats also found no bat fatalities (Arnett 2005, 2006). Additionally, none of the studies we reviewed reported bat fatalities associated with meteorological towers. These findings support the contention that bats collide with spinning turbine blades and that they do not strike stationary blades or towers (Arnett 2005).

Kerns et al. (2005) reported that the majority of bats were killed on low wind nights when power production seemed insubstantial but turbine blades were still moving, often at or close to full operational speed (17 revolutions/min; Arnett 2005, Horn et al. 2008). At the Meyersdale, Pennsylvania, and Mountaineer, West Virginia, sites, 82% and 85% of the bat fatalities, respectively, were estimated to have occurred on nights with median nightly wind speeds of <6 m/sec. The proportion of 10-min intervals from 2000 hours to 0600 hours when wind speed was <4 m/sec was positively related to bat fatalities at Mountaineer and Meyersdale, whereas the proportion of the night when winds were >6 m/sec was negatively associated with bat fatalities at both facilities (Fig. 4; Kerns et al. 2005). At Mountaineer and Meyersdale, median nightly wind speed was on average >6 m/sec during >81% of nights when no bats were found the next day (Table 3). Conversely, on nights before days when the highest numbers of bats were found, median nightly wind speed was 4.1 m/sec at Mountaineer and 4.2 m/sec at Meyersdale, and only 6.5–18.2% of these nights had wind speeds >6 m/sec (Table 3). In Iowa, maximum wind speeds during the intersearch periods in which bat fatalities occurred ranged from 2.4 m/sec to 5.3 m/sec (Jain 2005).

Kerns et al. (2005) also found a negative relationship between bat fatalities and percentage of the night that rain occurred (an index to presence of storm fronts); few bat fatalities were discovered during storms, whereas the highest number of fatalities occurred in the few days after storms, especially on low wind nights. These relationships between bat fatalities and storm presence were consistent between the Mountaineer and Meyersdale sites (Kerns et al. 2005). Higher barometric pressure was positively associated with higher bat fatalities at both sites, but more so at Meyersdale. Relative humidity, which was only collected at Meyersdale, was negatively associated with bat fatalities (Kerns et al. 2005). Temperature did not show an association with fatality rates at Mountaineer, but there was a weak positive association between temperature and fatalities at Meyersdale (Kerns et al. 2005). Lower relative humidity and higher barometric pressure typically were associated with conditions after weather fronts passed through the area. In Tennessee, Fiedler (2004) found that bat fatalities were positively related to average nightly wind direction and negatively associated with average nightly wind speed, wind speed difference between the first and second portions of the night, and maximum temperature. Fiedler (2004) suggested that the positive association with wind direction indicated that the more the nightly wind direction deviated from the predominant wind direction (SW), the greater the chance of a fatality event. Fiedler (2004) also hypothesized that presence of more northerly winds during fatal nights may be related to weather conditions conducive for fall migra-

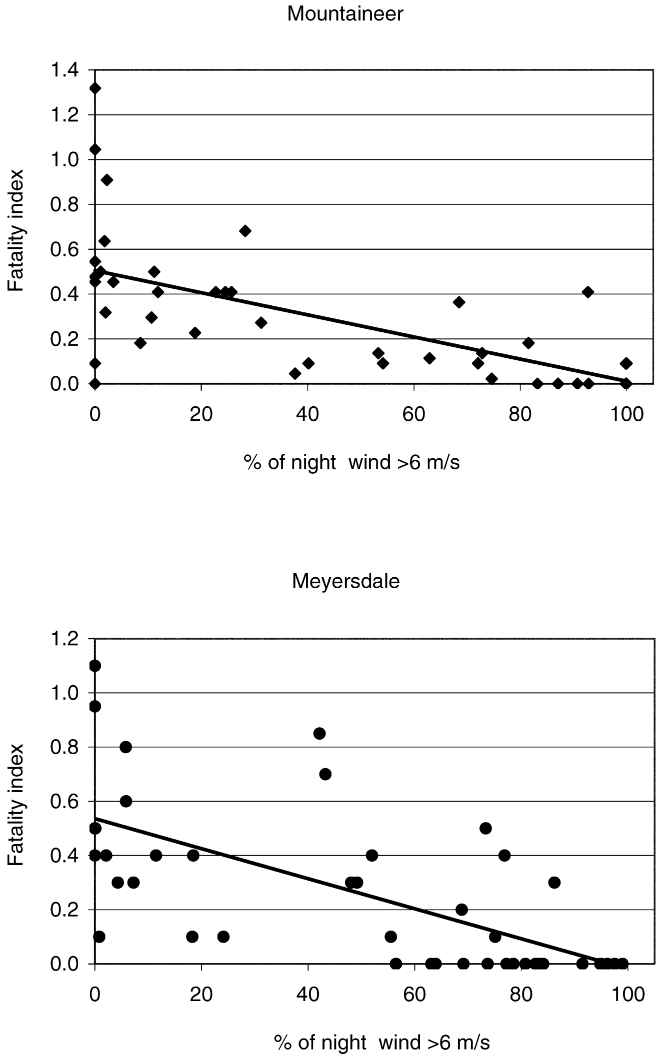

Figure 4. Relationship between daily fatalities (no. of fresh bat fatalities/no. of turbines searched) and average percentage of the night where wind speed at turbines was >6 m/sec at the Mountaineer Wind Energy Center in West Virginia, USA (31 Jul–11 Sep 2004) and the Meyersdale Wind Energy Center in Pennsylvania, USA (2 Aug–13 Sep 2004; Kerns et al. 2005). Fatality index is the total number of fresh bats found on a given day divided by the number of turbines searched that day.

tion, and negative associations with the other 3 variables indicated that fatality occurrence was more likely during cooler nights with calmer, less variable winds.

Aviation Lighting and Bat Fatality

Several species of bats are known to congregate and feed at different types of lights, and it has been hypothesized that towers lit with Federal Aviation Administration (FAA) lights may attract bats and increase the probability of collision with turbine blades, either because of or independently of a possible attraction to insect prey (Fenton 1997, Kunz et al. 2007). Federal Aviation Administration lights typically are installed on the turbine nacelle, close to the height of the rotor hub. However, none of the studies we reviewed demonstrated statistically significant differences in fatality between turbines equipped with FAA lights and those that were unlit. For example, at McBride Lake and Summerview, Alberta, the number of observed collisions did not differ from expected collisions for lit and unlit turbines at both sites (Brown and Hamilton 2006*a*). Kerns et al. (2005) found an average of 9.3 (+ 0.5 SE) bat fatalities per turbine at lit turbines and 9.7 (+ 0.3 SE) at unlit turbines at the Mountaineer, West Virginia, facility, and 11.9 (+ 1.7 SE) bat fatalities per turbine at lit turbines and 13.2 (+ 1.2 SE) at unlit turbines at the Meyersdale, Pennsylvania, facility. Jain et al. (2007) similarly found no significant deviation from expected number of bat fatalities within 40 m of turbines that were lit compared with unlit turbines at the Maple Ridge facility in New York. In Iowa, all towers were lit with some type of FAA lighting; 46 towers were lit with nonpulsating red beacons, 37 towers situated on the periphery of the wind facility had pulsating red beacons, and, due to proximity to the Lake Mills Municipal Airport, 6 towers northwest of the wind facility had a combination of flashing white beacons and nonflashing red beacons (Jain 2005). There was no significant difference in bat fatality detected among these towers with 3 types of FAA lighting (flashing red beacons, dual red beacons and flashing white beacons, and steady glowing red beacons). Controlled studies comparing bat fatalities at turbines with red and white FAA lights have not been conducted, and the response of bats to white lights on wind turbines remains unknown. Pulsing FAA lights that are red and white do produce strong ultrasonic pulses (W. Evans, Old Bird Inc., personal communication), and they may attract bats when they are in proximity to turbines.

DISCUSSION

We identified 5 key unifying patterns associated with bat fatalities at wind facilities among studies we reviewed: 1) fatalities were heavily skewed toward migratory bats and were dominated by lasiurine species in most studies, 2) studies consistently reported peak of turbine collision fatality in midsummer through fall from all studies in North America, 3) fatalities were not concentrated at individual turbines (i.e., fatalities were distributed among turbines at facilities), and current studies have not identified consistent relationships with habitat variables (e.g., distance to water), 4) red-strobe lights recommended by the FAA did not influence bat fatality, and 5) bat fatalities were highest during periods of low wind speed, and they were related to weather variables associated with the passage of weather fronts. These patterns generally were consistent with findings reported from wind facilities in Europe (Dürr and Bach 2004, Brinkmann 2006).

The most consistent theme is that fatality was heavily skewed toward migratory bats and a dominance of lasiurine species killed during midsummer through fall in North America, coinciding with bats' southward migration patterns (Cryan 2003). Of 15 species of bats that were reported as fatalities at wind facilities in Europe (10 sites in Germany alone), most were migratory species such as 2 species of *Nyctalus* and *Pipistrellus nathussi*, and most were killed in midsummer and fall (Dürr and Back 2004, Brinkmann

Table 3. Median nightly wind speed at turbines, proportion of 10-min intervals from 2000 hours to 0600 hours when wind speed was <4 m/sec, 4–6 m/sec, and >6 m/sec for nights when no bats were found the next day and nights with the highest bat fatalities at the Mountaineer, West Virginia, USA, and the Meyersdale, Pennsylvania, USA, wind energy facilities, 31 July–13 September 2004 (Kern et al. 2005).

	Mountaineer				Meyersdale			
	No bats ($n = 8$)		Highest fatalities ($n = 5$)		No bats ($n = 17$)		Highest fatalities ($n = 5$)	
Variable	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE
Wind speed (median nightly; m/sec)	8.6	0.88	4.1	0.22	8.0	0.34	4.2	0.58
% intervals wind speed at <4 m/sec	10.1	9.16	49.4	9.48	3.5	0.58	54.6	13.01
% intervals wind speed at 4–6 m/sec	8.1	3.04	44.1	7.65	15.9	3.15	27.2	4.96
% intervals wind speed at >6 m/sec	81.7	11.90	6.5	5.46	81.6	4.12	18.2	10.06

2006), a pattern that coincides with records of migrating bats striking other anthropogenic structures and their arrival at migration stopovers (Cryan and Brown 2007). Movement of migratory bats into new areas during late summer and early fall may be partially the result of exploratory activity (Cryan 2003), and the temporal pattern of bat fatality could simply be related to increased bat activity before and during migration. Some migratory species may summer in areas where they are colliding with turbines as well. Higher fatalities during migration also could be related to reduced echolocation and flight capabilities of juvenile bats (at least for red bats). However, little is known about use of echolocation during migration, and evidence suggests that bats are somehow attracted to turbines and that fatality is not a random event (Horn et al. 2008). We found that in most studies fatalities were dominated by adults, thus refuting the hypothesis that inexperienced juveniles may be more susceptible to turbines.

Kunz et al. (2007) discussed several hypotheses as to why bats may be attracted to and killed by turbines. It is possible that migrating tree-roosting species perceive turbines as possible roost trees and investigate them upon encounter (Arnett 2005, Kunz et al. 2007, Horn et al. 2008). Thermal images of bats attempting to land or actually landing on stationary blades and the turbine mast generally support the roost attraction hypothesis (Kunz et al. 2007), but the ultimate attraction to ridge top sites where turbines are located might be the availability of insect prey (Horn et al. 2008). Cryan and Brown (2007) presented evidence that migrating hoary bats rely on vision to navigate across landscapes and are drawn to visual stimuli during migration, although it is unknown as to how far bats may visually perceive such stimuli. Once in proximity, bats may misconstrue turbines as suitable day or night roosts or as perches to facilitate feeding, although lasiurine species do not exhibit such feeding behavior, and the perch tree attraction hypothesis conforms only to those species that use such a strategy. Alternatively, the initial attraction for migrating bats moving across a landscape might be the prominence of turbines and the possibility of a suitable roost worth investigating. Video images of bats chasing turbine blades rotating at slow speeds offer further insight to possible attraction, and bats may investigate moving blades simply out of curiosity, because movement is mistaken as evidence of prey, or because of attractive sounds (Horn et al. 2008). Also, audible sounds emitted from turbines may attract bats from considerable distances (Kunz et al. 2007).

Cryan and Brown (2007) hypothesize that dominance of migratory tree bats killed during summer and fall at turbines and other anthropogenic structures is related to flocking and mating behaviors exhibited by tree bats. Fleming and Eby (2003) proposed that flocking behavior in migratory bats during migration increases the chance of finding mates. The mating hypotheses (Cryan and Brown 2007) center on a general attraction to the tallest prominent features in a landscape where bats can meet along their migratory routes and breed. Evidence supports the hypothesis that migratory bats congregate in the fall during migration. Adult male and female hoary bats tend to be geographically separated during spring and summer (Findley and Jones 1964, Barclay 1993, Cryan 2003), but these disparate distributions begin to overlap during fall migration to wintering grounds (Cryan 2003). Hypothesized fall aggregation and mating behaviors could explain why migratory tree-roosting species are killed most frequently by turbines, and they may also explain why fatalities are skewed toward adults rather than juveniles.

Johnson (2005) reported that, in open prairie and farmland, bat fatalities seemed to be low during the maternity season; only 66 of the 1,628 reported fatalities (4.1%) occurred between 15 May and 15 July. At several wind energy facilities studied to date, low fatalities were documented during the maternity season, even though relatively large numbers of bats were present in the area (Gruver 2002, Howe et al. 2002, Johnson et al. 2003*a*, Fiedler 2004). Most of these wind energy facilities were in open areas such as crop fields, grasslands, and shrub steppe, and mating bats may be more prone to collision at wind farms constructed in bat foraging habitats, such as those constructed in forested areas. Johnson et al. (2004) contended that it was unlikely resident bats would spend significant amounts of time foraging near turbines in crop fields or pastures, but that may not be the case for species such as Brazilian free-tail bats that are well known to use agricultural areas for foraging (Cleveland et al. 2006). Roughly equal numbers of Mexican free-tail carcasses were discovered beneath turbines in forest, crop, and mixed grass prairie habitats at one facility in Oklahoma (Piorkowski 2006). Little brown bats and eastern pipistrelles are known to migrate several hundred kilometers to hibernate (Davis and Hitchcock 1965, Griffin 1970, Humphrey and Cope

1976), thereby being exposed to wind energy facilities along their migratory routes. Fall transient colonies form as early as August, peaking in September or October (Barbour and Davis 1969, Johnson et al. 2005), a period that corresponds with high fatalities documented at some wind energy facilities that we reviewed. Factors such as potential roost attraction, movement or sound attraction, or available prey may explain wind turbine-caused fatalities in species such as big brown bats and little brown myotis. Some species of bats are known to night-roost, and many species hawk for insect prey (Kunz 1982; J. Szewczak, Humboldt State University, personal communication), possibly supporting the roost attraction hypothesis for explaining deaths of species other than lasiurines.

Bat fatalities were related to periods of low wind speed and weather conditions typical of the passage of storm fronts at facilities on forested ridges in the eastern United States (Fiedler 2004, Kerns et al. 2005). Cryan and Brown (2007) reported that fall arrivals of hoary bats on Southeast Farallon Island were related to periods of low wind speed, dark phases of the moon, and low barometric pressure, supporting the view that migration events may be predictable. Low barometric pressure can coincide with passage of cold fronts that may be exploited by migrating birds and bats (Cryan and Brown 2007). The positive correlation in timing of fatalities between the Meyersdale, Pennsylvania, and Mountaineer, West Virginia, facilities supports the hypothesis that fatalities may be related to broad landscape, and perhaps regional patterns, movements that are influenced by weather and insect abundance (Kerns et al. 2005). Erickson and West (2002) reported that regional climate patterns as well as local weather conditions can predict activity of bats. On a local scale, strong winds can influence abundance and activity of insects, which in turn influences bat activity. Bats are known to suppress their activity during periods of rain, low temperatures, and strong winds (Erkert 1982, Erickson et al. 2002). Episodic hatches of insects that are likely associated with favorable weather and flight conditions may periodically increase local bat activity (Erickson and West 2002). More studies incorporating daily fatality searches are needed so that patterns such as those described above can be determined at multiple sites across regions. These data would be critical for developing robust predictive models of environmental conditions preceding fatality events, and, thus, prescribing possible mitigation (e.g., curtailment of operations to reduce or eliminate fatality; Arnett 2005, Cryan and Brown 2007, Kunz et al. 2007).

Limitations and Assumptions of Bat Fatality Studies

There are several limitations to the studies we reviewed that warrant discussion to provide the appropriate context for interpreting results and for developing future research needs. We refer readers to tables in the appendices to appreciate how each study was conducted and how estimates of fatality are potentially biased. With few exceptions, most work conducted to date has been short term (e.g., only one field season), and the frequency of study (e.g., season length and time into the night at which research is conducted) may also be inadequate to assess seasonal and annual variability. For example, the study of Kerns et al. (2005) only encompassed a 6-week period, which typically might be expected to include the peak period of bat fatality; however, unseasonably low temperatures and record hurricane events in 2004 may have reduced or delayed bat activity on ridges and thus influenced findings. Longer-term, full-season (Apr–Nov) studies are needed to elucidate patterns, better estimate wind–turbine-related fatalities, and develop predictive models to estimate fatalities and evaluate their relationship with weather and habitat variables.

Fatality estimates cannot be directly compared among studies because of different sampling protocols (e.g., different search intervals and approach and level of intensity used when quantifying searcher efficiency and carcass removal for adjusting estimates). Use of standardized protocols to address specific questions would improve comparability of studies and credibility of efforts. Consistency in how studies are conducted also would greatly assist regulatory agencies during decision making in regard to statutory trust responsibilities.

Sizes of search plot sizes varied among studies. Many recent studies used rectangular plots with edges of plots a minimum distance from the turbine equal to the maximum blade tip height of the turbine. Distribution of fatalities as a function of distance from turbines suggests that most, but not all, fatalities occur in this area. However, topography, maturity of vegetation, size of carcass, wind direction, and other factors likely affect the distribution of bats killed by wind turbines. The distribution of observed bat fatalities can be used to approximate the number of fatalities missed (Kerns et al. 2005). Most studies have shown a tighter distribution of bat fatalities, compared with bird fatalities, around the base of the turbine tower (Kerns et al. 2005). Additional factors affecting the precision and accuracy of fatality estimates include search effort, including the number of turbines searched, intensity of searches within search plots, and the experience of observers (Anderson et al. 1999).

Vegetation cover and associated visibility can have a profound influence on searcher efficiency, and they can change over a growing season (e.g., Johnson et al. 2003*a*, 2004). Most studies have failed to adequately account for habitat variability when measuring field biases, and findings from studies should be evaluated carefully in this context. It is critical that future studies account for habitat variation during searcher efficiency and scavenging trials to achieve reliable estimates of fatality.

Past experiments that assessed carcass removal using small birds as surrogates for bats may not provide a reliable assessment of scavenging. Using bat carcasses estimated to have been killed the night before discovery, Erickson et al. (2003*a*) and Johnson et al. (2003*a*) found similar or lower scavenging rates on bat carcasses compared with small bird carcasses. However, small sample sizes may have biased estimates and limited the scope of inference of these 2 studies. Fiedler (2004) conducted 6 bias trials during the first phase of development at the Buffalo Mountain Energy Center in Tennessee and found no difference between bat and bird carcasses for searcher efficiency or scavenging time. Brown and Hamilton (2006*b*) also found similar searcher efficiency and carcass disappearance rates for bats and small birds at Summerview Wind Farm in Alberta. Kerns et al. (2005), however, reported significantly lower scavenging rates on birds compared with both fresh and frozen bat carcasses at the Mountaineer Wind Energy Center in West Virginia. Differences in scavenging rates between the 2 sites studied by Kerns et al. (2005) suggest that scavenging must be determined on a site-specific basis, and it should not be assumed similar between sites even in proximity and in similar habitat conditions between years. One year of data is inadequate to reliably predict the search interval or to assess bias corrections appropriately; thus, future surveys should account for temporal patterns of scavenging among vegetation types. Also, scavenging should be expected to change over time as scavengers become aware of and develop search images for novel sources of food beneath turbines (Arnett 2005).

Future Research

We concur with Dürr and Bach (2004) and Kunz et al. (2007) that the state of our knowledge of factors associated with bat fatality at wind facilities is unsatisfactory. Investigations of wind turbine and wildlife interactions and impacts are relatively recent, and there is a dearth of reliable information upon which to base decisions. Although postconstruction monitoring has been conducted at wind facilities in North America for more than a decade, relatively few studies have focused on bats, and some states and regions have very poor or no data on bat fatalities. For example, Texas, which has the largest installed capacity of wind energy in the continental United States, has no data on wildlife fatalities from any of its facilities. Only one study from California, the state with the second highest installed capacity of wind energy, reported bat fatality estimates that were corrected for field bias, although the corrections were based on one trial in December with only 8 bat carcasses (Kerlinger et al. 2006). We excluded several studies from our review, in part because they did not systematically collect bats during fatality searches. Although past studies have helped elucidate unifying patterns that translate to testable hypotheses (Kunz et al. 2007), more extensive research is needed immediately to develop solutions to reduce or eliminate bat fatality.

Extensive postconstruction fatality searches for a full season of bat movement and activity (generally Apr–Nov in most regions, but this will vary in more southern regions such as the southwestern United States) are needed to fully elucidate temporal patterns of fatality, especially in areas where there is little or no information. Multiple years of postconstruction monitoring must be conducted at future wind facilities to address questions that center on 1) comparing fatality rates among facilities with varying topographic and habitat conditions within and among regions in North America and 2) elucidating patterns of fatality associated with weather conditions (e.g., wind speed, barometric pressure) and technical parameters (e.g., turbine size and ht, linear array of turbines vs. scattered individual turbine locations) of different facilities. Standard protocols and methods and a centralized data repository will be important for comparing results from multiple studies (Kunz et al. 2007).

It is clear that a large proportion of bat fatalities occur during fall migration, particularly on nights with low winds and relatively low levels of power production. Should this pattern prove to be persistent, curtailment of operations during predictable nights or periods of high bat kills could reduce fatalities considerably, potentially with modest reduction in power production (Kunz et al. 2007). We propose that manipulative experiments be implemented at wind facilities across different regions to test various curtailment treatments with regard to the effect on reducing bat fatalities and economic costs of treatments. Turbines can be programmed to feather (blades are pitched parallel to the wind but allowed to spin freely, although blades in this position move very slowly even in strong winds) at different wind speeds (e.g., 4 m/sec, 5 m/sec, or 6 m/sec), thus providing a viable way to test operational practices that may lead to reductions in fatality. Options to consider for experimental treatments include but are not limited to 1) full curtailment from sunset to sunrise (i.e., turbines feathered all night and not allowed to rotate at any wind speed), 2) partial curtailment from sunset to midnight (i.e., turbines feathered at all wind speeds just during this period when bats and insects may be most active; Arnett 2005, Arnett et al. 2006, Reynolds 2006, Horn et al. 2008), and 3) feathering turbines at different wind speeds for an entire night. Curtailment experiments should be a high priority for immediate research.

Limited knowledge of migratory behaviors seriously limits our understanding of how and why migratory bats are being killed by wind turbines (Larkin 2006); moreover, the lack of information available on numbers of bats moving through the air space when fatalities occur hinders interpretation of bat fatalities and limits regional comparisons of fatality rates. For example, although bat fatalities are estimated to be relatively low (<2 bats/MW) at many sites in the western United States, we do not know what proportion of the bats that moved through the airspace this represents; thus, 2 bats/MW could be proportionally the same as higher kills reported from forested ridges in the eastern United States. Future studies need to evaluate different methods and tools (e.g., radar, thermal imaging, and acoustic detectors) simultaneously to better quantify bat activity, migration, exposure risk of bats, and their interactions with turbines to develop the context within which fatalities can be compared.

Potential population effects of wind–turbine-related bat fatality remain unknown from available studies (Kunz et al. 2007). For many species, especially foliage and tree-roosting lasiurines that are most frequently killed, no quantitative information regarding long-term population trends can be drawn from existing data, in part because detection probabilities cannot be determined from current sampling methods (Carter et al. 2003). Although daunting, developing methods to assess populations and ways of investigating relationships between bat abundance and fatality risks at local and regional scales should be a priority.

MANAGEMENT IMPLICATIONS

Results from studies we reviewed did not reveal consistent patterns to assist with macro- (facility-scale) or micro (turbine-scale)-siting decisions to avoid bat fatalities. Studies that addressed relationships between bat fatalities and weather patterns found that most bats were killed on nights with low wind speed (<6 m/sec). Curtailing operations during low wind periods, particularly in late summer and fall, could reduce bat fatality substantially. For example, at the Meyersdale and Mountaineer facilities bat fatality would have been reduced by 82% and 85%, respectively, had turbines not been operating on nights when mean wind speed was <6 m/sec from 1 August to 13 September 2004 (E. B. Arnett, Bat Conservation International, unpublished data). Different curtailment strategies must be tested to determine efficacy and costs associated with reductions in bat fatalities. Given our current state of knowledge and the projected future development of wind energy facilities in the United States, the potential for significant cumulative population impacts to bats is an important concern (Kunz et al. 2007). Based on estimates of installed capacity and the limitations and assumptions with respect to fatality rates, projected annual fatalities of bats in the Mid-Atlantic Highlands in the eastern United States could range from 33,017 to 61,935 (2,158-MW installed capacity) or from 58,997 to 110,667 (3,856-MW installed capacity) bats per year by 2020 in just this one region (National Research Council 2007). These projections, although hypothetical, should be of particular concern for species of migratory tree bats that experience the highest fatalities at wind energy facilities in North America.

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Appendix A. Study area location, acronyms, and citations for bat fatality studies conducted at wind facilities in North America, 1996–2006.

Study area location	Acronym	References
Canada		
Castle River, AB	CRAB	Brown and Hamilton 2002
McBride Lake, AB	MLAB	Brown and Hamilton 2006*a*
Summerview, AB	SVAB	Brown and Hamilton 2006*b*
Eastern United States		
Buffalo Mountain, TN (phase 1)	BMTN1	Nicholson 2003, Fiedler 2004
Buffalo Mountain, TN (phase 2)	BMTN2	Fiedler et al. 2007
Maple Ridge, NY (phase 1)	MRNY1	Jain et al. 2007
Meyersdale, PA	MYPA	Kerns et al. 2005
Mountaineer, WV (2003)	MTWV1	Kerns and Kerlinger 2004
Mountaineer, WV (2004)	MTWV2	Kerns et al. 2005
Rocky Mountains, USA		
Foote Creek Rim, WY	FRWY	Young et al. 2003
Pacific Northwest, USA		
High Winds, CA	HWCA	Kerlinger et al. 2006
Klondike, OR	KLOR	Johnson et al. 2003*b*
Nine Canyon, WA	NCWA	Erickson et al. 2003*a*
Stateline, OR/WA	SLOR	Erickson et al. 2003*b*
Vansycle, OR	VAOR	Erickson et al. 2000
Midwestern United States		
Buffalo Ridge, MN (phase 1)	BRMN1	Johnson et al. 2003a
Buffalo Ridge, MN (phase 2)	BRMN2	Johnson et al. 2003*a*, 2004
Buffalo Ridge, MN (phase 3)	BRMN3	Johnson et al. 2003*a*, 2004
Lincoln, WI	LIWI	Howe et al. 2002
Top of Iowa, IA	TOIA	Jain 2005
South-central United States		
Woodward, OK	WOOK	Piorkowski 2006

Appendix B. Study period and characteristics of wind facilities for bat fatality studies in North America, 1996–2006.

Study area[a]	Study period	No. and capacity of turbines	Tower ht (m)	Rotor swept area (m^2)	Habitat[b]
Canada					
CRAB	1 Apr 2001–31 Dec 2002	60 0.66-MW	50	1,735	CROP, grazed GR
MLAB	1 Jul 2003–30 Jun 2004	114 0.66-MW	50	1,735	CROP, grazed GR
SVAB	1 Jan 2005–31 Dec 2006	39 1.8-MW	65	5,027	CROP, grazed GR
Eastern United States					
BMTN1	1 Sep 2000–30 Sep 2003	3 0.66-MW	65	1,735	DFR
BMTN2	1 Apr–31 Dec 2005	3 0.66-MW	65	1,735	DFR
		15 1.8-MW	78	5,027	DFR
MRNY1	17 Jun–15 Nov 2006	120 1.65-MW	80	5230	CROP, grazed GR, DF
MYPA	2 Aug–13 Sep 2004	20 1.5-MW	80	4,072	DFR
MTWV1	4 Apr–11 Nov 2003	44 1.5-MW	70	4,072	DFR
MTWV2	31 Jul–11 Sep 2004	44 1.5-MW	70	4,072	DFR
Rocky Mountains, USA					
FRWY	1 Nov 1998–31 Dec 2000	69 0.66-MW	40	1,385	SGP
Pacific Northwest, USA					
HWCA	4 Aug 2003–30 Jul 2005	90 1.8-MW	60	5,027	CROP, grazed GR
KLOR	1 Feb 2002–31 Jan 2003	16 1.5-MW	65	3,902	CROP, GR
SLOR	1 Jul 2001–31 Dec 2003	454 0.66-MW	65	1,735	SH, CROP
VAOR	1 Jan 1999–31 Dec 1999	38 0.66-MW	65	1,735	CROP, GR
NCOR	1 Sep 2002–31 Aug 2003	37 1.3-MW	60	3,019	GR, SH, CROP
Midwestern United States					
BRMN1	Apr 1994–Dec 1995; 15 Mar–15 Nov 1996–1999	73 0.33-MW	36	855	CROP, CRP, PAST
BRMN2	15 Mar–15 Nov 1998–1999; 15 Jun–15 Sep 2001–2002	143 0.75-MW	50	1,661	CROP, CRP, PAST
BRMN3	15 Mar–15 Sep 1999; 15 Jun–15 Sep 2001–2002	138 0.75-MW	50	1,809	CROP, CRP, PAST
LIWI	Jul 1999–Jul 2001	31 0.66-MW	65	1,735	CROP
TOIA	15 Mar–15 Dec 2003, 2004	89 0.9-MW	72	2,108	CROP
South-central United States					
WOOK	May, Jun 2004, 2005	68 1.5-MW	64	3,526	RCMGP, CROP

[a] See Appendix A for study area abbreviations.

[b] CROP = agricultural crops; DF = deciduous forest; DFR = deciduous forested ridge; GR = grassland; SH = shrub-steppe; SGP = short grass prairie; RCMGP = redcedar–mixed grass prairie savanna.

Appendix C. Characteristics of monitoring studies and factors influencing the estimates of bat fatalities at wind facilities in North America, 1996–2006.

Study area location[a]	Search interval	Searcher efficiency[b] (no. bats/no. trials)	% estimated searcher efficiency	Carcass removal[b] (no. bats/no. trials)	Mean no. days carcasses lasted
Canada					
CRAB	[c]	6/1	66	0	
MLAB	[c]	0		0	
SVAB	[c]	69/1	59	50	10
Eastern United States					
BMTN1	3 days	42 bats, 55 birds/6	37	42 bats, 55 birds/6	6.3
BMTN2	7 days	48 bats/1	41	48 bats/1	Prepeak: 8.7 peak: 1.9
MRNY1	Daily, 3 days, 7 days[d]	41 bats/4	42	51 bats/5	>9 days
MYPA	Daily[e]	161 bats/13	25	153/[f]	18.0
MTWV1	[g]	30 birds/1	28	30 birds/1	6.7
MTWV2	Daily[h]	215 bats/13	42	228/[f]	2.8
Rocky Mountains, USA					
FRWY	14 days	16/1	63	10 (1 trial)	20
Pacific Northwest, USA					
HWCA	15 days	48 birds/1	50	8/1	[i]
KLOR	28 days	36 birds/8	75	32 birds/8	14.2
SLOR	14 days, 28 days	171 birds/18	42	171 birds/18, 7 bats/1	16.5
VAOR	28 days	42 birds/8	50	40 birds/8	23.3
NCWA	14 days, 28 days	34 birds/8	44	32 birds/8	11.0
Midwestern United States					
BRMN (1996–1999)	14 days	306 birds/60	29.4	40/4	10.4
BRMN (2001–2002)	14 days	68/10	53.4	46/4	10.4
LIWI	14 days	50/2	70	50/2	approx. 10
TOIA	2 days	73/na	71.5	156 birds/6	>2
South-central United States					
WOOK	8 surveys[j]	0/0	[k]	0	[k]

[a] See Appendix A for study area abbreviations.

[b] No. of carcasses, bird or bat, used and the no. of trials conducted for quantifying estimates of searcher efficiency and carcass removal.

[c] Search interval was 3 days in May, Jun, Sep, and Oct and 7 days in Jul and Aug.

[d] Daily searches conducted at 10 of 120 turbines for 127 days (3-day [$n = 10$ turbines] and 7-day [$n = 30$ turbines] searches also were conducted).

[e] Daily searches conducted at 10 of 20 turbines for 43 days and all turbines searched once each week on the same day.

[f] Bats were continually placed for carcass removal trials during the 6-week study period.

[g] Search interval was 9 days in May and Jun, 27 days in Jul and Aug, and 7 days in Sep and Oct 2003.

[h] Daily searches conducted at 22 of 44 turbines for 43 days and all turbines searched once each week on the same day.

[i] One trial conducted in Dec 2005; 5 of 8 bats were scavenged in 1 day. Average days carcasses lasted not provided.

[j] Two surveys per month conducted 14 days apart in May and Jun each yr in 2004 and 2005.

[k] Adjusted fatality rates based on estimates for searcher efficiency and carcass removal generated from other studies (see Piorkowski 2006).