A SYNTHESIS OF OPERATIONAL MITIGATION STUDIES TO REDUCE BAT FATALITIES AT WIND ENERGY FACILITIES IN NORTH AMERICA

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EXECUTIVE SUMMARY

Widespread and often extensive fatalities of bats have increased concern about impacts of wind energy development on bats and other wildlife. Minimizing these fatalities is critically important to both bat conservation and public acceptance of wind-energy development. Currently, only operational mitigation (stopping turbine blades from spinning) during predictable high risk periods has demonstrated effective reductions of fatalities of bats.

We synthesized information from 10 different operational mitigation studies in North America. Most studies found at least a 50% reduction in bat fatalities when turbine cut-in speed (wind speed at which turbines begin producing electricity into the power grid) was increased by 1.5 m/s above the manufacturer's cut-in speed. Similar reductions in bat fatality were reported by one study that implemented a raised cut-in speed given temperatures were above 9.5°C. One study demonstrated equally beneficial reductions with a low-speed idling approach, while another discovered that feathering turbine blades (pitched 90^{o} and parallel to the wind) at or below the manufacturer's cut-in speed resulted in up to 72% fewer bats killed when turbines produced no electricity into the power grid. Other studies that did not demonstrate statistically significant effects could be explained by lack of treatments being implemented during the study (i.e., winds were either too low or high to enable comparison of treatments), and the relatively low reduction in bat fatality (approximately 20–38%) at one study may be explained by the high percentage of Brazilian free-tailed bats (*Tadarida brasiliensis*), a species known to fly at higher wind speeds. Few studies have disclosed actual power loss and economic costs of operational mitigation, but those that have suggest that <1% of total annual output would be lost if operational mitigation were employed during high risk periods for bat fatalities. In addition to the lost power revenues, wind energy companies also incurred costs for staff time to set up the processes and controls, and to implement the curtailment from offsite 24-hour operations centers.

We conclude that increasing cut-in speed between 1.5 and 3.0 m/s or feathering blades and slowing rotor speed up to the turbine manufacturer's cut-in speed yields substantial reductions in fatality of bats. Given the magnitude and extent of bat fatalities worldwide, the conservation implications of our findings are critically important. Research efforts should continue to focus on incorporating additional variables, in addition to wind speed (e.g., temperature, time of night, bat activity) into treatments and explore using automated systems to maximize wind production while still minimizing bat fatalities. Although additional studies are needed to optimize operational mitigation, we believe increasing cut-in speeds to the levels tested in these studies (generally 1.5–3.0 m/s) offers an ecologically sound and economically feasible strategy for reducing bat fatalities at wind energy facilities and should be implemented broadly.

INTRODUCTION

Wind-generated electricity is renewable, produces no emissions and consumes no water (Union of Concerned Scientists. 2011), but often high fatalities of bats have been recorded at wind energy facilities worldwide (Durr and Bach 2004, Kunz et al. 2007, Arnett et al. 2008, Baerwald and Barclay 2009, Rydel et al. 2010). Bat fatalities at wind energy facilities received little attention in North America until high numbers of fatalities were reported in the eastern U.S. (Johnson 2005, Arnett 2005, Arnett et al. 2008). Recent estimates suggest that cumulative bat fatalities at wind energy facilities in North America from 2000–2011 ranged from over 650,000 to more than 1.3 million (Arnett and Baerwald 2013). Based on installed capacity at the end of 2011, an additional 196,190–395,886 bats may have been killed in 2012 (Arnett and Baerwald 2013). These fatalities raise concern about 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, Frick et al. 2010) and continued expansion of both onshore and offshore wind energy development is anticipated worldwide (EIA 2011, U.S. Department of Energy 2011).

Previous studies indicate that a substantial portion of bat fatalities occur during relatively low-wind conditions during the late summer-fall bat migration period (Arnett et al. 2008, Rydell et al. 2010). Bats significantly reduce their flight activity during periods of rain, low temperatures, and strong winds (Erickson and West 2002, Reynolds 2006, Horn et al. 2008, Weller and Baldwin 2012) and are less at risk to collision with wind turbines under these conditions. Thus, altering turbine operations when bats are most at risk was proposed as a possible means of reducing impacts to bats by Kunz et al. (2007) and Arnett et al. (2008). Indeed, several previous or concurrent studies have shown that raising turbine cut-in speeds (i.e., the wind speed at which the generator is connected to the grid and producing electricity; U.S. Fish and Wildlife Service 2012) from the manufactured speed (usually 3.5–4.0 m/s for modern turbines) by 1.5–3.0 m/s results in significant reductions in bat fatalities compared to normally operating turbines (Baerwald et al. 2009, Arnett et al. 2011).

However, altering turbine operations, even on a limited basis, potentially poses operational and financial difficulties for project operators. Normally, turbines “freewheel” at wind speeds below operational cut-in speeds. Even though turbines are not producing any electricity while freewheeling, they still may rotate at high speeds that are lethal to bats. Thus, altering turbine operations to eliminate blade movement at or below normal cut-in speed also may reduce bat fatalities without raising cut-in speeds.

We synthesized information on existing studies that tested the effectiveness of operational mitigation on reducing fatalities of bats at wind facilities in North America. Our objectives were to: 1) present key information on each study and summarize general findings; 2) identify unifying themes from these studies; 3) determine the economic costs of experiments and estimated costs under different curtailment prescriptions and timeframes; and 4) assess key lessons learned and offer suggestions for future research to optimize operational mitigation so as to reduce economic costs while maintaining effectiveness of mitigation.

REVIEW OF EXISTING STUDIES

We synthesized information from operational mitigation studies conducted at 10 existing wind energy facilities in North America, 2 in Canada and 8 in the U.S. (Appendices 1–3). We summarized information regarding each site's location and characteristics of study sites, surrounding habitat, turbines used, duration of studies, methods employed, and type of operational mitigation tested. We used data from 2 studies published in scientific journals (Baerwald et al. 2009, Arnett et al. 2011), 6 studies reported in publicly-available reports (Good et al. 2012, Young et al. 2011, 2012, 2013, Stantec Consulting Ltd. 2012, Martin et al. 2013, Tidhar et al. 2013), and 2 studies conducted by some of the authors (WEST Inc., unpublished data), but location and project owner are anonymous. For the purposes of this review, we used the following terminology and definitions, which are consistent with those used by Arnett et al. (2011) and U.S. Fish and Wildlife Service Land-based Wind Energy Guidelines (2012).

> *Curtailment*: The act of limiting the supply of electricity to the grid during conditions when it would normally be supplied. This is usually accomplished by cutting-out the generator from the grid and/or feathering the turbine blades.
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> *Cut-in speed*: The wind speed at which the generator is connected to the grid and producing electricity. The manufacturer's set cut-in speed for most contemporary turbines is between 3.0 and 4.0 m/s. For some turbines, their blades will spin at full or partial RPMs below cut-in speed when no electricity is being produced.
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> *Feathering or Feathered*: Adjusting the angle of the rotor blade parallel to the wind, or turning the whole unit out of the wind, to slow or stop blade rotation. Normally operating turbine blades are angled perpendicular to the wind at all times.
>
> *Free-wheeling*: Blades that are allowed to slowly rotate even when fully feathered and parallel to the wind. In contrast, blades can be "locked" and cannot rotate, which is a mandatory situation when turbines are being accessed by operations personnel.
>
> *Increasing cut-in speed.* The turbine's computer system (referred to as the Supervisory Control and Data Acquisitions or SCADA system) is programmed to a cut-in speed higher than the manufacturer's set speed, and turbines are programmed to stay feathered at 90^{o} until the increased cut-in speed is reached over some average number of minutes (usually 5–10 min), thus triggering the turbine blades to pitch back "into the wind" and begin to spin normally.

We also analyzed turbine rotor speed in relation to wind speed for several different types of turbines to assess the proportion of the night when tip speeds were >22.4 m/s (50 mph) at or below each turbine's normal manufacturer's cut in speed. Turbine operation data included turbine rotor speed (rpm) and wind speed (m/s) at five- or ten-minute intervals (depending on the facility). Wind speeds were assigned to speed classes with 0.5 m/s widths (i.e., 0–0.5 m/s, 0.5–1.0 m/s,…7.5–8.0), and rotor speeds were averaged across wind speed classes during the period over which curtailment treatments were applied. Resulting means were smoothed with a locally weighted scatterplot smoother (lowess) in program R, and plotted for visual interpretation.

SUMMARY OF KEY FINDINGS

Alberta, Canada

Baerwald et al. (2009) conducted this study at a wind energy installation in southwestern Alberta, Canada, approximately 40 km east of the Rocky Mountains. This facility had 39 Vestas V80 1.8-megawatt (MW) turbines with a nominal cut-in speed of 4.0 m/s. The 80 m diameter rotors were situated on top of 65 m towers. Turbines were arranged in 8 rows running northwest to southeast. The facility was located in a mixed agriculture and native and seeded grassland landscape, with 31 turbines in cultivated mixed agricultural fields and 8 in seeded pasture. Fatalities at this site were dominated by 2 species, hoary (*Lasiurus cinereus*) and silver-haired bats (*Lasionycteris noctivagans*).

The study period was timed to cover the peak period of migration by hoary and silver-haired bats (1 August–7 September 2007). Twenty-nine turbines were searched on a weekly basis during the experiment. Turbines were randomly chosen to receive 1 of 3 treatment groups: 1) 8 were control turbines (normally operating at a cut-in speed of 4.0 m/s), 2) 15 were treatment turbines, with cut-in speeds raised to 5.5 m/s, and 3) 6 were experimental idling turbines, with the blades manipulated to change the pitch angle, causing them to be motionless during low wind speeds. To locate bat carcasses, spiral transects placed 7 m apart were walked out to a distance of 52 m from the turbine. To control for any potential inherent difference in bat fatality rates between the experimental and control turbines, bat fatality rates for these turbines were estimated during post-construction fatality monitoring studies, when all turbines were fully operational, in 2005 and 2006. Bat fatality rates between treatment and control turbines were compared using a one-way analysis of variance (ANOVA) and a Tukey's test. Effectiveness of treatments by species was compared using Kruskal-Wallis and Wilcoxon/Mann-Whitney tests because the data could not be normalized.

In 2006, during the same time period and prior to the operational mitigation experiment, there were no significant differences in bat fatality rates between the turbines later selected as experimental or control for the 2007 study. This suggests there were no inherent differences in fatality rates among treatments prior to the experiment. In 2007, both sets of experimental turbines killed fewer bats than control turbines (control = 19.0 ± 2.7 bats/turbine, 5.5 m/s turbines = 7.6 ± 2.0 bats/turbine, idling turbines = 8.1 ± 3.1 bats/turbine; ANOVA, $F_{2, 26} = 6.34$, *P* = 0.006). There was no significant difference between the 2 sets of experimental treatments (Tukey's test, *P* >0.05). Although fatality rates for each species of bat were lower at both sets of experimental turbines, they were not significantly reduced when analyzed separately (hoary bat: control = 11.7 ± 2.8 bats/turbine, 5.5 m/s turbines = 4.6 ± 1.3 bats/turbine, idling turbines = 6.1 ± 1.7 bats/turbine; Kruskal-Wallis test $\chi^2 = 5.07$, *P* = 0.08; silver-haired bat: control turbines = 5.6 ± 1.7 bats/turbine, 5.5 m/s turbines = 2.3 ± 0.6 bats/turbine, idling turbines = 1.7 ± 1.0 bats/turbine; Kruskal-Wallis test $\chi^2 = 4.56$, *P* = 0.10). However, when Baerwald et al. (2009) combined the 2 experimental treatments and compared them to control turbines, the experimental turbines had lower fatality rates for each species (hoary bat: control turbines 11.7 ± 2.8 bats/turbine, experimental turbines 5.0 ± 1.0 bats/turbine; Wilcoxon test χ^2_1= 4.4, *P* <0.05; silver-haired bat: control = 5.6 ± 1.7 bats/turbine, experimental = 2.1 ± 0.05 bats/turbine; Wilcoxon test χ^2_1= 4.2, *P* <0.05).

Casselman, Pennsylvania 2008 and 2009

Arnett et al. (2011) reported on an operational mitigation study at Iberdrola Renewables' Casselman Wind Power Project (CWPP) located in Somerset County near Rockwood, Pennsylvania. There are 23 GE SLE 1.5-MW turbines at the CWPP each with a rotor diameter of 77 m, rotor-swept-area of 4,657 m^2, hub height of 80 m, variable rotor speeds from 12–20 rpm, and a cut-in speed of 3.5 m/s. The facility is located within the Appalachian mixed mesophytic forests ecoregion comprising the moist broadleaf forests that cover the plateaus and rolling hills west of the Appalachian Mountains. The turbines at this facility are situated in 2 "strings"; the western string consisted of 15 turbines sited on land predominated by forest, whereas the eastern string comprised 8 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, silver-haired bats, 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).

Experiments to test the effectiveness of changing turbine cut-in speeds on reducing bat fatality were implemented in 2008 and 2009. Arnett et al. (2011) included 12 of the 23 turbines at the Casselman site –8 on the western string and 4 on the eastern string– and defined 3 turbine treatments: (1) fully operational, (2) cut-in speed at 5.0 m/s, and (3) cut-in speed at 6.5 m/s, with 4 replicates on each night of the experiment. A randomized block design (Hurlbert 1984) was employed 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 (i.e., 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. When wind speeds were < 3.5 or > 6.5 m/s, 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. The researchers found little nightly variation in wind speed among turbines and assumed wind speeds were similar at all turbines at any given time.

Daily searches were conducted at the 12 experimental turbines from 27 July to 9 October 2008, and from 26 July to 8 October 2009. During this same period, daily searches also were conducted at 10 of the remaining 11 turbines that were part of a different study to determine relationships between bat activity and fatality. These 10 turbines provided an additional estimate of bat fatalities under unmodified operating conditions. Bat carcasses were 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. The design employed accounted for this effect by maintaining balance (four replicates of each treatment on each night) and reassigning treatments randomly to turbines each night. Two different analyses were used to evaluate effectiveness of changing turbine cut-in speed. In the first analysis the 12 experimental turbines were used to determine differences in fatality due to level of curtailment; and for the other analysis 22 turbines were used to determine differences in total fatalities between curtailed and fully operational turbines. 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; the data were fit to a Generalized Linear Mixed Model 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. Treatment means were tested for differences from one another using an *F* test and linear contrasts of means were tested 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. In the second analysis, the turbine was the experimental unit, and estimated fatalities, corrected for searcher efficiency and carcass removal, at the 12 turbines included in the experiment were compated to the 10 remaining turbines that were fully operational at all times. All carcasses found at a turbine were used to estimate the total number of bat fatalities that occurred at each turbine and to compare fatalities using one-way ANOVA.

In 2008, 32 fresh bat fatalities were found at the 12 treatment turbines; fatalities were well distributed among all turbines. There was strong evidence that the estimated number of fatalities differed among turbine treatments ($F_{2,33} = 7.36$, $p = 0.004$). There was no difference between the number of fatalities for the 5.0 and 6.5 m/s treatments ($\chi2 = 0.68$, $p = 0.41$). Total fatalities at fully operational turbines were estimated to be 5.4 times greater on average than at curtailed turbines (5.0 and 6.5 m/s treatments combined; $\chi12 = 14.11$, $p = 0.0005$, 95% CI: 2.08, 14.11); in other words, 82% (95% CI: 52–93%) of all fatalities at curtailment turbines likely occurred when the turbines were fully operational. For the second analysis, estimated total bat fatalities per turbine (i.e., all 3 carcasses found and corrected for field bias) were 1.48–5.09 times greater (mean = 2.57) at control turbines relative to curtailed turbines.

In 2009, 39 fresh bat fatalities were found at the 12 treatment turbines. Similar to 2008, there was strong evidence that the estimated number of fatalities 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 5.0 and 6.5 m/s treatments ($\chi2 = 0.24$, $p = 0.616$). Total fatalities at fully operational turbines were estimated to be 3.6 times greater on average than at curtailed turbines (C5 and C6 combined; $\chi2 = 12.93$, $p = 0.0003$, 95% CI: 1.79, 7.26); in other words, 72% (95% CI: 44–86%) fewer fatalities were recorded when turbines were curtailed than when they were fully operational. For the second analysis, estimated total bat fatalities per turbine (i.e., all carcasses found and corrected for field bias) were 1.23–2.58 times greater (mean = 1.80) at control turbines relative to curtailed turbines. The comparisons between control and curtailed turbines in both years of the study are conservative estimates of the difference because all treatment turbines were fully operational one-third of the time during the study.

Mount Storm, West Virginia 2010

Young et al. (2011) conducted an operational mitigation study at NedPower's Mount Storm Wind Energy Facility located in Grant County, in northeast West Virginia. This facility has 132 Gamesa G80 2-MW wind turbines mounted on 78-m hub height with a maximum height above ground of 118 m and an 80-m rotor-swept area. These turbines have a manufacturer's cut-in speed of 4.0 m/s, are variable speed and blades spin at approximately 9.1–19.0 rpm. The Project is located on the primary ridgeline of the Allegheny Mountains known as the Allegheny Front. Hardwood forest on the site consists primarily of oaks, maples, hickories, black cherry, black and yellow birch, and beech trees, while the spruce and conifer type consists of red spruce, hemlock, and a variety of pines, including red, pitch, and Virginia, used for reclamation of abandoned surface mines. Much of the site was previously strip mined for coal and consists of reclaimed areas. This facility is approximately 19 km long from north to south and turbines are generally positioned in rows of variable length oriented along a northeast to southwest axis (parallel to the primary ridgeline of the Allegheny Front). Eastern red bats, hoary bats, and silver-haired bats were killed most frequently at this facility in both years of the study.

The study included a design that incorporated weather forecasting to predict when bat mortality would be high based on wind speed. The risk to bats associated with freewheeling turbines (those spinning below the normal cut-in speed when they are not producing electricity) was evaluated as part of this study. The study also was designed to investigate whether limiting blade rotation of the turbines for first half of the night (approximately sunset plus 5 hrs) or the second half of the night (sunrise minus 5 hrs) was more effective. For nights when wind speeds were predicted to be below the normal turbine cut-in speed (4 m/s), turbine rotation was limited by feathering the turbine blades (pitching them more parallel to the wind) so there was only minimal rotation (<1 rpm). Normally, the turbines freewheel or spin at up to 9 rpm in winds under the cut-in speed of 4 m/s. The effect of restricting turbine rotation up to the cut-in speed for the first half of the night was compared to restricting turbine rotation during the second half of the night. Both of these treatment groups of turbines were compared to turbines that were allowed to operate under normal conditions to help evaluate when during a night bats are at greatest risk.

The study was conducted from 15 July–13 October 2010. Daily searches were employed at 24 turbines that were randomly assigned to 3 groups of 8 turbines each. Each turbine group was rotated weekly between the following treatments (I, II, III), such that each group received each treatment for 4 weeks over the duration of the late summer-fall study period, and groups were rotated weekly:

I. Turbine rotation restricted for first half of the night (approximately 5 hrs after sunset).

II. Turbine rotation restricted for second half of the night (approximately 5 hrs prior to sunrise).

III. Control group; no change to normal turbine operations.

Since treatments were cancelled on many nights during the study, only fatalities assumed to have occurred the previous night were used in the analysis. Fatality rates for each treatment were calculated along with corresponding 90% bootstrapped confidence intervals. Estimates without overlapping confidence intervals were considered significantly different. In addition to using fatality estimates, differences in treatments were examined by building a Poisson model to determine the relative difference in fatality rates based on the type of treatment. The magnitude of model coefficients represents the relative ratio of fatality rates between turbines subject to the treatments and those with no treatment (i.e., normal operations). Tests for variable selection were used to assess the statistical significance of the treatment covariates. The analysis for the turbine operations study considered two different data sets: those including nights when the treatments were cancelled because the weather forecast was for wind speeds greater than 4.0 m/s, and those excluding nights when treatments were cancelled (i.e., only those nights when turbine rotation was restricted).

When nights with cancelled treatments were included, 256 bat casualties were found during the study period (15 July–13 October) and were included in the turbine operations analysis that included nights with cancelled treatments. One-hundred eleven bat carcasses were found at control turbines compared to 59 bat carcasses found at turbines with rotation restricted during the first half of the night (treatment I) and 86 bat carcasses found at turbines with rotation restricted during the second half of the night (treatment II). This resulted in observed daily fatality rates and corresponding 90% bootstrap confidence intervals of 0.151 (0.114–0.187), 0.080 (0.052–0.109), and 0.117 (0.093–0.141) bats/turbine/study period for control, treatment I, and treatment II, respectively. Lack of overlap between confidence intervals for observed fatality rates under treatment I and control suggest a significant difference between casualties at turbines with rotation restricted during the first part of the night versus control turbines ($\alpha = 0.10$). Overlapping confidence intervals for observed fatality rates under treatment II and control and between treatments I and II suggest that there was no difference between bat fatalities at turbines with rotation restricted during the second part of the night versus control turbines or treatment I turbines ($\alpha = 0.10$).

Poisson modeling of observed fatality rates resulted in significant treatment covariates. The parameter estimate for treatment I was -0.63, which implies that the odds of a fatality occurring when turbine rotation is restricted during the first part of the night are 1.88 times less likely than with normal operations, with all other variables being equal. Variable selection tests for this covariate were significant ($z = -3.92$, $p < 0.01$), suggesting that restricting turbine rotation during the first part of the night has a significant effect in explaining differences in observed fatality rates among treatment I and control turbines. Parameter estimates for restricted turbine rotation during the second part of the night also were significant in the model ($z = -1.78$, $p = 0.08$) with a value of -0.26. This corresponds to approximately 1.29 times the odds of a fatality occurring with normal operations than when turbine rotation is restricted during the second part of the night, all other variables being equal. A nightly paired t-test comparison between the two treatments (first part of night, and second part of night) showed that the difference between them was significant at $\alpha = 0.10$ ($t = -1.84$, $p = 0.068$).

When nights with cancelled treatments were excluded, 104 bat carcasses were found during the study period (15 July–13 October) on nights when the two treatments were in place. Fifty-nine of these carcasses were found at control turbines during treatment nights, compared to 16 bat carcasses found at turbines with rotation restricted during the first half of the night (treatment I) and 29 bat carcasses found at turbines with rotation restricted during second half of the night (treatment II). This resulted in observed daily fatality rates and corresponding 90% bootstrap confidence intervals of 0.18 (0.13–0.22), 0.05 (0.03–0.07), and 0.09 (0.06–0.12) bats/turbine/study period for control, treatment I, and treatment II conditions, respectively. Non-overlapping confidence intervals for observed fatality rates under each treatment suggest that fatality rates at turbines with rotation restricted is lower than rates at control turbines ($\alpha = 0.10$).

Poisson modeling of observed fatality rates resulted in significant treatment covariates. The parameter estimate for the treatment I was -1.3, which implies that the odds of a fatality occurring when turbine rotation is restricted during the first part of the night are 3.69 times less likely than with normal operations, with all other variables being equal. Variable selection tests for this covariate were significant ($z = -4.63$, $p < 0.01$), supporting the conclusion that restricting turbine rotation during the first part of the night explained differences in observed fatality rates. Parameter estimates for restricted turbine rotation during the second part of the night also were significant in the model ($z = -3.13$, $p < 0.01$) with a value of -0.71. This corresponds to approximately 2 times the odds of a fatality being recorded with normal operations than when turbine rotation is restricted during the second part of the night, all other variables being equal. A nightly paired t-test comparison between the two treatments (first part of night, and second part of night) showed that the difference between them was not significant ($t = -1.57$, $p = 0.124$).

For both analyses, restricting turbine rotation during the first half of the night reduced bat mortality by 47% and 72%, respectively, which were substantially lower than the control group. For the second half of the night, the reduction in bat mortality was not as substantial, but still resulted in 22% and 50% reduction for the two analyses, respectively.

Mount Storm, West Virginia 2011

This study conducted by Young et al. (2011) was based on results from the previous year that showed a reduction in bat mortality resulted from feathering turbine blades below the 4.0 m/s cut-in wind speed on nights when the wind was predicted to be low. For the 2011 study, the turbine blade feathering was automated so that the turbines would self-regulate as wind speeds changed. The general process for turbine operations was that if wind speeds dropped below the normal cut-in speed of 4.0 m/s at the turbine for a period of 6 min, a pause command was sent to the turbine which initiated blade feathering. Conversely, if the wind speed rose above 4.0 m/s for a period of 6 min the turbine was programmed to run normally.

To evaluate the effects of this treatment on bat mortality, the 24 turbines in the study were assigned to two groups of 12 turbines each for the duration of the late-summer and fall monitoring (16 July 16–15 October). Each turbine group was rotated weekly between the following two treatments (I and II), such that each group of turbines would receive each treatment for six weeks over a 12-week study period:

I. Blades feathered automatically.
II. Control group; allowed to operate normally with no automated blade feathering.

Groups were rotated weekly (i.e., repeated six times over 12 weeks). The analysis for the turbine operations study compared the bat mortality rate between the two treatment groups and looked at the correlation between bat mortality rate and percent of the night that turbines were feathered for the group for which the blades were feathered automatically in response to changes in wind speed.

During the study 39 fresh bat carcasses were found at turbines that had the automatic blade feathering and 43 fresh bat carcasses were found at control turbines. In general, the number of bat carcasses found each week by group was similar throughout the study. A Chi-square test for comparison of fatality counts was $\chi 2 = 0.2459$, df = 1, p = 0.62. The chi-square test indicated no significant difference ($p > 0.1$) in fatality counts (weighted by effort) between control and feathered turbines. Bat fatality estimates for the study period were 6.45 and 7.35 bats/turbine for the feathered and control turbines, respectively.

Turbine data from the project for the period 16 July through 13 October were used to estimate proportion of night that feathering was in place and was correlated with nightly bat fatality rates for Group I and Group II turbines. There was an increase in nightly bat fatality when the proportion of night when feathering was taking place increased for Group I turbines. Feathering at Group I turbines reduced bat mortality when all study dates were considered (r = 0.225, p = 0.052), and when only planned feathering dates were considered (r = 0.365, p = 0.037). Feathering at Group II turbines did not reduce bat mortality when all study dates were considered (r = 0.079, p = 0.498), and when only planned feathering dates were considered (r = 0.074, p = 0.640). More than 60% of the weather data readings collected did not have rpm readings, which did not allow for effectively determining when blade feathering was active during the study.

Fowler Ridge, Indiana 2010

The Fowler Ridge Wind Farm (FRWF) is located in Benton County, Indiana, and consists of 355 wind turbines in three operating phases with a total capacity of 600 MW. Phase I had 122 Vestas V82 1.65-MW turbines and 40 Clipper C96 2.5-MW turbines, Phase II had 133 1.5-MW General Electric (GE) SLE turbines, and Phase III had 60 Vestas V82 1.65-MW turbines. All three turbine models were located on 80-m towers, while rotor diameters were 77 m for the GE turbines, 82 m for the Vestas V82 turbine, and 96 m for the Clipper C96 turbine. The standard cut-in speed for all three turbines was 3.5 m/sec. Of the roughly 59,000 acres within one half-mile (0.80 km) of turbine locations, row crops, primarily corn and soybeans, comprised about 93% of the land cover. As with most sites in the East and much of the Midwest, eastern red bats, hoary bats, and silver-haired bats made up the greatest proportion of fatalities at this facility in both years of the study.

Experiments were conducted in 2010 and 2011 using different methods. In 2010, bat fatality rates were measured at two different cut-in speed adjustments or treatments and two sets of control turbines with no cut-in speed adjustment (Good et al. 2011). Nine turbines were randomly selected from the sample of 36 turbines being searched daily for use as a reference sample for the duration of the study. Treatments for cut-in speed adjustment and a second set of reference turbines were rotated on a weekly basis among the remaining 27 daily search turbines, with nine turbines assigned to each group. The treatments included turbines with cut-in speeds raised to 5 and 6.5 m/s. Turbines were randomly assigned to control and treatment groups among the 27 turbines, and treatments were distributed temporally to ensure each turbine received 3–4 weeks of treatment or control cut-in speeds. Square 80 x 80 m plots at the 36 turbines were maintained relatively free of vegetation through use of mowing and herbicides.

Fatality rates for each cut-in speed were calculated along with corresponding 90% bootstrap confidence intervals. Estimates without overlapping confidence intervals were considered significantly different. In addition, differences in bat fatality between cut-in speed treatments were examined by building a Poisson model to determine the relative difference in fatality rates based on cut-in speed. The magnitude of model coefficients represents the relative ratio of fatality rates between curtailed turbines and those with no cut-in speed adjustment. Tests for variable selection were used to assess the statistical significance of the cut-in speed covariates. The estimated time since death for each bat carcass was evaluated to determine which curtailment condition the bat fatality occurred during. Carcasses of bats that were estimated to have died prior to the start of the study and carcasses where the length of time since death could not accurately be determined were not included in the analysis.

Data on estimated time of death were used to determine the curtailment condition that the fatality most likely occurred during. Two hundred fifty-two bat carcasses were determined to have occurred at turbines while under normal operational cut-in speeds of 3.5 m/s (control). This compares to 63 dead bats at turbines with cut-in speeds raised to 5.0 m/s and 27 dead bats found at turbines with cut-in speeds raised to 6.5 m/s. Bat fatalities were primarily eastern red bats (71.6%), followed by silver-haired bats (18.7%), hoary bats (15.5%), big brown bats (2.3%), tri-colored bats (0.3%) and Indiana bats (*Myotis sodalis*; 0.3%).

The observed fatality rates and corresponding 90% bootstrap confidence intervals were 14.0 (11.6–16.5), 7.0 (7.0–9.1), and 3.0 (1.8–4.2) bats/turbine for control, 5.0 m/s, and 6.5 m/s treatment conditions, respectively. Non-overlapping confidence intervals for observed fatality rates under each cut-in speed condition indicate a significant difference between treatments. An approximate 50% reduction in overall bat mortality was observer by raising the cut-in speed from 3.5–5.0 m/s, while an approximate 78% reduction in overall bat mortality was realized by raising the cut-in speed from 3.5–6.5 m/s.

Poisson modeling of observed fatality rates resulted in significant cut-in speed covariates and week effect covariate. Although blocking by week can potentially eliminate temporal effects, a definite trend was observed by week and therefore week was left as a fixed effect in the model to account for this variation. The parameter estimate for the 5.0 m/s cut-in speed was -0.69, which corresponds to a 0.5 = exp (-0.69) incident rate ratio (i.e., the ratio of the fatality rate occurring at turbines with cut in speeds of 5.0 m/s to the fatality rate occurring at turbines with cut-in speeds of 3.5 m/s) supporting a conclusion of a 50.0% reduction in fatality rates when turbines have a cut-in speed of 5.0 m/s having adjusted for all other model variables. The corresponding 90% confidence interval for the 5.0 m/s incident rate ratio implies a reduction in fatality rates of between 37.3% and 60.6%. The parameter estimates for the 6.5 m/s cut in speed treatment also were significant with a value of -1.54, which corresponds to a 0.2 incident rate ratio. This implies a reduction of 78.6% in fatality rates for turbines curtailed below wind speeds of 6.5 m/s with a 90% confidence interval of 70.5–84.9%. Non-overlapping confidence intervals between cut-in speeds of 5.0 and 6.5 m/s suggest a significant difference in fatality rates between these two treatments. The incident rate ratio between treatment types is 0.4 which corresponds to a 57.3% reduction in fatalities at 6.5 m/s cut-in speeds when compared to 5.0 m/s cut-in speeds.

Based on weather data collected at study turbines and an on-site meteorological tower, the average nightly wind speed (between 7:00 pm and 7:00 am) at the Fowler Ridge facility was 5.70 m/s during the study period. Nightly wind speeds were below 5.0 m/s approximately 43.4% of the time, and were below 6.5 m/s approximately 63.7% of the time. It was not possible to know exactly when each bat fatality occurred during a night, so it could not be determined whether the cut-in speed restrictions were active at a particular turbine when the fatality occurred. However, compared to turbines with no cut-in speed adjustments, the turbines were estimated to be operating approximately 21.6% less at the 5.0 m/s and 42.1% less at the 6.5 m/s cut-in speed treatments.

Fowler Ridge, Indiana 2011

The effectiveness of feathering turbine blades below multiple cut-in speeds for reducing bat fatality rates was evaluated at Fowler Ridge during the fall of 2011 (Good et al. 2012). Bat fatality rates were measured at three different speed adjustments, or “treatments”, and two sets of “control” turbines with no cut-in speed adjustment. Nine turbines were randomly selected from the sample of 36 turbines with cleared plots searched in 2010, and were considered a “control” sample, operating normally for the duration of the study. The control group comprised three GE SLE 1.5-MW turbines, three Clipper C96 2.5-MW turbines, and three Vestas V82 1.65-MW turbines. Treatments for blade feathering and a second set of “control” turbines were rotated on a nightly basis between the remaining 168 turbines, with 42 turbines assigned to each group. The treatments included turbines with blades feathered below 3.5 m/s, below 4.5 m/s, and a control group with no feathering. Turbines were assigned to control and treatment groups among the 168 turbines on a nightly basis using a balanced block design to ensure that equal numbers of each turbine type were assigned to each treatment.

Fatality rates at turbines with normal operation parameters and those at turbines feathered below 3.5 m/s, 4.5 m/s, and 5.5 m/s were compared using a chi-square test of proportions to determine if significantly fewer fatalities were found under feathered turbine operation than under normal turbine operation. In addition to a chi-square test of proportions, differences in observed fatality rates by feathering condition were examined by building a negative binomial model to determine the relative difference in fatality rates. The magnitude of model coefficients represented the relative ratio of fatality rates between feathered operation at a given cut-in speed and those with no feathering. Tests for variable selection were used to assess the statistical significance of the *f* covariates corresponding to the levels of feathered operation. Since feathering condition was rotated nightly among turbines, only carcasses of bats that were estimated to have died the night prior to searches were included in the analysis.

A total of 105 bat carcasses were determined to have occurred at turbines while operating under normal operational cut-in speeds of 3.5 m/s (control) throughout the fatality searches. This compares to 66, 42, and 25 bat carcasses found at turbines where blades were feathered below 3.5 m/s, 4.5 m/s, and 5.5 m/s, respectively. Bat fatalities were composed of 57.1% eastern red bats, 23.5% hoary bats, 12.2% silver-haired bats, 5.0% big brown bats, 1.3% tri-colored bats, 0.4% Seminole bats, and 0.4% little brown bats.

Chi-square tests of proportions show that decreases in observed bat fatality rates between control turbines with no feathering compared to feathered turbines were statistically significant. Chi-square tests of proportions between successive treatment levels also showed significant decreases in fatality counts: (3.5 m/s feathered versus 4.5 m/s feathered; chi-square=5.1, df=1, p-value=0.02; 4.5m/s feathered versus 5.5 m/s feathered; chi-square=4.2, df=2, p=0.04).

Negative binomial modeling of observed fatality rates resulted in significant blade feathering covariates. The parameter estimate for feathering below a 3.5 m/s cut-in speed corresponded to a 36.3% reduction in fatality rates, with a corresponding 90% confidence interval (90% CI) of 12.4–53.8%. Feathering below a 4.5 m/s cut-in speed resulted in a parameter estimate of 56.7% (90% CI: 5–69.8%). A parameter estimate corresponding to a 73.3% (90% CI: 60.0–82.5%) reduction in fatality rates was estimated when the turbines were feathered below a 5.5 m/s cut-in speed.

Sheffield, Vermont 2012

The Sheffield Wind Facility (SWF) is located near the town of Sheffield in Caledonia County, Vermont. The facility consists of 16 Clipper 2.5-MW wind turbines positioned along two “strings” on 2 mountain ridges. All turbines have an 80-m hub height, but four of the turbines have a 96-m rotor diameter and 6,032 m^2 rotor-swept-area, and 12 of the turbines have a 93-m rotor diameter and 5,843 m^2 rotor-swept area. The manufacturer’s cut-in speed is 4.0 m/s. The SWF occurs within the Northern Vermont Piedmont biophysical region, which is comprised of gentle, rolling foothills and river valley topography, dominated by calcareous rocks in the uplands, and sand and gravel deposits in the valleys. A total of 83 bat carcasses were recovered, of which 55% (n = 46) were hoary bats, 28% (n = 23) were eastern red bats, and 17% (n = 14) were silver-haired bats. No cave roosting species were found during the study.

Daily searches were conducted from 3 June–30 September for a total of 120 nights. Rectangular plots were centered on each turbine, with 6 m transect widths and a maximum plot size of 126 m

X 120 m. All 16 turbines were used, with 8 fully operational (i.e., cut-in speed at 4.0 m/s) and 8 with a cut-in speed at 6.0 m/s. Treatment cut-in speeds were implemented during periods when the ambient air temperature was ≥9.5°C (49°F). A randomized block design (Hurlbert 1984) was used and treatments were randomly assigned to turbines each night of the study, such that each turbine received each treatment for 60 nights.

The experimental unit was the turbine-night and turbines were considered a random blocking factor. The total number of fatalities estimated to have been killed the previous night in each treatment at each turbine was modeled as a Poisson random variable. The data were fit to a generalized linear mixed model (SAS PROC GLIMMIX), assuming a Poisson distribution with a log link for carcass count, curtailment treatment and turbine were considered fixed and random effects, respectively.

Sixty-two of the 83 bats recovered were considered to have died the previous night and were used in the analysis. A minimum of 1 fresh bat was found at each of the 16 turbines. Treatment turbines had a statistically significant effect on bat fatalities ($F_{1,15} = 11.09$, $p = 0.005$). An average of 1.0 (95% CI: 0.6, 1.8) fresh bats/turbine were found at treatment turbines compared to 2.7 (95% CI: 1.9, 3.9) fresh bats/turbine found at fully operational turbines. Total fatalities at fully operational turbines were estimated to be 2.6 (95% CI: 1.4, 4.8) times greater than at curtailed turbines, resulting in an estimated 60% (95% CI: 29%, 79%) reduction in bat fatalities.

Wolfe Island, Ontario 2011

The Wolfe Island Wind Farm (WIWF) is located on Wolfe Island on Lake Ontario. The facility has 86 2.3-MW Siemens Mark II wind turbines with an 80-m hub height, 93-m rotor diameter and standard cut-in speed of 4.0 m/s. Dominant land cover types include row-crop agriculture, hay fields and pasture. Fatalities at this facility were dominated by hoary bats (50%) with similar numbers of eastern red bats (17.3%), silver-haired bats (15.4%) and big brown bats (*Eptesicus fuscus*; 15.4%; Stantech Consulting, Ltd. 2012).

From July 2010 through June 2011, the estimated annual bat mortality rate was 9.71 bats/MW, which is below the adaptive management threshold of 12.5 bats per MW as set forth by the Provincial government. The operator (TransAlta) proactively developed and implemented a research program to evaluate practical measures to reduce the effects of operating WTGs on bats at Wolfe Island. Fourteen turbines in each of 3 treatments (control, cut-in speed raised to 4.5 and 5.5 m/s) were randomly selected and were searched twice/week from 15 July to 30 September 2011. Searches were conducted using transects with 7-m spacing within a 50-m radius of the turbine. The experimental treatments were fixed for the entire study period and were implemented from sunset to sunrise.

Estimated bat fatality rates, adjusted for searcher efficiency and scavenging, were 2.28 bats/MW (control), 1.19 bats/MW (4.5 m/s), and 0.91 bats/MW (5.5 m/s), indicating a reduction in mortality of approximately 48–60% for turbines with cut-in speeds raised to 4.5 m/s and 5.5 m/s, respectively. However, because the number of actual bat fatalities used to make these estimates was low (7, 8, and 5 fatalities found at control, 4.5 and 5.5 m/s turbine groups, respectively), the authors did not believe statistical analysis was appropriate (Stantec Consulting Ltd. 2012) and results should be interpreted with caution.

Beech Ridge, West Virginia

This project is located in Greenbrier and Nicholas counties, West Virginia, and is located along Beech Ridge on a 63,000-acre tract of forestlands managed for commercial timber harvesting (Tidhar et al. 2013). The Project has 67 GE 1.5-MW wind turbines with 80-m hubs and 77-m diameter blades; the nominal cut-in speed is 3.5 m/s. The facility lies within the Central Appalachian Broadleaf Forest Ecological Subregion within the southern portion of the Allegheny Mountains ecological section. This ecological section is characterized by a dissected plateau of high ridges, low mountains, and narrow valleys. Beech Ridge is largely forested, and the landscape is a mosaic of deciduous forest in various stages of growth interspersed with areas cleared for roads, timber harvest activities, and historic mining activities. Eastern red bats were most commonly found at this facility, and other species included hoary, silver-haired, and tri-colored (*Perimyotis subflavus*) bats.

The cut-in speed for all turbines was raised to 6.9 m/s all night long throughout the entire study period. Turbines were feathered so that they did not rotate at wind speeds below 6.9 m/s. This Project was required to implement turbine curtailment at all 67 turbines; therefore, no control turbines were available to compare bat mortality at curtailed turbines to. To assess efficacy of the curtailment for reducing bat fatality, bat fatality rates for the study period were qualitatively compared to measured bat fatality rates at other regional wind energy facilities. Three spatial scales for meta-analysis were used for comparison: a) eastern North America which included all wind energy facilities in the Northeast, Southeast, Southern Plains and Midwest regions; b) Northeastern region which included all wind energy facilities in Maine, New Hampshire, New York, Pennsylvania, West Virginia, and Ontario, Canada; and c) other wind energy facilities in West Virginia.

At all spatial scales used for comparison the bat fatality rate observed at Beech Ridge was below the median and mean of the range of bat fatality rates observed at these other facilities. At the Eastern North America scale, the estimated bat fatality rate at the Project (2.03 fatalities/MW/year) was approximately 73% less than the average for other annualized estimates, which was approximately 7.40 bat fatalities/MW/year. The observed bat fatality estimate at the Project also was approximately 73% less than the average for other annualized projects located just within the Northeastern region. Only two facilities in West Virginia have published comparable, publicly-available fatality studies: Mount Storm and Mountaineer. Bat fatality rates at Mount Storm ranged from 6.62–24.32 bat fatalities/MW/year, while rates at Mountaineer were

25.17 and 31.69 fatalities/MW/year. The bat fatality rate at the Project was approximately 89% less than the average for other annualized West Virginia projects.

Criterion, Maryland

This project is located along a 5-mile section of Backbone Mountain in Garrett County, Maryland (Young et al. 2013). The Project has 28 Clipper 2.5-MW wind turbines with 80-m hubs and 93-m diameter blades; the nominal cut-in speed is 4.0 m/s. The topography of the Project area is steeply sloping on the western side of the ridge and relatively gently sloping on the eastern side; and the ridgeline maintains an elevation of approximately 975 m above mean sea level. The facility falls within the Ridge and Valley province of the Central Appalachian Ecoregion, characterized by heavily forested, steep ridges that alternate with folded sandstone crests and limestone plateaus. The Project is situated on largely undeveloped, previously logged forestland interspersed with some open farmland and consists of rugged terrain traversed with old logging roads. Land use in the vicinity of the Project is dominated by forest and hay fields. Bat species found as fatalities included eastern red bat (53.7%), hoary bat (32.9%), silver-haired bat (7.3%), big brown bat (3.7%), tri-colored bat (1.2%) and unidentified bat (1.2%).

During the period 15 July–15 October 2012, the turbine blades were feathered to minimize rotation to less than 2 RPMs during periods when wind speeds were equal to or less than 5.0 m/s at night. Half of the 28 turbines (n = 14) were randomly selected for fatality monitoring, and each turbine was searched once per week using cleared plots within a 40-m radius of the turbine. Since no control turbines were used during the study, effectiveness of curtailment treatments was determined by comparing bat fatality rates for the study period while operational curtailment was in place in 2012 with those at the same facility over the same time period in 2011 when no operational curtailment was in place.

The estimated bat fatality rate in 2012, when turbines were curtailed, was 10.97 bats/turbine (90% CI = 4.81–20.19), whereas the estimated fatality rate in 2011 was 28.78 bats/turbine (90% CI = 24.09–35.17). These results indicate a reduction in bat fatality of approximately 62% when the turbines were feathered below 5 m/s, but this analysis assumes that other factors affecting levels of bat fatality were similar between 2011 and 2012, which may not have been true.

Anonymous Project 1, USFWS Region 3

This wind energy facility (AN01) is located in USFWS Region 3 (Midwest Region that includes Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin). Although the developer of this project allowed use of the data, they stipulated that the name and location of the project should not be disclosed. This wind energy facility is composed of 240 1.65-MW turbines which have an 80-m hub height and an 82-m rotor diameter. The standard cut-in speed for these turbines was 3.5 m/sec. Based on land cover classifications, most (over 90%) of the wind resource area was composed of tilled agriculture, with corn (*Zea mays*) and soybeans (*Gylcine* *max*) being the predominant crops Fatalities at this facility were dominated by eastern red bats, hoary bats, and silver-haired bats.

This study was conducted from 1 August–1 October, 2010, a time period selected to cover the period when 82–97.4% of bat fatalities occurred during previous studies of the facility in 2007, 2008 and 2009. Twelve turbines were selected for the study using a systematic design with a random start. Each of the study turbines had a search plot of 80 X 80 m cleared around the turbine by mowing standing crops using a brush mower pulled by a small tractor. This allowed for all areas within 40 m of a turbine to be searched. This distance was based on previous studies at the facility, where 83% of all bat carcasses were found within 40 m of a turbine. Eleven of the turbines were in either corn or soybean fields and the remaining turbine was in an alfalfa (*Medicago sativa*) field.

Treatments for cut-in speeds were rotated between the twelve turbines on a weekly basis using a Latin square design, with four turbines having cut-in speeds raised to 4.5 m/s, four turbines having cut-in speeds raised to 5.5 m/s, and four turbines having a normal (control) operational cut-in speed of 3.5 m/s during each week. The Latin square design ensured that each turbine received the same number of days under each cut-in speed treatment. The study lasted nine weeks; therefore, each of the 12 turbines operated for three weeks over the course of the study at each cut-in speed. Cut-in speed treatments were set to begin approximately one hour before sunset and to end approximately one hour after sunrise.

Daily searches were conducted on all 12 turbines. The estimated time since death for each bat carcass found was evaluated to determine which bats should be excluded from the analysis or were likely killed the previous week. This resulted in removal from the analysis of 10 bats found during the first week of the study which were presumed to have been killed prior to study initiation. Another two bats were removed from the analysis because it was not possible to determine which study week they were killed, including one bat in week 2 and one bat in week 5 of the study. Five bats were assumed to have been killed the week before they were found and were assigned to that time period for analysis. Overall, 88.6% of bats found during the study were included in the analysis to determine effects on mortality of raising cut-in speeds on wind turbines.

Differences in cut-in speed were examined by building a Poisson model to determine the relative difference in counts based on cut-in speed. A Poisson model was considered appropriate in this case, since the response variable is a count of bat fatalities. From this model, the magnitude of differences and significance of variables in the model was determined.

A total of 93 bats found during the study were used for the cut-in speed analysis as they could be confidently assigned to a treatment based on the estimated time of death in relation to when the cut-in speeds were changed. Fifty-three bat carcasses were found at turbines with normal operational cut-in speeds of 3.5 m/s (control). This compared to 25 and 14 bat carcasses found at turbines with cut-in speeds raised to 4.5 m/s and 5.5 m/s, respectively.

A Poisson model was built considering cut-in speed and week as fixed effects and the turbine as a random effect. Although blocking by week can potentially eliminate temporal effects, a definite trend was observed by week. Therefore, week was considered as a fixed effect in the model. In the Poisson model, a cut-in speed of 4.5 m/s had a parameter estimate of -0.64, which corresponds to an approximate 47% decrease in the odds of a fatality with this cut-in speed when all other variables are equal. This cut-in speed was significant in the model (z=-2.57, p=0.01). The cut-in speed of 5.5 m/s had a parameter estimate of -1.26 in the model. This corresponds to an approximate 72% decrease in odds of a bat fatality occurring at a turbine with a cut-in speed of 5.5 m/s when all other variables are equal (z=-4.13, p<0.001).

Based on data obtained from the turbine SCADA system, the average wind speed at the facility during the 1 August–30 September study period was 5.9 m/s. During the study period, wind speeds at the facility were below 4.5 m/s approximately 29% of the time, and were below 5.5 m/s approximately 48% of the time. It was not possible to know exactly when each bat fatality occurred during a night, so it could not be determined whether the cut-in speed restrictions were active at a particular turbine when the fatality occurred.

This was the first study to demonstrate that cut-in speeds raised to 4.5 m/s reduce bat fatalities substantially, albeit not to the same level obtained with a cut-in speed of 5.5 m/s. This also was the second study to evaluate raising cut-in speeds at a wind energy facility located in a corn and soybean agro-ecosystem in the Midwestern U.S., (see Fowler Ridge, Indiana summary).

Anonymous Project 2, USFWS Region 8

This wind energy facility (AN02) is located in USFWS Region 8 (Pacific Southwest Region which includes California and Nevada). Although the developer of this project allowed use of the data, they stipulated that the name and location of the project should not be used. The facility consists of 40 2.3-MW wind turbines (manufacturer not disclosed) situated on 80-m towers with rotor blades 101 m in diameter. The nominal cut-in speed of the turbines is 3.0 m/s. This facility lies within a basin on relatively flat terrain; and the predominant land cover is desert scrub, big sagebrush (*Artemisia tridentata*) shrubland and xeric mixed sagebrush shrubland. Brazilian free-tailed bats (*Tadarida brasiliensis*) dominated fatalities at this facility (73.5%).

The study was conducted from 2 August–30 September 2012. Daily searches were conducted at 40 study turbines. Searchers walked along transect lines spaced 5 m apart within a 126 X126 plot under each study turbine. Treatment turbines were stratified into 4 groups based on their distance from a point source for bats. Treatment turbines were assigned one of 4 cut-in speeds (3.0 m/s [turbine manufacturer's cut-in speed], 4.0 m/s, 5.0 m/s, and 6.0 m/s) for 4 hours (sunset to 4 hours past sunset) during each night of the study. A fifth treatment (5.0 m/s for the entire night [5.0 m/s AN]) also was included to test the effectiveness of curtailing for a greater duration of the night. Nightly cut-in speed treatments were assigned using a randomized block design, with the turbine as the blocking factor and turbine-night as the sampling unit. However, randomization was constrained to ensure that 1) each turbine received each treatment the same number of times over the course of the study, and 2) each treatment was applied to two turbines within each group on each night of the study. As there were 5 treatments, full design balance was achieved every 5 nights. The process was repeated 12 times to generate cut-in speed assignments for a 60-night study period.

A total of 136 bat fatalities were found during the study. Unlike other curtailment studies reviewed in this paper, most (73.5%) of the bat fatalities were Brazilian free-tailed bats (*Tadarida brasiliensis*), with smaller numbers of hoary bats (22.8%) and silver-haired bats (3.7%). Compared to the control turbines set to a cut-in speed of 3.0 m/s, the following reductions in bat fatality were obtained in each treatment: 20.1% at 4.0 m/s, 34.5% at 5.0 m/s, and 38.1% at 6.0 m/s during the first four hours after dark, and 32.6% for turbines raised to 5.0 m/s all night long. None of the reductions in fatality were considered statistically significant (chi-square test p>0.05) between turbines with cut-in speeds raised to 5.0 or 6.0 m/s, regardless if the treatment occurred only during the first four hours after dark (5.0 and 6.0 m/s) or was left in place all night long (5.0 m/s). The lack of significance was likely due to low statistical power, since the number of fatalities observed was relatively low.

Lost Power Output

To date, only 2 of the 10 sites evaluated have released information regarding lost power for operational mitigation studies. Baerwald et al. (2009) reported that by increasing the cut-in speed at some turbines, the amount of time these turbines would likely have produced electricity was reduced by an average of 42.3%. However, they found that the costs were not as great as originally anticipated due to a combination of market prices at the time of their experiment and the fact that most electricity is generated above the experimental rotor start-up speed of 5.5 m/s. Baerwald et al. (2009) estimated that over the 1-month experiment, total revenue lost from the 15 turbines with increased cut-in speed was between $3,000 and $4,000 (Canadian currency). They noted that because of technological limitations of the V80 turbines, cut-in speeds had to be altered for the entire duration of the study, 24 hours a day, not only at night when bats are active. Thus, loss of wind generation could have been reduced if treatments could have been applied only during the night. Furthermore, Baerwald et al. (2009) only projected lost revenue for the 15 treatment turbines and did not hypothetically project lost power and revenue across the entire wind facility had mitigation been applied during the period of highest risk to bats, which represents a more realistic economic loss for operational mitigation.

At the Casselman site, power loss was equivalent to approximately 2% of the total projected output for the 12 turbines during the 75 day study period[s] of Arnett et al. (2011). Hypothetically, had the treatments 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 treatment 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 treatment had been applied to all 23 turbines during the study period, lost output would have been 11% of total output for the study period and 1% of total annual output, which reflects the cubic effect of wind speed on power production (Albadi and El-Saadany 2009). In addition to decreased revenue from lost power, companies also incur minor costs for staff time to set up processes and controls and to implement curtailment treatments (Arnett et al. 2011).

Turbine Rotor Speed in Relation to Wind Speed

Curtailment strategies are only effective when they reduce the opportunities for animals to interact with fast-moving turbine blades. Figure 1 depicts the relationship between blade tip speed, rpms, and wind speed for wind turbines at 5 different wind facilities, with turbines grouped by blade length. Most of the turbines under fully operating conditions, independent of blade length, had tip speeds at or above 100 mph. Almost all cut-in speed treatments reduced tip speeds below 50 mph when winds were below the cut-in speed. Almost all turbines undergoing normal operations had tip speeds in excess of 50 mph, even when wind speeds were below the normal cut-in. This suggests that steps, such as feathering blades, can be taken to reduce tip speeds and hazards to bats, even without increasing turbine cut-in speeds above the manufacturers' set cut-in speed. Figure 2 summarizes the proportion of the night when blade tip speed exceeds 50 mph from different turbines located at different wind energy facilities. The dashed grey line in each panel indicates the cut-in speed for the turbines and values greater than zero to the left of the cut-in speed represent missed opportunities to prevent hazards to bats under curtailment strategies. Under normal operation, the proportion of the night when tip speeds were greater than 50 mph when wind speed was at or below the cut-in speed ranged from 20 to 100%. Feathering below 3.0, 3.5, and 4.0 m/s (normal cut-in speeds for turbines in the studies we synthesized) dramatically reduced the proportion of time blade tips were spinning >50 mph, except site C during year 2 for that type of turbine (Figure 2). Raising cut-in speed between 4.5 and 6.5 m/s and feathering blades up to these new cut-in speeds also substantially reduced the proportion of time blades were spinning >50 mph substantially. However, proportion of the night when tip speeds exceeded 50 mph increased as wind speed approached the new cut-in speeds (Figure 2). Some of the high-speed blade movement below cut-in wind speeds may be attributed to the SCADA systems ability to adjust the pitch of the blades in response to average wind speed over an interval, rather than instantaneously.

Figure 1. Relationship between blade tip speed and wind speed for wind turbines at 5 wind facilities under normal operating conditions, feathered up to normal cut-in or with increased cut-in speeds. The y-axis shows the speeds of blade tips on the left, and RPMs on the right, and turbines are grouped by blade length. The lines plotted here are locally weighted smoothed estimates for all of the data for each nominal turbine cut-in speed for each study.

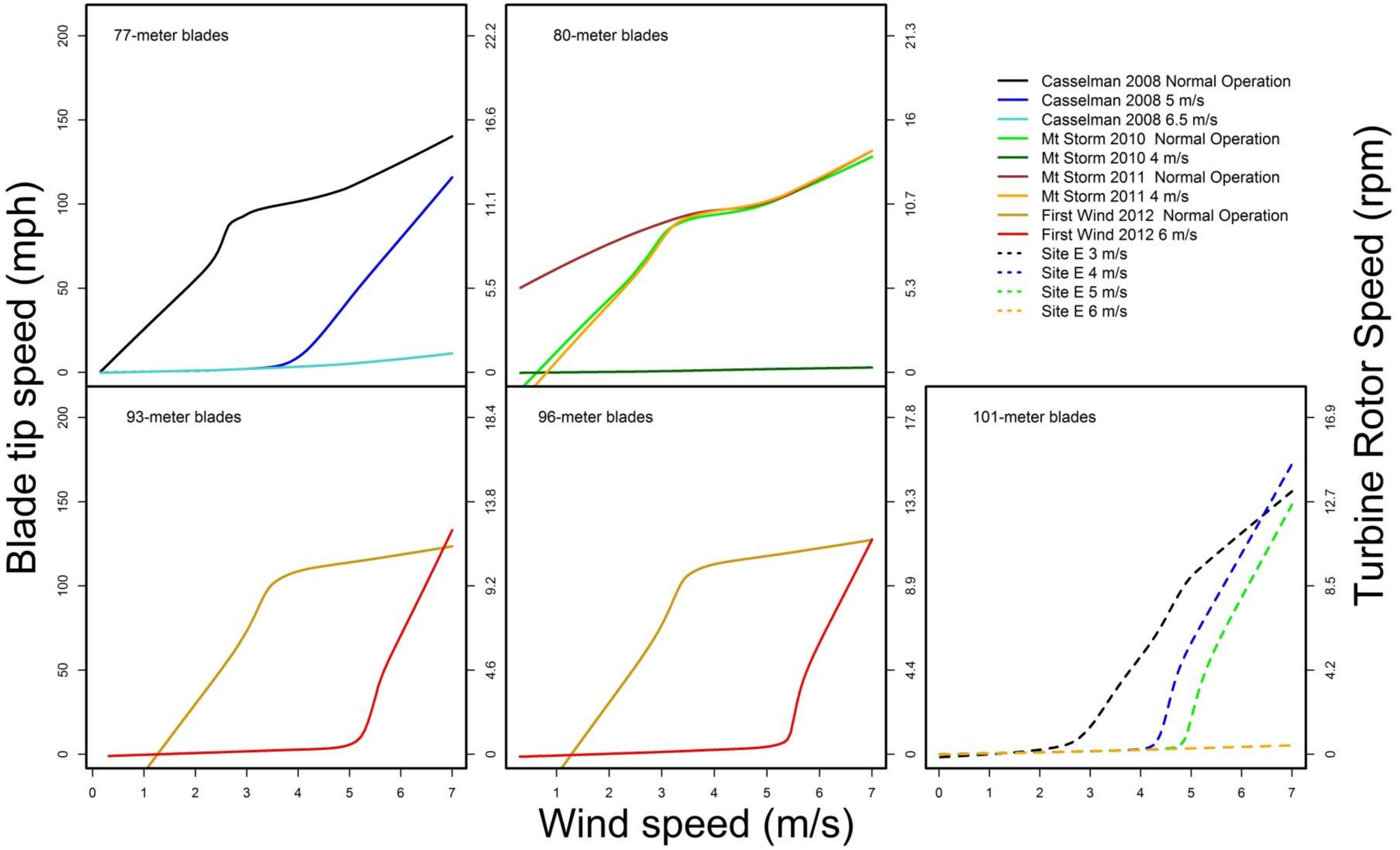
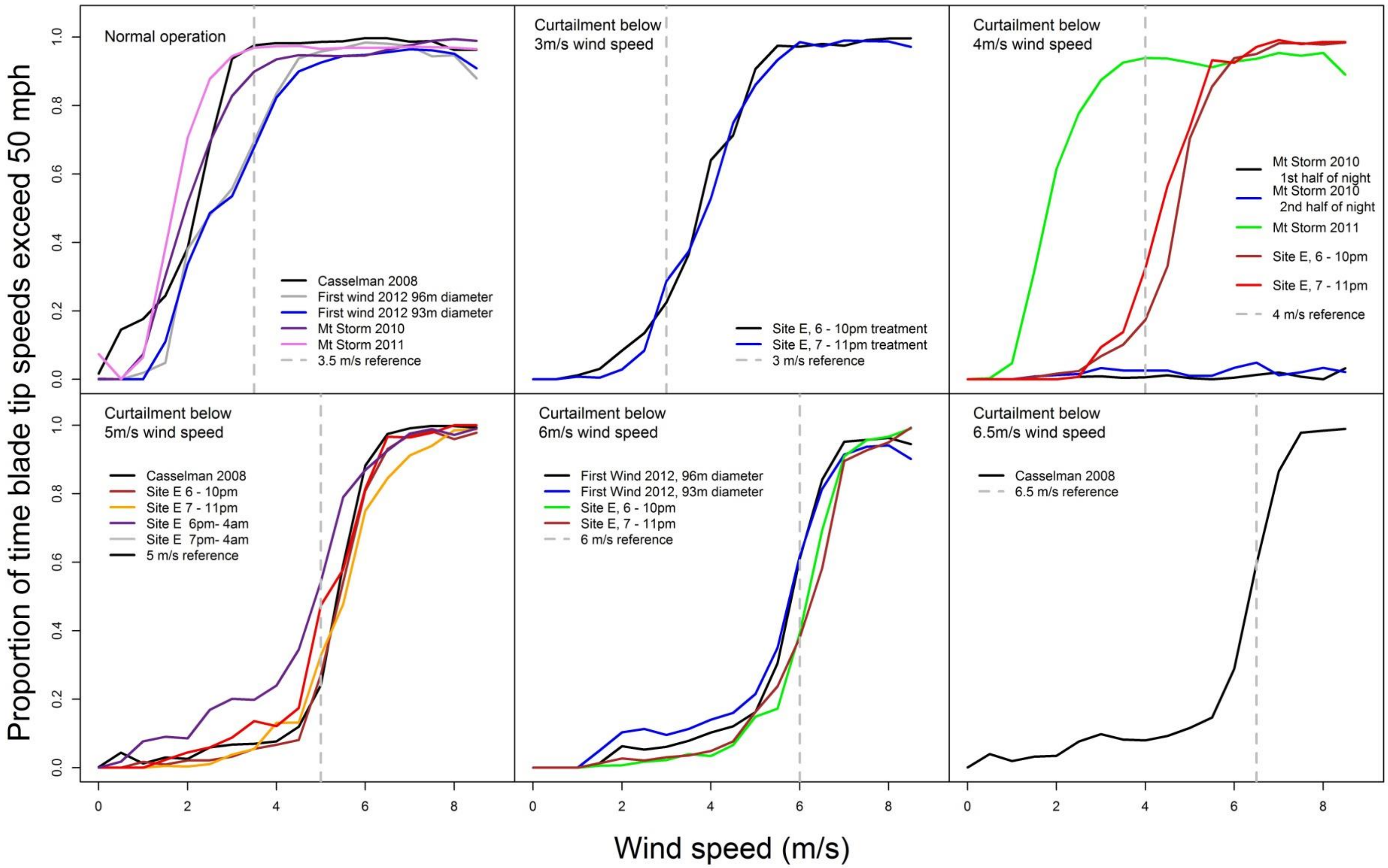


Figure 2. Proportion of the night when blade tip speed exceeds 22.4 m/s (50 mph) from different turbines located at different wind energy facilities. The dashed grey line in each panel indicates the cut-in speed for the turbines. Normal operation is illustrated in the top left panel for comparison. Values greater than zero to the left of the cut-in speed represent missed opportunities to prevent hazards to animals under curtailment strategies.



DISCUSSION

Our synthesis demonstrates consistent, substantial reductions in bat fatalities at wind energy facilities when turbine blades are feathered and rendered basically motionless 1) below the manufacturer's normal cut-in speed, or 2) up to the raised cut-in speed up to 3.0 m/s above the normal cut-in speed of turbines. The Casselman and Fowler Ridge studies were the first to test multiple changes in turbine cut-in speed. The largest difference between methods used by Arnett et al. (2011) and the 2010 study at Fowler Ridge was the frequency at which cut-in speeds were changed. Arnett et al. (2011) switched the turbines selected for the cut-in speed adjustment on a nightly basis, whereas cut-in speeds were adjusted on a weekly basis during the 2010 study at Fowler Ridge (Good et al. 2011). Both studies assumed that the time of death was correctly classified for all bats found, regardless of daily or weekly changes of treatments, which must be considered when interpreting findings from studies using either experimental design.

Arnett et al. (2011) found no significant differences in bat fatality rates between turbines with cut-in speeds raised to 5.0 m/s and 6.5 m/s. The Fowler Ridge study is the first to demonstrate that bat fatality rates were not only significantly different between control and treatment turbines, but that bat fatality rates were significantly different between cut-in speeds raised to 5.0 m/s versus turbines with cut-in speeds raised to 6.5 m/s. The reasons for the significant differences between these 2 facilities could be related to differences in wind scenarios. Wind data collected at the Fowler Ridge facility suggest that wind speeds were between 5.0 m/s and 6.5 m/s for a significant amount of the late-summer and fall survey period (19.4%). Wind speeds could have potentially been more common between 5.0 m/s and 6.5 m/s at the Fowler site compared to the Casselman study area; however, data regarding the percentage of time wind speeds were within discreet ranges were not available (Arnett et al. 2011).

Martin et al. (2013) was the first study to incorporate temperature as part of the experimental treatment. Treatment turbines were only curtailed at temperatures above 9.5°C, which likely reduced the amount of time turbines were curtailed. This study demonstrated similar reductions in fatalities as those only using wind speed, suggesting that other environmental factors may be important in optimizing operational mitigation strategies that maximize wind production while reducing bat fatalities.

Most of the turbines under fully operating conditions, independent of blade length, had tip speeds at or above 100 mph at or even below their normal cut-in speed and high proportions of the night when tip speeds exceeded 50 mph. Assuming tip speeds >50 mph are lethal to bats, there appears to be ample opportunity to reduce bat fatalities by feathering turbine blades at or below normal turbine cut-in speed when no electricity is being produced. Results from studies that feathered blades or implemented a low-speed idle at or below cut-in demonstrated significant reductions in bat fatality (Baerwald et al. 2009, Young et al. 2011). We contend that feathering turbine blades at or below normal cut-in speed could be implemented at many facilities, even retroactively, with those turbine models that have SCADA systems capable of relatively easy programming.

There are reasonable explanations why significant reductions in bat fatality were not demonstrated at some of the studies implementing operational mitigation. At Mount Storm in 2011, Young et al. (2012) noted that the amount of total operating time during the study when treatments would have been in place was less than 10%, so their ability to distinguish between the two groups of turbines was compromised. At the AN02 study, reductions in fatalities for all treatments were <50% (20–38% for the 3 treatments) and no statistically significant differences were found among treatments. This site was dominated by fatalities of Brazilian free-tailed bats that are known to fly at heights and associated wind speeds (up to 3,000 m; McCracken et al. 2008) that are greater than those presumed to be used by most species of bats frequently killed by wind turbines. Thus, it is plausible that the morphology, flight behavior and foraging ecology influenced the effectiveness of operational mitigation for this species.

Higher bat activity (e.g., Reynolds 2006, Horn et al. 2008, Weller and Baldwin 2011) and fatalities (Arnett et al. 2008, Rydell et al. 2011) have been consistently related to low wind speeds, higher temperatures and weather conditions typical of the passage of storm fronts. The casual mechanism underlying this relationship remains unclear, but perhaps migration is less efficient for bats in high wind speeds and thus migratory movement by these species is reduced (Baerwald et al. 2009). 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). Erickson and West (2002) reported that regional climate patterns as well as local weather conditions can be analyzed to predict foraging and migratory activity of bats. On a local scale, strong winds can influence abundance and activity of insects, which in turn influence bat activity. Bats are known to reduce their foraging activity during periods of rain, low temperatures, and strong winds (Erkert 1982, Erickson and West 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 linking fatality and activity with other climatic and environmental variables are needed to identify patterns that will aid in developing robust predictive models of environmental conditions preceding fatality events, and for predicting when operational curtailment will be most effective to reduce bat fatalities while minimizing costs (Weller and Baldwin 2011).

Numerous factors influence power loss and, thus, financial costs of changing cut-in speed of wind turbines to reduce bat fatalities. These include, but are not limited to, the type and size of wind turbines and computer hardware used, market or contract prices of power, power purchase agreements and associated fines for violating delivery of power, and variation in temporal consistency, as well as speed and duration of wind across different sites. Wind speeds in the Mid-Atlantic Highlands region are typically lowest in late summer and early fall (S. McDonald, Iberdrola Renewables, unpublished data). Power loss at the CWPP was considerably different from that reported by Baerwald et al. (2009) primarily because Arnett et al. (2011) curtailed turbines only at night when bats are flying and because of different market pricing for electricity between the two study sites. Technological limitations of the Vestas V80 turbines studied by Baerwald et al. (2009) forced them to change the cut-in speed for the entire duration of the study, 24 hours a day. Baerwald et al. (2009) noted that costs incurred by companies could be further reduced if correlations between weather variables other than wind speed and fatality risk can be established and automated so treatments only occur during these high-risk conditions, as suggested by Weller and Baldwin (2011). Conversely, Baerwald et al. (2009) also suggested that if market or contract prices fluctuate and are higher during mitigation periods identified by these studies, or if wind regimes are more influenced by lower wind speeds, or if reduced electricity production violates contract terms, then costs would likely be greater than those reported here. The loss in power production resulting from the CWPP experimental treatments was surprisingly low when considering the full annual productivity lost, but power loss was 3 times higher for the 6.5 m/s change in cut-in speed compared to the 5.0 m/s treatment, reflecting the cubic effect of wind speed and power produced (Albadi and El-Saadany 2009). In southwestern Alberta and the Mid-Atlantic region, winds are low in the late summer/early fall, which coincides with the timing of bat migration and high fatality rates and minimizes the economic costs of mitigation. Sites with high bat fatality rates in other areas of North America may not have this relationship, and altering cut-in speeds may be more costly and/or less beneficial (Baerwald et al. 2009, Arnett et al. 2011).

Given the magnitude and extent of bat fatalities worldwide, the conservation implications of this operational mitigation are important. Arnett and Baerwald (2013) estimated that between 650,104 and 1,306,378 bats have been killed at wind facilities throughout North America. Unfortunately, our understanding of biological impacts is hindered by a lack of knowledge of bat populations (O’Shea et al. 2003) and the impacts of wind energy relative to other factors affecting bat populations. However, several species are known or suspected to be in decline (Racey and Entwistle 2003, Winhold and Kurta 2006, Jones et al. 2009, Frick et al. 2010). Moreover, bats have low reproductive potential (i.e., reproducing once per year and typically only having one to two pups) and require high adult survivorship to avoid population declines (Barclay and Harder 2003), they are unable to recover quickly and large-scale impacts may place populations at risk (Findley 1993, Henderson et al. 2008). Until populations and associated impacts are quantified, it will be difficult to determine if a 50% reduction in bat fatalities, for example, from changing turbine cut-in speed over time, is adequate to mitigate impacts or whether it simply delays inevitable population-level impacts. We believe that gathering information on populations is important and fundamental to truly evaluating biological impacts, but these data are not expected to be available for most species of bats in the near future. In the absence of these data, we recommend implementation of operational mitigation in areas of the country where bat mortality is high as an effective strategy for in minimizing bat fatalities especially until better population data and understanding of impacts is possible.

Further research at other sites is needed to determine whether lower changes in cut-in speed can provide similar biological effects to higher cut-in speeds but with less financial cost. Additional studies evaluating changes in turbine cut-in speed among different sizes and types of turbines, wind regimes, habitat types, and species of bats (e.g., Brazilian free-tailed bats) would help fully evaluate the general effectiveness of this mitigation strategy (Baerwald et al. 2009, Arnett et al. 2011). Nevertheless, changing cut-in speeds to the levels reported in the studies synthesized here offers an ecologically sound and economically feasible strategy for reducing bat fatalities at wind energy facilities.

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Appendix 1. Study Area and acronym, percent of species [a] composition of bat fatalities, mean reduction in bat fatalities, lost production and citations for operational mitigation studies conducted at wind energy facilities in North America.

Study Area Location	Study Area Acronym	Mean Fatality Reduction (%)	Lost production	Literature Citation
Canada				
Summerview, Alberta	SVAB	57% (4.0 m/s), 60% (5.5 m/s)	~$3,000-4,000 Canadian, but turbines were curtailed 24 hours and only projected for study period	Baerwald 2008; Baerwald et al. 2009
Wolfe Island, Ontario	WIWF	60% (5.5 m/s) 4.8 (4.5 m/s)	n/a	Stantec Consulting, Ltd. 2012
United States				
Cassleman, Pennsylvania	CWPP	2008: 82% 2009: 72%	0.3% (5.0 m/s) 1% (6.5 m/s)	Arnett et al. 2010; Arnett et al. 2011
Fowler Ridge, Indiana	FRWF	2010: 50% (5.0 m/s) 78% (6.5 m/s)	n/a	Good et al. 2010, 2011
		2011 Feathering below 3.5–36.3%, below 4.5–56.7%, below 5.5–73.3	n/a	
Mount Storm, West Virginia	MTSO	2010: 47% (treatment I) 23% (treatment II)	n/a	Young et al. 2010, 2011

		2011: 9.3% (not significant)	n/a	
Sheffield, Vermont	SWF	60% (6.0 m/s)	n/a	Martin et al. 2013
Beech Ridge, West Virginia	BRWF	Assumed 73% to 89% compared to regional fatality estimates	n/a	Tidhar et al. 2013
Criterion, Maryland	CRWF	62% compared to previous year	n/a	Young et al. 2013
Anonymous 1, USFWS Region 3	AN01	47% (4.5 m/s) 72% (5.5 m/s)	0.2% (4.5 m/s) 0.8% (5.5 m/s)	
Anonymous 2, USFWS Region 8	AN02	20.1% (4.0 m/s) 34.5% (5.0 m/s) 32.6% (5.0 all night) 38.1% (6.0 m/s) No significant difference among treatments	n/a	

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[a] EPFU = big brown bat, LABO = eastern red bat, LACI = hoary bat, LANO = silver-haired bat, LASE = Seminole bat, MYLU = little brown bat, PESU = tri-colored bat, TABR = Brazilian free-tailed bat, UNBA = unidentified bat, and UNMY = unidentified myotis.

Appendix 2. Study period and characteristics of wind facilities for operational mitigation studies in North America.

Study	Study Period	Number, Type and Capacity of Turbines	Tower Height	Rotor Diameter and Swept Area	Normal Cut-in Speed	Land cover
Canada						
SVAB	8/1/2006–9/7/2006	39 Vestas V80 1.8-MW	65 m	80 m; 5,027 m^2	4.0 m/s	Agriculture/ grazed pasture
WIWF	7/15/2011–9/30/2011	86 Siemens Mark II 2.3-MW	80 m	93 m; 5,843 m^2	4.0 m/s	Pasture, hayfields, crops
United States						
CWPP	7/27/2008–10/9/2008 7/26/2009–10/8/2009	23 GE SLE 1.5 MW	80 m	77 m; 4,838 m^2	3.5 m/s	Deciduous forest/ grassland
FRWF	8/1/2010–9/7/2010 8/1/2011–10/15/2011	Vestas V82 1.65-MW Clipper C96 2.5-MW GE SLE 1.5-MW	80 m	82 m; 5,153 m^2 96 m; 6,032 m^2 77 m; 4,838 m^2	3.5 m/s 4.0 m/s 3.0 m/s	Agriculture (Corn & Soybeans)
MSTO	7/15/2010–10/13/2010 7/16/2011–10/15/2011	Gamesa G 80 2-MW	78 m	80 m; 5,027 m^2	3.5 m/s	Deciduous forest/ grassland
SWF	7/3/2012–9/30/2012	Clipper C96 2.5-MW	80 m	96 m; 6,032 m^2 93 m; 5,843 m^2	4.0 m/s	Deciduous forest
BRWF	4/1/2012–10/28/2012	67 GE 1.5-MW	80 m	77 m; 4,838 m^2	3.5 m/s	Deciduous forest
CRWF	7/15/2012–10/15/2012	28 Clipper Liberty 2.5-MW	80 m	93 m; 5,843 m^2	4.0 m/s	Deciduous forest
ANO1	8/1/2010–10/1/2010	1.65-MW	80 m	82 m; 5,153 m^2	4.0 m/s	Agriculture (Corn & Soybeans)
ANO2	8/2/2012–9/30/2012	2.3-MW	80 m	101 m; 6,347 m^2	3.0 m/s	Saltbush/sagebrush

Appendix 3. Characteristics of monitoring studies and factors influencing the estimates of bat fatalities at operational mitigation studies in North America.

Study	Cut in Speeds Tested (m/s)	No. turbines studied	Frequency of Treatments	Duration of Cut-In Speed Treatment	Search Interval	Search Area and Transect Width
Canada						
SVAB	4.0, 5.5 m/s	29	Fixed	24 hours a day	Weekly	52 m circular plots; 7 m transects
WIWF	4.5, 5.5 m/s	42	Fixed	Sunset to sunrise	Twice per week	50 m circular plots; 7 m transects
United States						
CWPP	5.0, 6.5 m/s	12; 4 in each treatment	Nightly	0.5 hour before sunset to 0.5 hour after sunset	Daily	60 x 60 m attempted, due to terrain, no search area was perfect square; 6 m transects
	2010: 5.0 & 6.5 m/s	2010: 36 Total Control (18); 5.0 m/s (9) 6.5m/s (9)	2010: Weekly	Sunset to sunrise (at night only)	Daily	2010: 80 x 80 m cleared plots; 5 m transects
FRWF	2011: 3.5, 4.5, & 5.5 m/s	2011: 117 Total 42 per treatment with road and pad searches + 9 control with cleared 80 m radius plots	2011: Nightly	Sunset to sunrise (at night only)	Daily	2011: Road and pad on 168 turbines, 9 turbines with 80m radius cleared area; 5 m transects

MSTO	2010: 4.0 m/s; turbines stalled so not able to idle at <4 for 1st half of night (treatment A) or 2nd half of night (treatment B)	2010: 24: 8 in each treatment	Weekly	2010: first ½ of night	Daily	Variable
	2011: Feathered below 4.0	2011: 24: 12 in each treatment	Weekly	2011: all night	Daily	
SWF	6.0 m/s	8 in each treatment	Daily	All night at ambient temperature ≥9.5°C	Daily	126 X 120 m plots; 6 m transects
BRWF	6.9 m/s	67	Fixed	All night	Every other day	Maximum of 40 m from turbine depending on terrain with all plots mowed, 5-m transects
CRWF	Feathered below 5.0 m/s	14	Fixed	All night	Weekly	40 m radius cleared plots, 5-m transects
ANO1	4.5, 5.5 m/s	12; 4 in each treatment	Weekly	1 hour before sunset to 1 hour after sunrise	Daily	80 x 80 m cleared plots; 6 m transects
ANO2	4.0, 5.0, and 6.0 m/s	40; 8 control, 8 (4.0), 8 (5.0), 8 (5.0 all night), 8 (6.0)	Nightly	6 or 7 p.m. to 10 or 11 p.m., all night 6 or 7 p.m. to 4 or 5 a.m.	Daily	126 x 126 m plots; 5 m transects