Variation in bat and bird fatalities at wind energy facilities: assessing the effects of rotor size and tower height

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Abstract: Wind energy is a rapidly growing sector of the alternative energy industry in North America, and larger, more productive turbines are being installed. However, there are concerns regarding bird and bat fatalities at wind turbines. To assess the influence of turbine size on bird and bat fatalities, we analyzed data from North American wind energy facilities. Diameter of the turbine rotor did not influence the rate of bird or bat fatality. The height of the turbine tower had no effect on bird fatalities per turbine, but bat fatalities increased exponentially with tower height. This suggests that migrating bats fly at lower altitudes than nocturnally migrating birds and that newer, larger turbines are reaching that airspace. Minimizing tower height may help minimize bat fatalities. In addition, while replacing older, smaller turbines with fewer larger ones may reduce bird fatalities per megawatt, it may result in increased numbers of bat fatalities.

Résumé : L'énergie éolienne constitue un champ de l'industrie de l'énergie de remplacement qui est en croissance rapide en Amérique du Nord; il en résulte une installation de turbines plus grandes et plus productives. Il y a cependant des préoccupations concernant les mortalités des oiseaux et des chauves-souris dans ces turbines éoliennes. Afin d'évaluer l'effet de la taille des turbines sur les mortalités des oiseaux et des chauves-souris, nous avons analysé des données provenant d'installations de production d'énergie éolienne en Amérique du Nord. Le diamètre du rotor de la turbine n'influence pas de taux de mortalité des oiseaux ni celui des chauves-souris. La hauteur de la tour de la turbine n'a pas d'effet sur les mortalités des oiseaux par turbine, mais les mortalités des chauves-souris augmentent de façon exponentielle en fonction de la hauteur de la tour. Cela laisse croire que les chauves-souris migratrices volent à des altitudes plus basses que les oiseaux qui migrent la nuit et que les turbines nouvelles de plus grande taille atteignent cet espace aérien. La réduction de la hauteur des tours pourrait aider à faire baisser les mortalités des chauves-souris. De plus, alors que le remplacement des turbines plus anciennes et de plus petite taille par un nombre plus restreint de grandes turbines peut diminuer les mortalités des oiseaux par mégawatt, il peut avoir pour effet d'augmenter les mortalités des chauves-souris.

[Traduit par la Rédaction]

Introduction

Wind energy is one of the fastest growing energy sectors in North America (CanWEA 2006; AWEA 2006). In Canada, the wind energy industry has set a goal of 10 000 MW of installed capacity by 2010, seven times the current capacity (CanWEA 2006). While wind energy is an important alternative to the burning of fossil fuels in efforts to reduce the production of greenhouse gases, it too has environmental impacts.

Concerns regarding the effects of wind energy facilities on wildlife initially focused on bird fatalities, especially those of migrating raptors and passerines (e.g., Rogers et al. 1977; Orloff and Flannery 1992). Fatality rates were particularly high at some early, large-scale wind energy facilities in California (e.g., Altamont; Orloff and Flannery 1992). Newer wind facilities are generally associated with lower bird fatality rates (Erickson et al. 2001, 2002).

While early studies rarely if ever mentioned bats (e.g., Rogers et al. 1977), and the focus continues to be on birds (Barrios and Rodríguez 2004; de Lucas et al. 2004; Drewitt and Langston 2006), some recent studies at newer wind farms report large numbers of dead bats (e.g., Osborn et al. 1996; Johnson et al. 2003*a*, 2004; Kerns and Kerlinger 2004; Arnett 2005). Bat fatalities at wind energy facilities in North America consistently occur in late summer and fall and involve migratory species, especially hoary bats (*Lasiurus cinereus* (Beauvois, 1796)), eastern red bats (*Lasiurus borealis* (Müller, 1776)), and silver-haired bats (*Lasionycteris noctivagans* (Le Conte, 1831)) (Erickson et al. 2002; Johnson et al. 2003*a*, 2004; Kunz et al. 2007).

The shift in concerns regarding wind energy facilities and wildlife from that involving birds to that involving bats raises many questions regarding the causes and consequences of bat fatalities. Unfortunately, our understanding of the behaviour of migratory bats is extremely limited (e.g., Cryan 2003). Various hypotheses have been proposed to explain different aspects of the variation in bat, and bird, fatalities (e.g., Kunz et al. 2007), but few studies have attempted to test these. For example, considerable variation in annual fatality rates has been reported among wind energy facilities (Table 1). This could be due to migratory bats and birds using well-defined migratory routes, some of which occur where wind facilities have been built (Nelson and Curry

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Table 1. Wind turbine and bat and bird fatality data for North American wind energy facilities used in the analyses.

					Annual		Corrected annual		
Location	No. of turbines	Diameter (m)	Height (m)	Megawatt capacity / turbine	No. of bat fatalities / turbine	No. of bird fatalities / turbine	No. of bat fatalities / turbine	No. of bird fatalities / turbine	References
Alberta									
Castle River	41	47	50	0.66	0.93	0.098			Brown and Hamilton 2002
Magrath	20	77	65	1.5	1.35	1.95	1.76	2.62	K. Brown, personal communication (2006)
McBride Lake	114	47	50	0.66	0.47	0.36			K. Brown, personal communication (2006)
Summerview	39	80	67	1.8	13.64	1.28	18.48	1.90	K. Brown, personal communication (2006)
California									
Altamont	1526	18	24	0.11	0.001	0.199	0.01	0.791	Smallwood and Thelander 2005
Diablo Winds	31	47	50	0.66	0.00	0.387	0.00	1.19	WEST Inc. 2006
High Winds	90	80	60	1.8	0.644	0.906	3.43	2.31	Kerlinger et al. 2006
San Gorgonio	2947	19	24.4	0.155	0.001	0.042			McCrary et al. 1986; Anderson et al. 2005
Tehachapi	637	20	30	0.0002	0.002	0.071			Anderson et al. 2004
Colorado									
Ponnequin	44	47.5	60	0.71	0.159	0.155			G. Johnson, personal communication (2006); P. Cryan, personal communication (2006)
Iowa									
IDWGP* site	3	47	50	0.75		0.00		0.00	Erickson et al. 2001
Top of Iowa	89	52	71.6	0.9	1.42	0.135	8.04	0.646	Jain 2005
Massachusetts									
Princeton	8	15	30.5	0.04	0.00	0.00			Johnson and Strickland 2004
Minnesota									
Buffalo Ridge I	73	33	37	0.34	0.085	0.147	0.070	0.884	Osborn et al. 1996, 2000; Johnson et al. 2000, 2003*a*
Buffalo Ridge II	143	47	50	0.75	1.30	0.250	2.01	2.27	Johnson et al. 2000, 2002, 2003*a*, 2004; Osborn et al. 2000; Erickson et al. 2001
Buffalo Ridge III	138	47	50	0.75	0.963	0.667	2.06	4.45	Johnson et al. 2000, 2002, 2003*a*, 2004; Osborn et al. 2000; Erickson et al. 2001
New York									
Copenhagen	2	33	40	0.34	0.00	0.00			Johnson and Strickland 2004
Madison	7	67	66.5	1.65	0.00	0.571			Johnson and Strickland 2004
Ontario									
Exhibition Place	1	48	94	0.75	0.00	2.00			James and Coady 2003, 2004
Pickering	1	78	78	1.8	8.00	3.00	10.7	4.00	James 2003
Oregon									
Klondike	16	70	65	1.5	0.375	0.500	1.19	1.44	Johnson et al. 2003*b*
Vansycle	38	47	50	0.66	0.263	0.316	0.737	0.632	Erickson et al. 2000
Pennsylvania									
Meyersdale	20	72	80	1.5	13.1	0.045	27.0	0.925	Kerns et al. 2005
Somerset	8	58	57	1.3	0.125	0.00			Johnson and Strickland 2004
Saskatchewan									
Cypress	16	47	45	0.66	0.00	0.125	0.00	1.40	Northern Envirosearch Ltd. 2004

Table 1 (*concluded*).

Location	No. of turbines	Diameter (m)	Height (m)	Megawatt capacity / turbine	Annual: No. of bat fatalities / turbine	Annual: No. of bird fatalities / turbine	Corrected annual: No. of bat fatalities / turbine	Corrected annual: No. of bird fatalities / turbine	References
Tennessee									
Buffalo Mountain	3	47	65	0.66	10.7	4.33	21.4	9.33	Tennessee Valley Authority 2002; Fiedler 2004
Vermont									
Searsberg	11	40	40	0.54	0.00	0.00	0.00	0.00	Kerlinger 2002
Washington									
Nine Canyon	37	62	60	1.3	0.730	0.973	3.21	3.59	Erickson et al. 2003
Washington–Orgeon									
Stateline	454	47	50	0.66	0.297	0.606	1.12	1.93	WEST Inc. and Northwest Wildlife Consultants, Inc. 2004
Wisconsin									
NE Wisconsin	31	47	65	0.66	1.16	0.403	4.26	1.29	Howe et al. 2002
West Virginia									
Mountaineer	44	72	69.5	1.5	9.92	0.545	42.7	2.59	Kerns and Kerlinger 2004; Kerns et al. 2005
Wyoming									
Foote Creek Rim	69	42	40	0.6	0.381	0.391	1.30	1.49	Young et al. 2003

*Iowa Distributed Wind Generation Project.

1995). On the other hand, the size and height of wind turbines have increased over the years, from 18 m diameter rotors on top of 24 m towers to the newest turbines with 90 m diameter rotors and towers as tall as 94 m (Table 1). There is considerable debate as to whether turbine size influences fatalities of bats and birds (e.g., Rogers et al. 1977; Johnson et al. 2002; National Wind Coordinating Committee 2004; Drewitt and Langston 2006). It could be that the larger rotor-swept area of newer turbines increases the risk to birds and bats on a per turbine basis. It may also be that newer, taller turbines have their blades extending up into the airspace traveled by migrating bats and birds. This hypothesis is supported by radar and other studies which indicate that most nocturnally migrating bats and birds fly more than 100 m above the ground (Blokpoel and Burton 1975; Kerlinger 1995; Bruderer 1997; Osborn et al. 1998; Howe et al. 2002; Mabee and Cooper 2004; Plissner et al. 2006). To test the hypothesis that wind turbine size and height influence fatality rates of bats and birds, and determine whether the effect differs between the two groups, we compiled and analyzed data from studies at wind energy facilities across North America.

Methods

We compiled data on the characteristics of North American wind energy facilities (e.g., number of turbines, rotor diameter, tower height, installed megawatt (MW) capacity) and on bat and bird fatalities. Turbine tower construction (e.g., lattice vs. monopole towers) differed among facilities, but large turbines always involved monopole towers, and we thus did not include tower type as a variable. Data were available from some published scientific papers, but primarily from unpublished government, industry, and consultant reports, as well as from personal communications. Fatality rates are determined based on searches for carcasses under turbines. Most searches occurred at weekly intervals or longer and likely underestimated the actual number of fatalities owing to removal of carcasses by scavengers (e.g., Osborn et al. 2000; Johnson et al. 2002, 2003*a*; Morrison 2002; Young et al. 2003; Arnett 2005). Thus, many of the more recent studies experimentally estimated scavenger losses and corrected fatality estimates accordingly (e.g., Arnett 2005). Similarly, efficiency of detecting carcasses varies, for example, owing to differences in the vegetation surrounding turbines (e.g., Osborn et al. 2000; Johnson et al. 2003*a*; Arnett 2005). Again, such biases have been estimated and corrected for in many studies. The methods used to correct fatality estimates varied among studies, as did searcher efficiencies and scavenger losses. Thus, the confidence in those estimates also varied. We present both uncorrected and corrected (when available) estimates of fatalities per turbine per year (Table 1). However, for statistical analyses we only used the corrected values, as they represent the best estimates of fatality rates.

Results

We compiled wind turbine and fatality data for 33 sites (Table 1). In some cases several studies were conducted at the same site in different years, while in others a single study occurred over several years. In both cases, we averaged fatality rates across years. At only 21 sites for bats and 22 sites for birds were fatality estimates adjusted for searcher efficiency and scavenger removal. We used these studies for statistical analyses using SAS® version 9.1 (SAS Institute Inc. 2002).

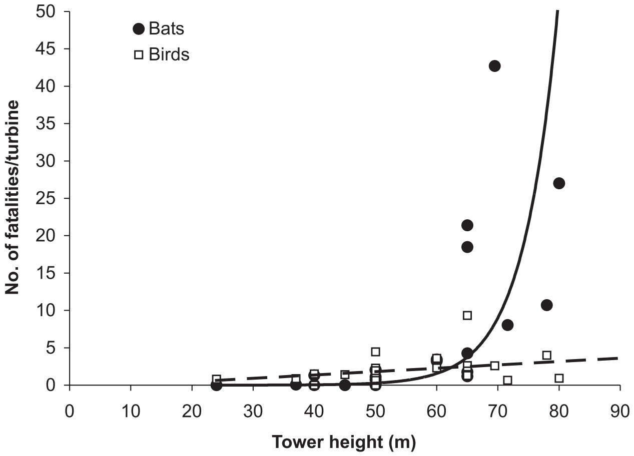
Turbine characteristics varied among sites, with blade diameter varying from 18 to 90 m and with height of the nacelle (rotor hub) varying from 24 to 94 m (Table 1). Corrected annual fatality rates also varied greatly among sites, from 0 to over 9 per turbine for birds and from 0 to over 40 per turbine for bats (Table 1). We log-transformed (rate + 0.01) the corrected fatality rates and analyzed them using analysis of covariance (ANCOVA) with organism (bat or bird) as the main effect, and rotor-swept area and turbine tower height (or height of the top of the blades) as covariates. We included the interaction between organism and tower height to determine whether turbine height influenced the fatalities of birds and bats differently. The interaction between rotor-swept area and organism was not significant ($P = 0.77$) and was thus removed from the ANCOVA model. Corrected fatality rate varied significantly, whether we used tower height ($F_{[4,39]} = 89.19$, $P < 0.001$, $R^2 = 0.49$) or blade height as our measure of turbine size. We used tower height because the R^2 value for that model was slightly higher. Fatality rate increased with tower height ($F_{[1,39]} = 13.47$, $P < 0.001$), but did not vary with blade-swept area ($F_{[1,39]} = 0.2$, $P = 0.64$). Fatality rates of bats and birds were influenced differently by tower height ($F_{[1,39]} = 10.10$, $P = 0.003$). Fatality rates of both bats and birds were relatively low at short turbines (<65 m high), but bat fatalities increased exponentially with turbine height, while bird fatalities did not change (Table 1, Fig. 1). The highest bat fatality rates occurred at turbines with towers 65 m or taller.

Discussion

The historic development of wind energy technology has involved increased rotor diameter and tower height, resulting in greater energy output per turbine (National Wind Coordinating Committee 2004). Our analyses of the data available from North America indicate that this has had different consequences for the fatality rates of birds and bats at wind energy facilities. It might be expected that as rotor-swept area increased, more animals would be killed per turbine, but our analyses indicate that this is not the case. Rotor-swept area was not a significant factor in our analyses. In addition, there is no evidence that taller turbine towers are associated with increased bird fatalities. The per turbine fatality rate for birds was constant with tower height. However, bat fatalities increased exponentially as turbine height increased, with turbine towers 65 m or taller having the highest fatality rates.

Two examples illustrate the influence of tower height on bat fatalities. The Buffalo Mountain wind energy facility in Tennessee has three turbines with relatively small rotors (47 m diameter) but tall towers (65 m), and the second highest corrected bat fatality rate of any of the facilities for which we had data (Tennessee Valley Authority 2002; Fiedler 2004). This indicates that relatively small rotors may cause high bat fatalities if they are mounted on tall towers. In southwestern Alberta, three wind energy facilities within a 30 km radius have had fatality data collected at them. Both Castle River and McBride Lake wind farms have short turbines (50 m towers) and low bat fatality rates (annually <1 bat/turbine, uncorrected; Brown and Hamilton 2002). Summerview, with 65 m towers, has an uncorrected annual rate of almost 14 bats/turbine (K. Brown, personal communication (2006); E. Baerwald, unpublished data). This suggests that within the same geographical area, bat fatalities vary with tower height.

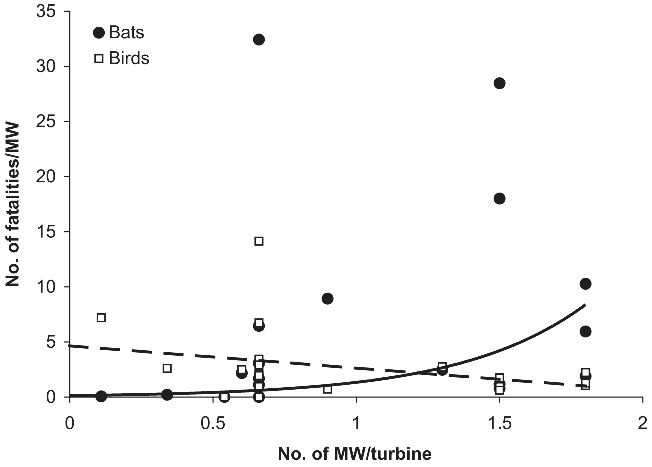
Fig. 1. Relationship between corrected annual bat and bird fatalities per turbine and the height of wind turbine towers at wind energy facilities in North America. No. of bat fatalities / turbine = $0.00004e^{0.1757\text{height}}$ ($R^2 = 0.55$). No. of bird fatalities / turbine = 0.052height – 0.450 ($R^2 = 0.10$). Although the relationship for birds is not significant ($P > 0.1$), the best fit (broken) line is presented for ease of interpretation.



Why does tower height have a different effect on bat and bird fatalities? Of the birds killed at wind farms, a significant proportion is killed during the day (National Wind Coordinating Committee 2004), and their ability to detect and avoid turbines (Osborn et al. 1998; de Lucas et al. 2004) may not vary with turbine size.

Some of the birds and all of the bats killed by wind turbines are killed at night. The majority of these are migrants killed during fall migration (e.g., Erickson et al. 2001; Johnson et al. 2002, 2003*a*, 2004; National Wind Coordinating Committee 2004). Radar and other studies at various locations indicate that nocturnal migrants (bats and birds) fly at heights ranging from <100 m to >1 km (Kerlinger 1995; Bruderer 1997; Osborn et al. 1998; Howe et al. 2002; Mabee and Cooper 2004; Plissner et al. 2006). Although currently it is not possible to distinguish bats from birds using radar, one explanation for our results is that, on average, migrating bats fly at lower altitudes than birds do and that turbines on towers 65 m or taller are reaching into that airspace, resulting in increased bat mortalities. Why bats do not detect and avoid the blades remains unknown. It has been suggested that at least some bats do not echolocate while migrating (Crawford and Baker 1981), a reasonable assumption if bats are traveling well above natural obstacles. However, we have recorded the echolocation calls of migratory species at the tops of turbines (E. Baerwald, unpubublished data; see also Fiedler 2004), so at least some individuals do echolocate. It may be that the speed of the blades (>200 km/h at

Fig. 2. Relationship between the corrected bat and bird fatalities per megawatt (MW) of installed capacity and the rated MW capacity per turbine at wind energy facilities in North America. The relationship for bats is significant ($F_{[1,19]} = 5.40$, $P = 0.031$; no. of bat fatalities / MW = $-1.90e^{2.22\text{MW/turbine}}$, $R^2 = 0.22$). Although the relationship for birds is not significant ($P = 0.9$), the best fit (broken) line is presented for ease of interpretation.



the tips; National Wind Coordinating Committee 2004) precludes bats from detecting them in time to react (Kunz et al. 2007). It may also be that bats are attracted to either the sound or the movement of the moving blades (Gruver 2002; Kunz et al. 2007).

There is considerable variation in the fatality rates of birds and bats among sites that is not explained by the size of the turbines alone. Turbines differ in other ways that may influence fatality. For example, some older turbines were constructed using lattice towers rather than the tubular monopoles used by modern turbines. Lattice towers might provide perching opportunities for birds, while monopoles have been hypothesized to mimic potential roost trees for bats (Kunz et al. 2007). The wind speed at which blades begin to rotate varies among turbine models (e.g., http://www.vestas.com/vestas/global/en/Products/Wind_turbines/ [accessed 15 March 2007]). This could be significant because bats do not appear to collide with stationary blades but rather are killed by rotating blades, especially at low wind speeds (Fiedler 2004; Arnett 2005; E. Baerwald and R.M.R. Barclay, unpublished data). However, it seems unlikely that the small differences in the wind speed at which blades begin to rotate result in the large variation in fatality rates among wind energy facilities. Other factors influencing fatality rates may include differences in the number of species present in the area (Drewitt and Langston 2006) and their population sizes, the use of migration corridors (Nelson and Curry 1995), variation from site to site in the height at which birds and bats fly, and variation in numbers of migrants from year to year (e.g., Johnson et al. 2003*b*). Little is known about these factors, especially regarding the migratory behaviour of bats. In addition, confidence in the estimated fatality rates varies from site to site, depending on searcher efficiency and the magnitude of scavenger losses.

Our analysis indicates that there is no relationship between the number of birds killed per megawatt annually and the rated power output of the turbines (Fig. 2). Changes in turbine structure, lighting, and placement have resulted in reduced fatalities of birds since the early concerns at wind energy facilities in California (Erickson et al. 2002). In contrast, fatalities of bats per megawatt of installed energy capacity are greater at some of the new, larger turbines, and overall, bat fatalities increase per megawatt (Fig. 2). In addition, while fatalities of birds are distributed among many species, only three species make up the majority of bats killed. Therefore, the potential impact on bat populations may be greater. What was once a bird issue has become a bat issue. Further studies are required to understand the causes and consequences of this, and to develop preventative measures. However, based on our analysis of the existing data, replacing several small turbines (with low power output) with one large one (with higher power output), as has been proposed for Altamont Pass, California (Smallwood and Thelander 2004), may help reduce bird fatalities but is likely to increase the number of bats killed per megawatt of installed capacity. We recommend minimizing the height of new turbine towers (within the constraints imposed by rotor size), and investigating other potential mitigation methods, in an effort to minimize bat fatalities.

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