Altering turbine speed reduces bat mortality at wind-energy facilities

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Wind-turbine operations are associated with bat mortality worldwide; minimizing these fatalities is critically important to both bat conservation and public acceptance of wind-energy development. We tested the effectiveness of raising wind-turbine cut-in speed – defined as the lowest wind speed at which turbines generate power to the utility system, thereby reducing turbine operation during periods of low wind speeds – to decrease bat mortality at the Casselman Wind Project in Somerset County, Pennsylvania, over a 2-year period. Observed bat mortality at fully operational turbines was, on average, 5.4 and 3.6 times greater than mortality associated with curtailed (ie non-operating) turbines in 2008 and 2009, respectively. Relatively small changes to wind-turbine operation resulted in nightly reductions in bat mortality, ranging from 44% to 93%, with marginal annual power loss ($\leq$ 1% of total annual output). Our findings suggest that increasing turbine cut-in speeds at wind facilities in areas of conservation concern during times when active bats may be at particular risk from turbines could mitigate this detrimental aspect of wind-energy generation.

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Wind-energy development is rapidly increasing worldwide, owing to concerns about climate change and the increasing financial costs of and long-term environmental impacts from fossil-fuel use (Pasqualetti *et al.* 2004; Arnett *et al.* 2007). Although wind-generated electricity is renewable and generally considered environmentally "clean", extensive fatalities of bats have been recorded at wind facilities worldwide (Dürr and Bach 2004; Kunz *et al.* 2007; Arnett *et al.* 2008; Figure 1). Because of the distinctive life-history traits of bats, their populations are sensitive to changes in mortality rates and tend to make slow recoveries following declines (Barclay and Harder 2003).

Turbine-related fatalities raise concern about potential impacts on bat populations at a time when many species of bats are known – or suspected – to be in decline (Racey and Entwistle 2003; Winhold *et al.* 2008) and continued development of wind energy is planned (Kunz *et al.* 2007; EIA 2010).

Previous research suggests that more bat fatalities occur during relatively low-wind periods in summer and fall months (Arnett *et al.* 2008). Bats restrict their flight activity during periods of rain, low temperatures, and strong winds (Eckert 1982; Erickson and West 2002). Studies at proposed and operating wind facilities have also documented lower bat activity during high (usually >6.0 m s^{-1}) wind speeds (Reynolds 2006; Horn *et al.* 2008). Non-spinning turbine blades and turbine towers do not kill bats (Horn *et al.* 2008) and shutting down turbines during low-wind (usually < 6.0 m s^{-1}) periods in summer and fall has been hypothesized as a means for reducing bat fatalities (Kunz *et al.* 2007; Arnett *et al.* 2008). Raising turbine cut-in speed (ie the lowest wind speed at which turbines generate power to the utility system) above the manufactured cut-in speed (usually 3.5–4.0 m s^{-1} on modern turbines) renders turbines non-operational until the higher cut-in speed is reached and turbines then begin to spin and produce power. Thus, raising turbine cut-in speed during low-wind periods should reduce bat kills. Indeed, results from the only published study on the subject indicate that increasing turbine cut-in speed to 5.5 m s^{-1} reduced bat mortality by nearly 60% as compared with normally operating turbines (Baerwald *et al.* 2009).

We studied how increasing turbine cut-in speed affects bat fatalities at wind turbines. Our objectives were (1) to determine if rates of bat fatality differed between fully operational turbines and turbines with cut-in speeds of 5.0 m s^{-1} and 6.5 m s^{-1}, and (2) to quantify the economic costs of different curtailment programs and timeframes. We predicted that bat fatalities would be (1) significantly higher at fully operational turbines as compared with observed mortality associated with both cut-in speed treatments and (2) significantly lower at turbines with a cut-in speed of 6.5 m s^{-1} as compared with that at turbines with 5.0 m s^{-1}, because increasing cut-in speed reduces operating time to generate power.

Study area

The study was conducted at the Casselman Wind Project (39° 51' 22.41" N, 79° 08' 32.22" W to 39° 51' 08.58" N, 79° 06' 18.60" W) in Somerset County near Rockwood, Pennsylvania. This facility lies within the Appalachian mixed mesophytic forest ecoregion that encompasses moist broadleaf forests of the Appalachian Mountains (Brown and Brown 1972; Strausbaugh and Core 1978). Elevations

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Figure 1. *Wind facilities on forested ridges in the eastern US are associated with large numbers of bat deaths, especially migratory foliage-roosting species like the hoary bat (*Lasiurus cinereus*).*

range from 732–854 m. Twenty-three General Electric SLE 1.5-megawatt (MW) turbines – each with a rotor diameter of 77 m, rotor-swept-area of 4657 m^2, hub height of 80 m, variable rotor speeds from 12–20 revolutions per minute, and a cut-in speed of 3.5 m s^{-1} – are situated at the facility in two "strings"; the western string consists of 15 turbines, sited on land predominated by forest, whereas the eastern string comprises eight turbines in open grassland that was reclaimed after strip mining. In a study conducted simultaneously at this site, searches for bat carcasses indicated no difference in bat fatality rates between the two strings of turbines (Arnett *et al.* 2009). Migratory foliage-roosting bats – including hoary bats (*Lasiurus cinereus*), silver-haired bats (*Lasionycteris noctivagans*), and eastern red bats (*Lasiurus borealis*) – were the species killed most frequently at this site, representing 75% of all bat fatalities recorded (Arnett *et al.* 2009). Tri-colored bat (*Perimyotis subflavus*), big brown bat (*Eptesicus fuscus*), and little brown bat (*Myotis lucifugus*) fatalities also occurred, but in smaller numbers (Arnett *et al.* 2009).

Methods

We included 12 of the 23 turbines at the Casselman site – eight on the western string and four on the eastern string – and defined three turbine treatments: (1) fully operational, (2) cut-in speed at 5.0 m s^{-1} (C5), and (3) cut-in speed at 6.5 m s^{-1} (C6). We used a randomized block design (Hurlbert 1984) with "turbine" as the blocking factor and "night within turbine" as the sampling unit for treatment. Randomization was constrained so that on each night of sampling, each of the three treatments was assigned to four turbines, at least one of which was on the eastern string. Full balance of the design (ie each turbine assigned each treatment for an equal number of nights) was therefore achieved after 15 nights. The entire randomization process was repeated five times, for a total of 75 nights annually, resulting in each treatment occurring on 25 nights within each block (turbine) each year.

We found little nightly variation in wind speed among turbines and assumed wind speeds were similar at all turbines at any given time. The turbines used in our study generally do not rotate at wind speeds < 3.5 m s^{-1} and "feather" (ie turbine blades are pitched parallel with the wind direction and only spin at very low rotation rates if at all; Figure 2). Thus, application of treatments was dependent on ambient wind speed and treatments could have changed throughout the night. When wind speeds were < 3.5 or > 6.5 m s^{-1}, all turbines were in the same operational condition and no curtailment treatments were in effect for those times; treatments were in effect only when wind speeds were between 3.5 and 6.5 m s^{-1}. Evidence of bat mortality (presence of bat carcasses) was observed the day after treatments had been implemented, but it was impossible to determine the precise time of night and under exactly what wind speed fatalities occurred. Our design accounted for this effect by maintaining balance (four replicates of each treatment on each night) and reassigning treatments randomly to turbines each night. Treatment-related mortality was measured as the sum of all individual carcasses of bats estimated to have been killed during the previous night (referred to here as "fresh" carcasses) observed along transects near a given turbine (see below) after a particular treatment assignment, thereby evenly distributing the effect of varying wind speed within a night and among nights across all turbines and treatments in the study.

We delineated rectangular plots 126 m east–west by 120 m north–south (60 m from the turbine mast in each cardinal direction; 15 120 m^2 total area) centered on each turbine sampled; this area represented the maximum possible search area (Arnett *et al.* 2009, 2010). We established transects at 6-m spacing within each plot, and observers searched 3 m on each side of the transect line; thus, the maximum plot in the east–west direction could be up to 126 m wide. We did not attempt to locate fatalities in low visibility habitats (eg forest, dense grass); also, because the area cleared of forest within plots and the amount of dense vegetation in cleared areas varied among turbines, we did not search the entire maximum possible area surrounding most turbines. We used Global Positioning System (GPS) technology to estimate total area searched and area of each habitat within each turbine plot (Arnett *et al.* 2009, 2010).

Daily searches were conducted at turbines from 27 July to 9 October 2008, and from 26 July to 8 October 2009, coinciding with when most (usually > 80% of) bats are killed at wind facilities (Arnett *et al.* 2008). The study was intentionally established as a "blind" test, and searchers were unaware of turbine treatment assignments throughout the study's duration. On each day, visual searches commenced at sunrise and all study areas were searched within 8 hours (Figure 3). When a dead bat was found, observers placed a flag near the carcass and continued searching. Upon completion of searching, observers returned to each flagged carcass and recorded information on species, sex and age (where possible), turbine number, distance from turbine, azimuth from turbine, surrounding habitat characteristics, and estimated time of death (eg ≤ 1 day, 2 days; Figure 3). Carcasses were then removed from the plot.

The experimental unit was the set of 25 nights that received a particular cut-in treatment for each turbine. The total number of fresh carcasses found after each treatment at each turbine was modeled as a Poisson random variable; we fitted these data to a Generalized Linear Mixed Model using PROC GLIMMIX in SAS v 9.2 (SAS Institute 2008), and used the amount of searchable area as a means of standardizing predictions to reflect expected values when 100% of the area was searched (McCullagh and Nelder 1992). The block effect was negligible and results were almost identical when data were fit to a simple log-linear model. We tested whether treatment means differed from one another using an *F* test and tested linear contrasts of means with a single degree-of-freedom chi-square test, corresponding (respectively) to an *F* test and a single degree-of-freedom contrast *t* test in a General Linear Model analysis of variance context.

Figure 2. *A wind turbine shown in a "feathered" position during the curtailment experiment at the Casselman Wind Project in Somerset County, south–central Pennsylvania.*

Results

Between 27 July and 9 October 2008, 32 fresh carcasses of bats were observed near turbines. At least one fresh carcass was found near each turbine, and 10 of the 12 turbines had at least one fatality during a fully operational night. There was no evidence that fatalities occurred disproportionately at some turbines, and fatalities were well distributed among all turbines (Arnett *et al.* 2010). We found three fatalities at turbines curtailed when the preceding night's wind speeds were < 5.0 m s^{-1} (C5), six at turbines curtailed when the preceding night's wind speeds were < 6.5 m s^{-1} (C6), and 23 at fully operational turbines. Mean bat fatalities per turbine over 25 nights was 0.27 (95% confidence interval [CI]: 0.07, 1.05) for those with a 5.0 m s^{-1} cut-in speed, 0.53 (95% CI: 0.20, 1.42) for those with a 6.5 m s^{-1} cut-in speed, and 2.04 (95% CI: 1.19, 3.51) for fully operational turbines (Figure 4a). There was strong evidence that the number of fatalities over 25 nights differed among turbine treatments ($F_{2,33}$ = 7.36, *P* = 0.004). We found no difference between the number of fatalities for C5 and C6 turbines (χ_1^2 = 0.68, *P* = 0.41). Mean total fatalities at fully operational turbines were 5.4 times greater than those at curtailed turbines (C5 and C6 combined; χ_1^2 = 14.11, *P* = 0.0005, 95% CI: 2.08, 14.11). In other words, in 2008, we found that 82% (95% CI: 52–93%) fewer fatalities occurred when turbines were curtailed as compared with when turbines were fully operational.

Likewise, between 26 July and 8 October 2009, 39 fresh carcasses were observed near turbines. Similar to 2008, we found at least one fresh carcass near each turbine each night, and 11 of the 12 turbines had at least one fatality during a fully operational night; again, this indicates that fatalities were well distributed among turbines (Arnett *et al.* 2010). We found eight fatalities at turbines curtailed when the preceding night's wind speeds were < 5.0 m s^{-1} (C5), six at turbines curtailed when the preceding night's wind speeds were < 6.5 m s^{-1} (C6), and 25 at fully operational turbines. Mean bat fatalities per turbine over 25 nights was 0.73 (95% CI: 0.34, 1.56) for those with a 5.0 m s^{-1} cut-in speed, 0.55 (95% CI: 0.23, 1.31) for those with a 6.5 m s^{-1} cut-in speed, and 2.29 (95% CI: 1.46, 3.58) for fully operational turbines (Figure 4b). Again, there was strong evidence that the number of fatalities

Figure 3. *A field biologist records data on bat fatalities. (Inset) A little brown bat (*Myotis lucifugus*) carcass found beneath a wind turbine.*

over 25 nights differed among turbine treatments in 2009 ($F_{2,33}$ = 6.94, P = 0.005). There was no difference between the number of fatalities for C5 and C6 turbines (χ_1^2 = 0.24, P = 0.616). Mean total fatalities at fully operational turbines were 3.6 times greater than those at curtailed turbines (C5 and C6 combined; χ_1^2 = 12.93, P = 0.0003, 95% CI: 1.79, 7.26). In other words, in 2009, we found that 72% (95% CI: 44–86%) fewer fatalities occurred when turbines were curtailed in comparison with the number of fatalities when turbines were fully operational.

Financial costs of curtailment

Lost power output – attributable to the treatments applied during the experiment – was equivalent to approximately 2% of the total projected output for the 12 turbines during the 75-days-per-year we studied. Hypothetically, if the treatments had been applied to all 23 turbines at this facility for the duration of the study (one-half hour before sunset to one-half hour after sunrise for 75 days), the 5.0 m s^{-1} curtailment used would have resulted in 3% lost power output during the study period, but only 0.3% of total annual power output. If the 6.5 m s^{-1} curtailment were applied to all 23 turbines during the study period, lost output would have been 11% of total output for the period and 1% of total annual output. In addition to decreased revenue from lost power, the company also incurred minor costs for staff time to set up processes and controls and to implement curtailment treatments.

Discussion

Our findings were consistent with our prediction that bat fatalities would be significantly reduced by changing turbine cut-in speed and reducing operational hours during low-wind periods, and corroborate the results of a previous study (Baerwald *et al.* 2009). Both studies suggest that bat fatalities may be reduced by at least 44% when turbine cut-in speed is raised to 5.0 m s^{-1}. However, the actual conservation and population-level consequences of reducing fatalities by changing turbine cut-in speed remain unclear, owing to a dearth of information on bat populations – especially for migratory foliage-roosting bats (O'Shea *et al.* 2003; Cryan and Brown 2007). Without a better understanding of population size, demographics, and impacts of fatalities on bat population viability, it is not possible to determine the influences of any single source of mortality or of mitigation strategies on bat populations. It is thought that cumulative impacts of wind-energy development on bat populations can be expected (Kunz *et al.* 2007; Risser *et al.* 2007), in part because bats have low reproductive rates and are slow to recover from population declines (Barclay and Harder 2003). But until adequate demographic information on bat populations is obtained, the context and impact of wind-turbine-related fatalities and reductions in those fatalities remain uncertain.

Increased bat activity (Reynolds 2006; Horn *et al.* 2008) and fatalities (Arnett *et al.* 2008) at wind-power facilities have been related to low wind speed and weather conditions typical of passing storm fronts, but causal mechanisms underlying this relationship remain unclear. Bats may simply be migrating at higher altitudes – ie above turbine rotors – during high-wind periods, when observed fatalities are low. Alternatively, migration may be less efficient for bats in strong wind conditions, decreasing migratory movements by these species during such periods (Baerwald *et al.* 2009). Arrivals of hoary bats on Southeast Farallon Island off the coast of California during the fall migration were related to periods of low wind speed, dark phases of the Moon, and low barometric pressure, supporting the hypothesis that the timing of migration events is predictable (Cryan and Brown 2007). Low barometric pressure can coincide with the passage of cold fronts that may be exploited by migrating birds and bats (Cryan and Brown 2007). Regional climate patterns, as well as local weather conditions, can be used to predict the foraging and migratory activity of bats (Erickson and West 2002). On a local scale, strong winds can influence the abundance and activity of insects, which in turn influence the activity of insectivorous bats; such bats are known to reduce foraging activity during periods of rain, low temperatures, and strong winds (Eckert 1982; Erickson and West 2002). Episodic hatchings of insects that are likely associated with "favorable" weather and flight conditions may periodically increase local bat activity (Hayes 1997; Erickson and West 2002). More studies are needed to elucidate these patterns, as well as migration behavior, across regions to develop robust predictive models of environmental conditions preceding fatality events and for predicting when turbine curtailment will be most effective in reducing bat fatalities.

Our study design differs from that of Baerwald *et al.* (2009) in part because we were able to change allocation of treatments each night. By reassigning our treatments among turbines each night, we minimized the potential influence that turbine location might have had on mortality within the project. Additionally, any differences in searchable area among turbines were contained in the turbine blocking factor. Our comparison among treatments was within turbines, so we were able to use a simple count of fresh carcasses, unadjusted for observation bias, but using searchable area as an offset (McCullagh and Nelder 1992). The almost even distribution of fatalities among turbines indicates that there was no strong distinction in fatality among turbines, so detected effects can be reasonably attributed to the treatments. Our design is powerful, but it assumes correct determination of carcasses as "fresh" by field observers. We do not believe our misclassification rate was high (Arnett *et al.* 2009), nor did we have reason to believe the probability of misclassifying a carcass as fresh was associated with treatments, because observers were unaware of the treatment allocation scheme. Thus, errors in classification of fresh carcasses should be equal among turbines and treatments and should not have influenced results of our study. Moreover, we compared bat fatalities at 12 experimental turbines to those at 10 fully operational turbines at the Casselman facility that were sampled during the same time period for a different study (see Arnett *et al.* 2010). We estimated bat fatalities per turbine (ie all carcasses found and corrected for field bias) to be 1.48–5.09 times greater ($\bar{x}$ = 2.57) in 2008 and 1.23–2.58 times greater ($\bar{x}$ = 1.80) in 2009 at the fully operational turbines than at the experimental turbines (Arnett *et al.* 2010). These findings provide further support for our contention that reducing operational hours during low-wind periods reduces bat fatalities.

Numerous factors influence power loss – and thus financial costs – of raising cut-in speed of wind turbines to reduce bat fatalities. These factors include type and size of wind turbines, market or contract prices of power, electricity purchase agreements and associated fines for violating delivery of power, variation in temporal consistency, and speed and duration of wind across different sites. Estimated power loss during our experiment was considerably different from that reported by Baerwald *et al.* (2009), primarily because they projected estimated losses only for a 30-day period and for just the 15 turbines used in their experiment, whereas we projected power loss for a 75-day period and for all 23 turbines at the site, not just for our treatment turbines. Also, technological limitations of turbines studied by Baerwald *et al.* (2009) forced them to change cut-in speed for the entire duration of the study. Lost power production resulting from our experimental treatments was markedly low when considering total annual productivity, but power loss was three times higher for the 6.5 m s^{-1} change in cut-in speed as compared with the 5.0 m s^{-1} treatment. This difference in power loss reflects the cubic effect of wind speed on power production (Albadi and El-Saadany 2009). Contrary to our prediction, we found no difference in bat fatalities between the 5.0 m s^{-1} and 6.5 m s^{-1} treatments during either year of the study, and curtailment at 5.0 m s^{-1} proved to be far more cost-effective. However, we

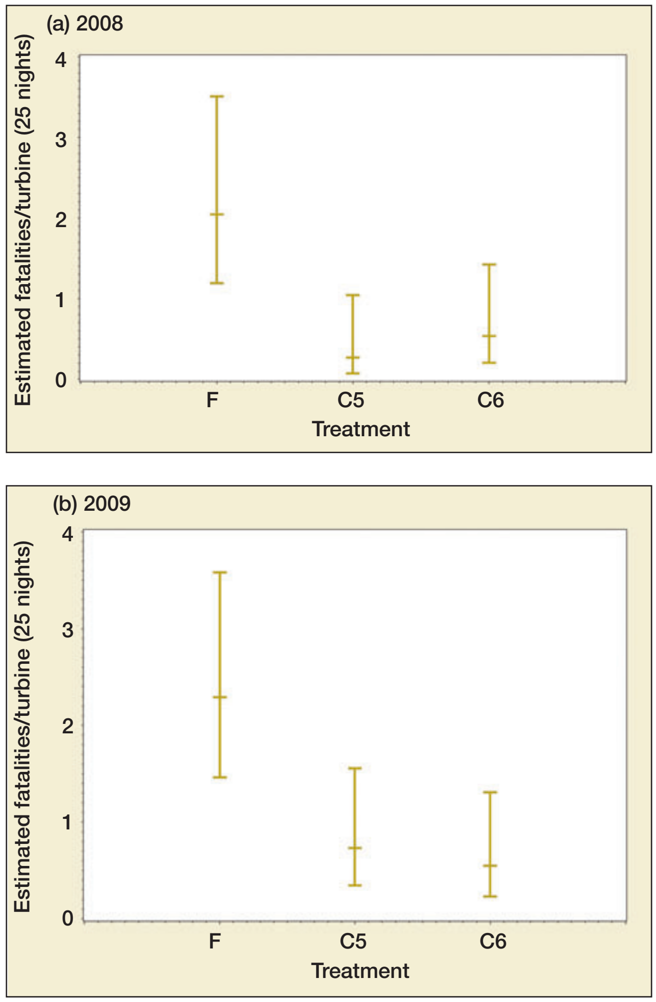

Figure 4. *Estimated number of fresh carcasses of bats per turbine, and 95% confidence intervals, over 25 nights for each of three treatments: cut-in speed at 5.0 m s^{-1} (C5), cut-in speed at 6.5 m s^{-1} (C6), and fully operational (F, no change to cut-in speed) for 12 turbines at the Casselman Wind Project in Somerset County, Pennsylvania; (a) 27 July to 9 October 2008 and (b) 26 July to 8 October 2009.*

found little differentiation in the amount of time different cut-in speed treatments were in effect (WebFigure1), which may explain in part why we found no difference in bat fatalities between the two treatments.

Our study is the first to randomly allocate different cut-in speeds on a nightly basis and to evaluate multiple cut-in speeds. We demonstrated reductions in average nightly bat fatality ranging from 44–93%, with marginal annual power loss. Our findings suggest that increasing cut-in speeds at other wind facilities during summer and fall months will reduce bat fatalities. Additional studies evaluating changes in turbine cut-in speed among different sizes and types of turbines, wind regimes, habitat types, and species of bats (eg Brazilian free-tailed bats, *Tadarida brasiliensis*) would be useful in assessing the general effectiveness of this mitigation strategy. Developing a broader understanding of the demographics and population viability of bats is fundamental in fully evaluating the implications of conservation strategies at wind facilities, but these data are unlikely to be available for most species of bats in the immediate future. We contend that wind operators should implement curtailment measures at turbine sites characterized by high or moderately high numbers of bat fatalities and that such sites warrant mitigation efforts even in the absence of bat population data.

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