Effects of Wind Turbine Curtailment on Bird and Bat Fatalities

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Mexican free-tailed bat (Tadarida brasiliensis) fatality, Golden Hills Wind Farm, Alameda County, California, 3 October 2017 (Photo: K. Shawn Smallwood).

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ABSTRACT - With the expansion of wind energy, bird and bat fatalities have also increased. Once wind turbines are installed, the only effective impact-reduction measure consists of operational curtailment – documented for bats but not for birds. We measured curtailment effects in an opportune before-after, control-impact (BACI) experimental design involving two wind projects monitored for fatalities using scent detection dogs and for nocturnal passage rates using thermal imaging during fall migration, where one project continued operating and the other shut down from the peak of migration to the study's end. We also compared bird fatality rates based on humans averaging 5-day search intervals among wind turbines of varying operable status, including operable, inoperable, vacant tower, and empty pad. Wind turbine curtailment in the BACI study had no significant effect on bird passage rates or fatality rates, whereas it significantly reduced bat passage rates and reduced bat fatality finds to 0. In the study of variable operable status among wind turbines, birds estimated to have died within 15 days of discovery averaged 35% more fatalities/MW at inoperable than at operable wind turbines, and fatalities declined substantially at vacant towers and empty pads. Of species represented by bird fatalities, 79% were found at inoperable wind turbines, including all 6 red-tailed hawk (*Buteo jamaicensis*) fatalities. Because the migration season is relatively brief, a seasonal curtailment strategy would greatly reduce bat fatalities while losing only a small fraction of a wind project's annual energy generation, but it might not benefit many species of birds.

INTRODUCTION

Wind energy development expanded rapidly over the last three decades while wildlife ecologists pursued mitigation strategies to minimize and reduce bird and bat fatalities caused by collisions with wind turbine blades. Based on different methods and averages drawn from different suites of source studies, annual estimates of fatalities across the USA were 600,000 (Hayes) and 888,000 bats (Smallwood 2013), 214,000 to 368,000 small birds (Erickson et al. 2014), and 234,000 (Loss et al. 2013) to 573,000 (Smallwood 2013) birds of all sizes. Since these estimates representing 2012, the installed capacity of wind energy nearly doubled by 2018. Whereas multiple mitigation measures were proposed, promised or required in conditional use permits in earlier wind projects, efficacy was either poor or unquantified due to lack of appropriate experimental design (Lovich and Ennen 2013, Sinclair and DeGeorge 2016), incomplete implementation, permit noncompliance, or fatality monitoring at search intervals that were too long for measuring mitigation treatment effects (Smallwood 2008). Careful micro-siting contributed to reduced fatality rates in repowered wind projects for select raptor species, but possibly at the expense of other birds and bats (Brown et al. 2016, Smallwood et al. 2017). Operational curtailment showed promise for bats (Arnett et al. 2011, 2013; Behr et al. 2017), whereas evidence has been lacking for birds despite years of seasonal curtailment in the Altamont Pass Wind Resource Area (APWRA) (Smallwood and Neher 2017). It would help to know whether operational curtailment can reduce bat fatalities in the APWRA where bat fatalities emerged as a substantial issue with repowering from old-generation wind turbines to modern wind turbines, and where the strategy had yet to be implemented. It would also help to know whether operational curtailment could reduce bird collision fatalities.

Bats appear to be attracted to wind turbines (Cryan et al. 2014), where they forage near and within the rotor plane (Horn et al. 2008, Foo et al. 2017). A curtailment strategy makes sense for reducing bat impacts, and the evidence indicates it works (Arnett et al. 2013). Evidence is lacking for any attraction to turbines by flying birds, but Tomé et al. (2017) reported no griffon vulture (*Gyps fulvus*) fatalities following implementation of a detect-and-curtail strategy based on radar detections. However, finding no fatalities might mean that none occurred or that fatalities occurred but none were found; the only reported detail of the fatality monitoring used to assess the detect-and-curtail strategy was search intervals of 2 weeks for half the year and monthly for the other half year (Tomé et al. (2017). Outside the context of an experimental design, and not knowing how many animals are normally killed absent an impact-reduction strategy, a finding of zero fatalities is difficult to interpret as an effect of the strategy (Sinclair and DeGeorge 2016). Measuring a treatment effect for small birds and bats is made even more difficult by low fatality detection rates due to quick scavenger removal (Smallwood et al. 2010) and low searcher detection of available carcasses (Smallwood 2017, Smallwood et al. 2018). Fortunately, shorter search intervals (Smallwood et al. 2018) and use of scent-detection dogs (Arnett 2006, Mathews et al. 2013) have vastly improved fatality detection.

Two studies, one using human searchers averaging 5-day intervals between searches (Smallwood et al. 2018) and the other using scent-detection dogs (Smallwood et al. in review), provided sufficient fatality detection rates for testing the effects of operational curtailment on volant wildlife. In the first, a 3-year study involving 187 old-generation wind turbines, 6% of the capacity never worked, 16% always worked in windy conditions, and 78% varied in operability due to mechanical and circuit failures – often remaining inoperable for months at a time. In the second study involving two wind projects composed of modern turbines, a project-wide shutdown to repair the circuit provided an opportune before-after, control-impact (BACI) paired-site experimental design. We were certain that wind turbines were inoperative during inoperable periods, but uncertain about how long wind turbines operated during operable periods. Operable wind turbines operate only when wind speeds exceed the turbine's cut-in speed, which varies by turbine model and season of the year. Fatalities attributed to inoperable periods could be assumed to have collided with the stationary structure of a wind turbine, whereas fatalities attributed to operable periods could have collided with either a stationary portion of the turbine or with the moving blades of the turbine's rotor. Limited as we were in our capacity to draw inference, our primary objective was to test whether and to what degree operational curtailment reduced bird and bat fatalities.

In our BACI study we also used a thermal-imaging camera to perform nocturnal bird and bat passage rate surveys, where passage rates were measured as the number of subjects passing through or within 1 m of the rotor plane. During passage rate surveys we could see whether wind turbines operated, giving us certainty over turbine operations concurrent with measurement of our passage rate metric. Our first objective was to compare passage rates through the rotor planes of both operative and inoperative wind turbines of a control group throughout the study and of an impact group before its shutdown. Our second objective was to test whether birds and bats altered their passage rates through the rotor planes of wind turbines after one project was shut down, and our third objective was to test whether passage rates were sensitive to the immediate operational status of a turbine. Our fourth objective was to test whether bird and bat passage rates composed of near-misses with wind turbine blades changed with operational status of the turbine.

STUDY AREA

Our studies included 5 wind projects averaging 4.2 km apart in the APWRA, Contra Costa and Alameda Counties, California (Table 1). The Buena Vista Wind Energy project (Buena Vista) consisted of 38 1-MW Mitsubishi wind turbines, 31 of which were accessible to us on land owned by East Bay Regional Park District, Contra Costa County. The Golden Hills Wind Energy project (Golden Hills) consisted of 48 1.79-MW General Electric (GE) wind turbines, 32 or which were accessible to us on privately held land in Alameda County. The Sand Hill project consisted of 403 wind turbines (23.123 MW) consolidated from 5 original projects, including 144 40-KW Enertech turbines in the original Altech I project, 12 65-KW Micon turbines in the original Swamp project, 183 65-KW Micon turbines in the original Taxvest project, 26 65-KW Micon turbines in the original Viking project, 26 65-KW Windmatic turbines in the original Venture Winds project, and 12 109-KW Polenko turbines at Venture Winds. The Santa Clara project included 200 0.95-MW Vestas turbines, 36 of which we monitored for one year. All 4 projects were on rolling hills covered by cattle-grazed annual grasses. Elevations ranged 41-280 m at Buena Vista, 115-477 m at Golden Hills, 61-179 m at Sandhill, and 226-351 m at Santa Clara.

METHODS

We performed two studies to test whether wind turbine curtailment affected birds and bats. One study, from 15 September through 15 November 2017, involved all of the wind turbines available to us in the Buena Vista and Golden Hills projects (Table 1). Because the entire Buena Vista project needed to be shut down for circuit repair from 06:00 hours on 2 October 2017 through the remainder of our study, we capitalized on the opportune BACI design, using Golden Hills as our experimental control. We measured treatment effects as (1) nocturnal passage rates through the rotor planes of wind turbines using a FLIR T620 thermal-imaging camera each night preceding fatality searches at the same turbines, and as (2) counts of found fatalities using scent-detection dogs in both instances.

Our other study, from April 2012 through March 2015, involved 151 Sand Hill turbines we selected for their documented histories of fatalities averaging 4.5× higher fatality rates than the others, and 36 Santa Clara turbines chosen to replace 17 turbines we lost to attrition at Sand Hill during the final year of monitoring (Smallwood et al. 2018). Besides undergoing project-wide shutdowns for 10 weeks each winter as mitigation for raptor fatalities, mechanical and circuit failures at these old turbines resulted in frequent forced shutdowns lasting up to all 1,086 days of our study, and for all but 16% of the turbines. We documented 570 wind turbine shutdowns, averaging 146 days per shutdown, and we documented 474 periods of operability, averaging 170 days per operable period. Amidst the periods of operability and inoperability interspersed among turbines, we performed 16,188 (46.4%) wind turbine searches over 474 periods of turbine operability, 17,392 (49.9%) turbine searches over 570 periods of inoperability, 882 (2.5%) turbine searches over 9 periods of vacant towers, and 363 (1.0%) searches over 4 periods of empty pads. Of the searches at inoperable turbines, 60.7% coincided with winter shutdowns as mitigation to reduce raptor fatalities and the rest coincided with mechanical or circuit malfunctions. Eight of the vacant towers were vacant through the study, and another supported a turbine between two periods of vacancy. Two empty pads were empty through the study, and a third supported a turbine between empty periods. We compared fatality estimates derived from fatality searches using experienced human searchers at turbines during periods of operability, inoperability, vacant towers, and empty pads, where vacant towers were towers lacking turbines and empty pads were spaces no longer hosting wind turbines or towers.

Passage rate surveys at Buena Vista and Golden Hills

Using a FLIR T620 thermal imaging camera, we performed 3-hour nocturnal surveys at turbines searched for fatalities the next morning, 14 September through 14 November 2017. Nocturnal surveys began at dusk, and included at least 1 round of 5-10 minute scans per turbine per hour, covering 2 to 3 wind turbines per night at Golden Hills and 3 to 5 turbines per night at Buena Vista. We video-recorded each timed scan to verify the classification accuracy of each subject as a bat or bird, but we could not identify bats or birds to species. Subjects identified as birds or bats with ≥70% confidence in identification accuracy were divided by hours of scan time and by rotor-swept ha of visible airspace within the camera's image-frame. Subjects passing through the rotor plane or ≤1 m parallel to the rotor plane contributed to passage rates. We summed passage rates by wind turbine by night, and averaged nightly turbine passage rates by project before and after the Buena Vista shutdown, which began 2 October 2017 and lasted through 15 November 2017 (Table 2).

In our BACI experiment we also compared passage rates defined by near misses, wind turbine-disrupted flights, and distracted flights inferred from interactions with other volant animals. Near misses were passages judged by the observer to have nearly collided with a blade. Disrupted flights included those resulting in possible, probable or certain collision, or displacements or jostling caused by pressure waves or vortices of passing blades. Certain collisions involved observations of animal-turbine contact, animal dismemberment, or animals falling without flight control all the way to the ground. Probable collisions involved blade sweeps very close to the animal, which subsequently disappeared from view. Possible collisions involved animals seen falling toward the ground after having missed the interaction between animal and wind turbine. Distracted flights included interactions with volant animals such as prey, or mobbing, harassing, chasing, following or fleeing other volant animals, or hovering ≤1 m from rotor sweeps or diving into airspace ahead of blade sweeps, or chasing or approaching or following along blades. Some distracted flights were also classified as disrupted flights, near misses or collisions, and some disrupted flights were also near misses, but no collisions were classified as near misses or disrupted flights.

Dog searches for fatalities at Buena Vista and Golden Hills

Using scent-detection dogs, we searched for bat and bird fatalities 5 days per week, 15 September through 15 November 2017. Our dog team consisted of a trained handler, an orienteer/data collector, and one dog at a time led by leash along transects oriented perpendicular to the wind and 10 m apart over search areas within the 270° arc between 210° and 300° from each turbine, which corresponds with the APWRA's prevailing upwind directions. We allowed dogs off leash for a more cursory search within the prevailing upwind 90° arc, because few bat and small bird fatalities are found upwind of wind turbines (Smallwood 2016, Brown et al. 2016). Maximum search radii were 75 m at Buena Vista and 105 m at Golden Hills. We left found carcasses in place for possible repeat discovery. We also tested the dog team by randomly placing fresh-frozen and thawed bird and bat carcasses within search areas, where carcasses were marked by clipping flight feathers or in the case of bats, removing one foot (Smallwood et al. 2018). These carcasses served as fatality detection trials used to adjust fatality finds for the proportion of fatalities not detected (Smallwood 2017, Smallwood et al. 2018). Fatality searchers were blind to the trials, and reported them in the same manner as turbine-caused fatalities, except that searchers also reported whether carcasses had been marked. To quantify carcass persistence, we checked trial carcasses until scavengers removed them or until the study ended.

Our dog team performed 28 turbine searches (26 turbines) at Buena Vista on or before the shutdown date, and 48 turbine searches (31 turbines) afterwards. They performed 14 turbines searches (14 turbines) at Golden Hills prior to the Buena Vista shutdown, and 41 turbine searches (31 turbines) afterwards.

Human searches for fatalities at Sand Hill and Santa Clara

Experienced fatality searchers walked parallel transects at 4-6 m intervals to a maximum search radius of 50 m, averaging 5 days between searches. They mapped and recorded attributes of fatalities, and left found fatalities in place for repeat detections. They also recorded detection trial carcasses that we integrated into routine fatality monitoring via trial carcass placements randomized by day and location. For estimating fatality rates, we logit-regressed detection trial outcomes on measured body mass of placed carcasses to derive a predictive model which we applied to typical body masses of species represented by found fatalities (Smallwood et al. 2018).

Over 3 years of monitoring in this study we completed 34,863 turbine searches, upon each of which we recorded the operational status of the turbine. We also conferred with the wind company regarding wind turbine operability. An operable wind turbine was one that was intact and able to generate electricity from wind, whereas an inoperable wind turbine was one that could not generate electricity because ≥1 blade was broken or missing, or some other broken part or bad circuit prevented energy generation. Rotors of inoperable wind turbines were often prevented from spinning by rope or cable tie-downs. From our recording of turbine operability, we defined 1,057 periods of contiguous status as operable (n = 474), inoperable (n = 570), vacant tower (n = 9), or empty pad (n = 4), where each period was specific to a single turbine's status.

We calculated point estimates and confidence intervals of fatality rates from periods of operational status.

Analytical methods

We compared mean passage rates of bats and birds through wind turbine rotors in a BACI paired-site experimental design using a 2-factor ANOVA with interest only in the significance of the interaction effect between time period and project site. To help interpret the results we also calculated measures of effect specific to the Buena Vista shutdown:

$$E[I_A] = \frac{C_A}{C_B} \times I_B,$$
$$IMPACT = \frac{(E[I_A] - I_A)}{E[I_A]} \times 100\%,$$

where $E[I_A]$ was the expected post-shutdown passage rate at the Buena Vista impact site, C_B and C_A were before and after passage rates at the Golden Hills control site, IMPACT was the percentage effect of the shutdown on passage rate.

Because treatment periods in the BACI design were too brief for calculating >1 fatality rate per period, we used χ^2 test for homogeneity. Our fatality rate metrics were fatality counts and fatalities/search. We also interpreted the results using the same measures of effect described above, but replaced passage rates with fatality counts or fatalities/search. We note that $E[I_A]$ is the expected value specific to treatment impact in the BACI design and not the same expected value in the χ^2 test for homogeneity.

For comparing fatality rates between wind turbine operational status and vacant towers, we estimated fatality rates $\hat{F}$ adjusted for the proportion of fatalities not found:

$$\hat{F} = \frac{F}{D},$$

where *F* was the unadjusted fatality rate, and *D* was trial carcass detection rate estimated from carcass detection trials that were integrated into routine monitoring (Smallwood et al. 2018). We estimated $\hat{F}$ and 95% confidence intervals from turbine-periods of operational status. A fully functional wind turbine monitored for 3 years would have 3 inoperable periods and 4 operable periods around the required winter shutdown, and some had ≥1 additional inoperable periods for malfunctions. The 6% of turbines that never operated were represented by 1 period of operational status. We compared fatality rate estimates derived from all found carcasses, from carcasses estimated ≤30 days since death, and from those estimated ≤15 days since death.

RESULTS

Buena Vista and Golden Hills BACI Experiment

Bat passage rates through Buena Vista wind turbine rotors decreased significantly after the shutdown (Table 3). The observed bat passage rate through shutdown Buena Vista turbines averaged 32.7 passes/hr/ha of rotor plane, which was 67% lower than the expected $E[I_A]$ rate of 97.9. The reduction was greater when restricting the analysis to passage rates through operable wind turbines at Golden Hills and pre-shutdown Buena Vista, resulting in 0 passes/hr/ha through shutdown Buena Vista turbines instead of the expected $E[I_A]$ of 86.1 (Table 3). Restricting the analysis of passage rates to include only passages involving near-miss collisions, we counted 0 near-miss passages through shutdown Buena Vista turbine rotors instead of the expected $E[I_A]$ 30.8 near-miss passes/hr/ha. The shutdown had no significant effect on bat passage rates through inoperative wind turbine rotors (Table 3), but the observed rate of 32.7 passes/hr/ha was twice that of the expected $E[I_A]$ passage rate of 16.3. There was no significant shutdown effect on bird passage rates (Table 3).

Bat fatalities found before and after the Buena Vista shutdown numbered 37 and 27 at Golden Hills, and 22 and 0 at Buena Vista (Table 4; $\chi^2 = 13.53$, d.f. = 1, $P<0.05$). Our BACI expected value, $E[I_A]$, was 16.0, which was substantially greater than the 0 we found.

Bird fatalities found before and after the Buena Vista shutdown numbered 16 and 17 at Golden Hills, and 8 and 5 at Buena Vista (Table 4; $\chi^2 = 0.64$, d.f. = 1, $P>0.05$). Our expected value, $E[I_A]$, was 8.5 bird fatalities, which numbered more than the 5 we found, although the χ^2 test was not significant. Nearly all of the birds in the test were small birds, so the test outcome was the same for small birds. The IMPACTs of the Buena Vista shutdown were 100% fatality reductions for bats and 41% reduction for birds, but factoring in search effort (fatalities/search) reduced the IMPACT to 0% for birds.

The birds we found as fatalities at Buena Vista after the shutdown were 4 western meadowlarks and 1 unidentified small bird (Table 4). After the Buena Vista shutdown, we continued to find western meadowlarks and red-tailed hawks at Golden Hills, where we also found fatalities of horned lark, northern rough-winged swallow, ruby-crowned kinglet, American pipit, Lincoln’s sparrow, and dark-eyed junco. Fatality counts of individual species were too few for chi-square tests.

Sand Hill and Santa Clara

We found too few bat fatalities for reliable comparison of bat fatality rates by wind turbine operability at Sand Hill and Santa Clara. We note, however, that we found a Mexican free-tailed bat fatality at an inoperable wind turbine.

Birds estimated to have died within 15 days of discovery averaged 35% more fatalities/MW at inoperable than at operable wind turbines, but 95% confidence intervals largely overlapped (Table 5). Bird fatalities/MW at vacant towers averaged only 5% of those at operable wind turbines and 4% of those at inoperable wind turbines. We found only 1 European starling at an empty pad.

Fatalities/MW compared similarly when including birds estimated to have died within 30 days and earlier. Fatalities/MW including deaths within 30 days of discovery averaged 28.9 (95% CI:

1.5-46.4) at operable turbines, 36.1 (95% CI: 1.6-56.3) at inoperable turbines, 1.7 (95% CI: 1.3-4.6) at vacant towers, and the 1 European starling at empty pads.

Fatalities/MW including all birds averaged 39.3 (95% CI: 1.8-60.8) at operable turbines, 46.2 (95% CI: 1.8-70.1) at inoperable turbines, 2.0 (95% CI: 1.4-5.3) at vacant towers, and 0.2 (95% CI: 0.0-0.5) at empty pads.

Seventy-nine percent of species represented by bird fatalities in this study were found at inoperable wind turbines. All 6 red-tailed hawk fatalities were found at inoperable wind turbines. We found one of these red-tailed hawks directly under an inoperable wind turbine with its bill dislocated into its face. Burrowing owls, great-horned owls, mourning doves, and western meadowlarks died at inoperable turbines at twice the rate as at operable turbines. Notable exceptions included American kestrels, which we found dead at operable turbines at twice the rate as at inoperable turbines, and northern flickers and 3 species of flycatcher which we found dead only at operable wind turbines.

DISCUSSION

The Buena Vista shutdown strongly affected bat passage rates, but not bird passage rates. After the shutdown, bats passed through inoperative turbine rotors at twice the rate other than expected, but this difference between 32.7 and 16.3 passes/hr/ha was not significant. Even more substantial, and significant, was the shutdown effect on bat passages through turbine rotors when the comparison was between operative Golden Hills turbines and shutdown Buena Vista turbines, resulting in 0 passages through shutdown turbine rotors instead of the expected 86. Comparing the expected 86 passages/hr/ha through operative wind turbines to the observed 32.7 passages/hr/ha through inoperative wind turbines suggests bats are 2.6 times more likely to pass through the turbines of operative versus inoperative wind turbine rotors.

The one bat fatality we found at an inoperable wind turbine in the Sand Hill project might have been killed by either of the neighboring wind turbines, which were operable at the time and only 40 m to either side of the inoperable turbine. Alternatively, it might have collided with a nonmoving turbine part. However, results from our BACI experiment at Buena Vista and Golden Hills indicate that shutting down wind turbines during bat migration also curtails bat fatalities. It appears that turbine rotors must spin for bats to collide with wind turbines. Therefore, for bat species vulnerable to population-level impacts caused by wind turbines, such as hoary bat (Frick et al. 2017), a seasonal curtailment strategy should substantially improve population viability.

On the other hand, operational curtailment appears to be ineffective at reducing fatalities of most bird species in our study. The winter shutdown, which was proposed as a mitigation measure by the wind companies and endorsed by Smallwood in 2005 (Smallwood 2008), and then implemented at most of the APWRA's old-generation wind turbines 2006-2014, was probably ineffective for reducing fatalities of most bird species (but see below). Few bats are active over winter, so the shutdown likely failed to reduce bat fatalities. It remains unknown whether the winter shutdown reduced golden eagle fatalities, though we note that historically fewer golden eagles have been found as fresh fatalities over the winter months (Nov-Feb) in the APWRA.

Because we found only 1 golden eagle fatality, and because it collided with a wind turbine unselected for this study, our study results cannot inform of curtailment effects on golden eagles. However, we note that we found this mortally wounded eagle at an operable turbine. Of the hundreds of eagle fatalities documented in the APWRA, we cannot recall any having been associated with an inoperable wind turbine. We suggest it is likely that some species, such as golden eagle, American kestrel, and flycatchers, are more vulnerable to a wind turbine's moving blades. It remains unknown, however, whether a curtailment strategy would minimize or reduce fatalities of these species.

Otherwise, our study suggests that for most bird species, more of the collision risk might be in the structure of a wind turbine than in the moving parts, as suggested by collision risk modeling performed before our study began (Richard Podolski, Pers. Comm. with K. S. Smallwood). Furthermore, our results suggest that vacant towers pose much lower collision risk than do inoperable turbines mounted on towers. We suspect that most of the risk of a mounted turbine is in the blades regardless of whether blades are moving. Although admittedly not birds, we have often found blades difficult to see due to low contrast against a sky backdrop or blending in against certain terrain backgrounds. At night the blades are even more difficult to see, especially when motionless. Operating wind turbines produce considerable noise, which might alert birds to potential hazard. The motion of operating turbines can also enhance blade visibility at night by periodically disrupting artificial background lighting of rural homes and distant cities (Fig. 2), or even the rising or setting of lit moon. Also, a quarter of the turbines flash aviation hazard lights at night. Whether birds perceive these hazard cues remains unknown, but could explain our lack of effect of turbine shutdown.

Our finding of only 2 bat fatalities after 34,863 turbine searches at Sand Hill and Santa Clara suggests that the old-generation wind turbines killed many fewer bats than the repowered modern turbines at Buena Vista and Golden Hills. Confounding the comparison, however, was the use of human searchers at Sand Hill and Santa Clara versus scent detection dogs at Buena Vista and Golden Hills. At Vasco Winds, which was another repowered project consisting of modern wind turbines adjacent to Buena Vista, humans searched half the 2.3-MW turbines on 80-m towers at 7-day intervals (Brown et al. 2016), which was 2 days longer than the average search interval achieved at Sand Hill and Santa Clara, and they searched along transects spaced at twice the distance. Despite these methodological disadvantages for detecting bats at Vasco Winds relative to Sand Hill and Santa Clara, human searchers found 31 bats after 2,652 turbine searches at Vasco Winds, or 204 times the number of bat fatalities per search. Modern turbines appear much more dangerous to bats compared to old-generation wind turbines, but it remains unknown whether the greater danger arose from the small difference in location or in increased tower height, lower RPM, or greater operability.

One implication of our findings is that fatality estimates based on proportion of the time wind turbines operate should work well for bats, so long as investigators have the means to carefully track wind turbine operations, but this approach will not work well for birds. ICF International (2016) defined their fatality rate metric as fatalities/MW/year of operable status, and they used it to conclude that winter shutdowns and the removals of a small number of designated high-risk turbines reduced fatality rates of 4 raptor species – golden eagle, red-tailed hawk, American kestrel, and burrowing owl – by 50%. Our results indicate that ICF International's (2016) conclusion was spurious because fatality rates of most bird species in the APWRA were unrelated to turbine operability.

Another implication of our findings relates to estimates of background mortality in wind projects. ICF International (2015) estimated surprisingly high background mortality over the winter months of 2014-2015, but most of their fatality searches overlapped shutdown wind turbines waiting for removal. Based on our findings, ICF International (2015) erroneously assumed that wind turbines must be operative to kill birds. They also assumed that all birds they found as fatalities at the derelict wind turbines had been consumed by raptors perching on the turbines, but this hypothesis was not supported by the much lower fatality rates we observed at vacant towers. The safest approach for estimating background mortality is to search areas that are empty of wind turbines, operable or not.

MANAGEMENT IMPLICATIONS

Because the migration season is relatively brief, a seasonal curtailment strategy would greatly reduce bat fatalities while not giving up a large proportion of a wind project's annual energy generation. The efficiency of such a migration-specific curtailment could improve by narrowing it to the first few hours following dusk. But for most bird species there does not seem to be a curtailment solution. For birds the most likely effective mitigation is careful macro- and micro-siting to avoid landscape settings where birds will more often encounter obstacles erected in their flight space. Unfortunately, micro-siting might not be as effective for bats because our results indicate bats are attracted to operative wind turbines.

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Table 1. Wind turbines in project (N) and selected/used in study of relationship between collision fatalities and turbine operational status during intervals preceding fatality searches at Golden Hills, Buena Vista, Sand Hill and Santa Clara Wind Energy Projects, Alameda and Contra Costa Counties, California, 2012-2015 and Fall 2017.

Project	Turbine model	MW	Hub height (m)	N		Monitoring		Searches	
				All	Selected /used	Duration (years)	Searcher	Total	At operable turbines (%)
Golden Hills	GE	1.790	80.0	48	32	0.17	Dogs	55	100.0
Buena Vista	Mitsubishi	1.000	45-65	38	31	0.17	Dogs	76	36.8
Altech I	Enertech	0.040	18.5	144	47/63	3.00	Humans	11,857	40.6
Swamp	Micon	0.065	24.6	12	5	3.00	Humans	1085	41.5
Taxvest	Micon	0.065	24.6	183	56/73	3.00	Humans	13,098	53.5
Viking	Micon	0.065	24.6	26	5/7	3.00	Humans	1519	53.3
Venture	Windmatic	0.065	18.5	26	15/16	3.00	Humans	2936	35.7
Venture	Polenko	0.109	24.4	12	11	3.00	Humans	1985	34.9
Santa Clara	Vestas	0.095	24.6	200	36	1.00	Humans	2345	58.3

Table 2. Nocturnal survey effort using a FLIR T620 thermal-imaging camera for measuring passage rates through rotor-swept airspace in a before-after, control-impact paired-site experimental design at Golden Hills and Buena Vista Wind Energy Projects, Alameda and Contra Costa Counties, California, Fall 2017.

Survey effort	Golden Hills		Buena Vista		Both projects	
	Before	After	Before	After	Before	After
Total survey hours	11.25	34.14	15.58	23.36	26.83	57.50
Survey hours at operative turbine	10.84	26.57	11.34	0.00	22.18	26.57
Survey hours at inoperative turbine	0.41	7.57	4.24	23.36	4.65	30.93
Sum rotor plane viewable (ha)	3.85	10.39	3.85	6.03	7.70	16.42

Table 3. Mean and 95% CI nocturnal passes/hour/ha of rotor plane in before-after, control-impact paired-site experimental design at Golden Hills (GH) and Buena Vista (BV) Wind Energy Projects, Alameda and Contra Costa Counties, California, Fall 2017. F represents the F-ratio specific to the interaction term in 2-factor ANOVA (D.F. = 1,142), where t denotes 0.10>P>0.05, * denotes P < 0.05 and ** denotes P < 0.001. Disrupted flights included those flights resulting in possible, probable or certain collision, or displacements or jostling caused by pressure waves or vortices of passing blades. Distracting flights included interactions with volant animals such as prey, or mobbing, harassing, chasing, following or fleeing other volant animals, or hovering ≤1 m from rotor sweeps or diving into airspace ahead of blade sweeps, or chasing or approaching or following along blades.

	Passes/hour/ha of rotor plane								
Taxa/Passage type	GH before		GH after		BV before		BV after		
Bats	$\bar{x}$	95% CI	$\bar{x}$	95% CI	$\bar{x}$	95% CI	$\bar{x}$	95% CI	F
All turbine rotors	9.2	1.5–16.9	16.0	8.1–24.0	56.4	29.8–82.9	32.7	2.2–63.1	3.52^{t}
Operative rotor	8.9	1.3–16.5	14.4	6.9–22.0	53.0	27.0–78.9	0.0		24.19**
Inoperative rotor	0.3	0.0–1.0	1.6	0.2–2.9	3.4	0.0–7.6	32.7	2.2–63.1	0.91
Collided	0.0		0.8	0.0–1.8	0.5	0.0–1.5	0.0		3.75^{t}
Near miss or disrupted flight	4.2	1.0–7.5	5.3	2.6–8.0	24.5	8.4–40.6	0.0		14.57**
Near miss, disrupted flight, or distracted	6.5	0.6–12.3	6.4	3.4–9.4	34.8	14.9–54.7	8.1	0.0–18.2	8.10*
Birds									
All turbine rotors	4.9	0.0–13.1	2.2	0.0–4.5	5.5	0.9–10.2	1.9	0.0–5.3	0.72
Operative rotor	4.9	0.0–13.1	1.7	0.3–3.0	5.0	0.4–9.5	0.0		1.46
Inoperative rotor	0.0		0.5	0.0–1.6	0.6	0.0–1.7	1.9	0.0–5.3	0.01
Near miss or disrupted flight	4.9	0.0–12.9	0.3	0.0–0.8	1.4	0.0–3.5	0.0		0.55
Near miss, disrupted flight, or distracted	4.6	0.0–12.9	0.3	0.0–0.8	1.4	0.0–3.5	0.3	0.0–0.8	0.68

Table 4. Summary of fatalities found by Conservation Canines' scent-detection dog teams at Buena Vista (BV) and Golden Hills (GH) during fall 2017, and fatalities per search before and after the Buena Vista wind turbines were shut down on 2 October 2017.

		Fatalities/search			
		Buena Vista		Golden Hills	
Species	Scientific name	Before	After	Before	After
Western red bat	*Lasiurus blossevillii*	0.143	0.000	0.071	0.000
Myotis	*Myotis*	0.000	0.000	0.071	0.000
Mexican free-tailed bat	*Tadarida brasiliensis*	0.214	0.000	1.214	0.220
Hoary bat	*Lasiurus cinereus*	0.071	0.000	0.429	0.146
Bat		0.357	0.000	0.857	0.293
Mallard	*Anas platyrhynchos*	0.000	0.000	0.071	0.000
Grebe	Podicipedidae	0.000	0.000	0.000	0.000
Turkey vulture	*Cathartes aura*	0.000	0.000	0.000	0.000
Northern harrier	*Circus cyaneus*	0.000	0.000	0.000	0.000
White-tailed kite	*Elanus leucurus*	0.000	0.000	0.000	0.000
Red-tailed hawk	*Buteo jamaicensis*	0.000	0.000	0.143	0.024
Large raptor		0.000	0.000	0.000	0.000
American kestrel	*Falco sparverius*	0.071	0.000	0.071	0.000
Prairie falcon	*Falco mexicanus*	0.000	0.000	0.000	0.000
Rock pigeon	*Columba livia*	0.000	0.000	0.000	0.000
Barn owl	*Tyto alba*	0.036	0.000	0.000	0.000
Burrowing owl	*Athene cunicularia*	0.000	0.000	0.214	0.000
White-throated swift	*Aeronautes saxatalis*	0.000	0.000	0.000	0.000
Pacific-slope flycatcher	*Empidonax difficilis*	0.036	0.000	0.000	0.000
Horned lark	*Eremophila alpestris*	0.000	0.000	0.071	0.024
Northern rough-winged swallow	*Stelgidopteryx serripennis*	0.000	0.000	0.000	0.049
Bewick's wren	*Thryomanes bewickii*	0.000	0.000	0.071	0.000
House wren	*Troglodytes aedon*	0.000	0.000	0.071	0.000
Ruby-crowned kinglet	*Regulus calendula*	0.000	0.000	0.000	0.049
American pipit	*Anthus rubescens*	0.000	0.000	0.000	0.024
Warbler	Parulidae	0.000	0.000	0.071	0.000
Black-throated gray warbler	*Dendroica nigrescens*	0.000	0.000	0.000	0.000
Townsend's warbler	*Dendroica townsendi*	0.036	0.000	0.000	0.000
Lincoln's sparrow	*Melospiza lincolnii*	0.000	0.000	0.000	0.024
Dark-eyed junco	*Junco hyemalis*	0.000	0.000	0.000	0.024
Blackbird	Icteridae	0.000	0.000	0.000	0.000
Western meadowlark	*Sturnella neglecta*	0.071	0.083	0.000	0.049
Brown-headed cowbird	*Molothrus ater*	0.000	0.000	0.000	0.000
Large bird		0.000	0.000	0.071	0.024
Small bird		0.036	0.021	0.286	0.122
All bats		0.786	0.000	2.643	0.659

Species	Scientific name	Fatalities/search			
		Buena Vista		Golden Hills	
		Before	After	Before	After
All small birds		0.250	0.104	0.857	0.366
All large birds		0.036	0.000	0.286	0.049
All birds		0.286	0.104	1.143	0.415

Table 5. Comparison of fatalities/MW among operable and inoperable wind turbines and vacant towers from April 2012 through March 2015 in the Sand Hill and Santa Clara Wind Energy Projects, Alameda County, California. Inoperability was either volitional during project-wide winter shutdowns as mitigation intended to reduce raptor fatalities or forced by mechanical or circuit failures, totaling 50% of turbine searches across 570 turbine-shutdown periods. Fatality estimates were adjusted for overall detection rates, *D* (Smallwood et al. 2018).

Common name	Species name	Estimated fatalities/MW by wind turbine operational status					
		Operable		Inoperable		Vacant tower	
		$\bar{x}$	95% CI	$\bar{x}$	95% CI	$\bar{x}$	95% CI
Mexican free-tailed bat	*Tadarida brasiliensis*	0.000		0.231	0.035–0.685	0.000	
Bat		0.561	0.056–1.661	0.000		0.000	
Grebe	Podicipedidae	0.000		0.080	0.022–0.235	0.000	
American coot	*Fulicra Americana*	0.000		0.262	0.037–0.625	0.000	
Killdeer	*Charadrius vociferus*	0.107	0.027–0.317	0.107	0.025–0.317	0.000	
Spotted sandpiper	*Actitis macularis*	0.135	0.030–0.400	0.000		0.000	
Glaucous-winged gull	*Larus glaucescens*	0.078	0.024–0.230	0.000		0.000	
Herring gull	*Larus argentatus*	0.000		0.078	0.022–0.231	0.000	
Thayer's gull	*Larus thayeri*	0.000		0.174	0.031–0.515	0.000	
Gull	Laridae	0.159	0.033–0.380	0.195	0.033–0.469	0.000	
Ferruginous hawk	*Buteo regalis*	0.000		0.124	0.027–0.367	0.000	
Red-tailed hawk	*Buteo jamaicensis*	0.000		0.183	0.032–0.541	0.000	
American kestrel	*Falco sparverius*	0.557	0.056–1.050	0.268	0.037–0.651	0.102	0.147–0.303
Barn owl	*Tyto alba*	0.268	0.041–0.664	0.238	0.035–0.508	0.000	
Burrowing owl	*Athene cunicularia*	1.210	0.079–2.100	2.105	0.091–3.207	0.000	
Great-horned owl	*Bubo virginianus*	0.076	0.024–0.224	0.152	0.029–0.362	0.000	
Mourning dove	*Zenaida macroura*	0.911	0.070–1.553	2.497	0.098–3.806	0.000	
Rock pigeon	*Columba livia*	10.937	0.204–13.596	10.768	0.185–13.397	0.392	0.253–0.921
Dove	Columbidae	0.346	0.046–0.744	0.308	0.040–0.737	0.000	
Common poorwill	*Phalanoptilus nuttallii*	0.000		0.193	0.032–0.571	0.000	
White-throated swift	*Aeronautes saxatalis*	0.000		0.151	0.029–0.448	0.000	
Northern flicker	*Colaptes auratus*	0.100	0.027–0.296	0.000		0.000	
Ash-throated flycatcher	*Myiarchus cinerascens*	0.156	0.032–0.462	0.000		0.000	

Common name	Species name	Estimated fatalities/MW by wind turbine operational status					
		Operable		Inoperable		Vacant tower	
		$\bar{x}$	95% CI	$\bar{x}$	95% CI	$\bar{x}$	95% CI
Pacific-slope flycatcher	*Empidonax difficilis*	0.411	0.049–1.218	0.000		0.000	
Say's phoebe	*Sayornis saya*	0.288	0.042–0.853	0.000		0.000	
Horned lark	*Eremophila alpestris*	0.000		0.142	0.028–0.421	0.000	
Common raven	*Corvus corax*	0.077	0.024–0.229	0.112	0.026–0.331	0.000	
American robin	*Turdus migratorius*	0.000		0.363	0.043–0.900	0.000	
European starling	*Sturnus vulgaris*	2.326	0.104–3.455	1.809	0.085–2.831	0.165	0.178–0.488
Yellow-rumped warbler	*Setophaga coronata*	0.000		0.656	0.055–1.565	0.000	
Lincoln’s sparrow	*Mellospiza lincolnii*	0.000		0.165	0.030–0.489	0.000	
Song sparrow	*Melospiza melodia*	0.000		0.150	0.029–0.445	0.000	
Sparrow	Emberizidae	0.000		0.293	0.039–0.869	0.000	
Red-winged blackbird	*Agelaius phoeniceus*	0.000		0.204	0.033–0.605	0.000	
Tricolored blackbird	*Aegolaius tricolor*	0.000		0.126	0.027–0.373	0.000	
Western meadowlark	*Sturnella neglecta*	0.662	0.061–1.213	1.256	0.073–2.151	0.000	
Blackbird	Icteridae	0.203	0.036–0.602	0.125	0.027–0.371	0.000	
House finch	*Haemorhous mexicanus*	0.241	0.039–0.714	0.310	0.040–0.742	0.241	0.206–0.714
Lesser goldfinch	*Spinus psaltria*	0.208	0.037–0.616	0.000		0.000	
Large bird		0.000		0.000		0.173	0.181–0.512
Medium bird		0.347	0.046–0.763	0.260	0.037–0.554	0.000	
Small bird		0.478	0.053–1.176	4.221	0.123–6.170	0.000	
All birds		20.842	1.239–34.517	28.075	1.500–45.802	1.073	0.964–2.937

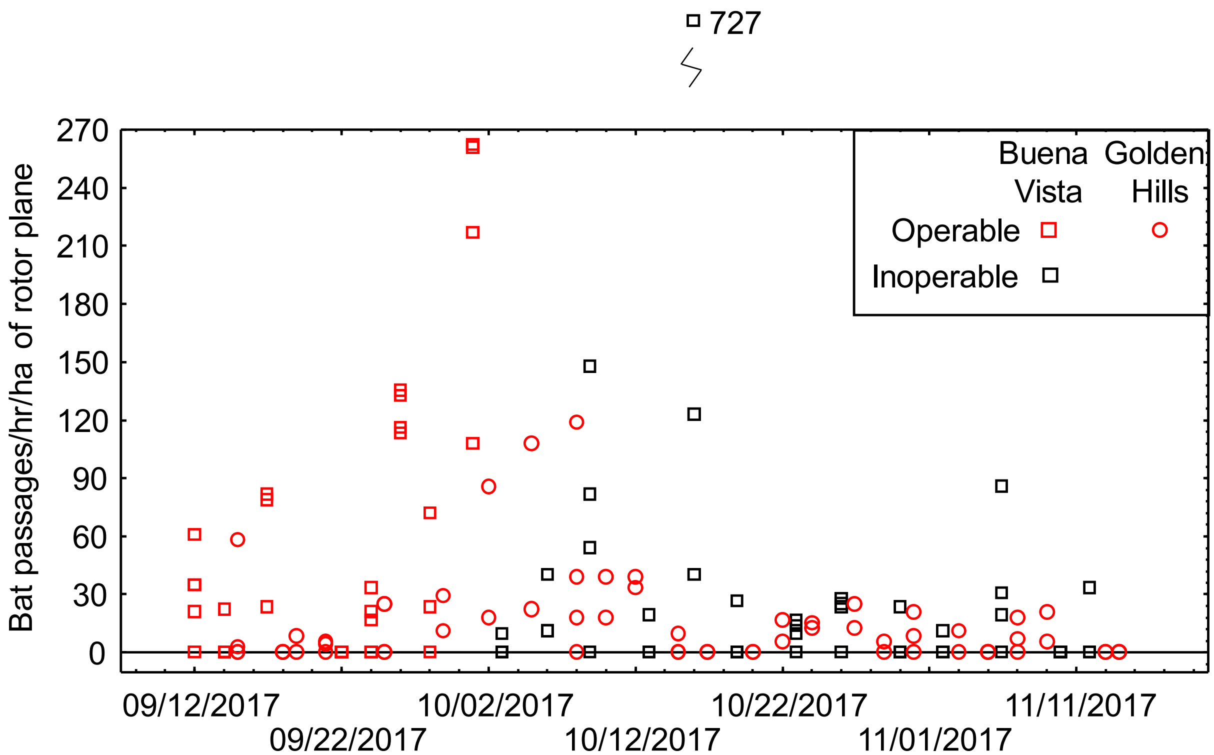

Figure 1. Bat passes/hr/ha of rotor plane at the Golden Hills and Buena Vista wind projects before and after the Buena Vista shutdown on 2 October 2017, Alameda and Contra Costa Counties, California, where passages were those with ≥70% confidence the subjects were bats.

Figure 2A. Blocked background artificial light viewed eastward at rotor-height through the Altamont Pass Wind Resource Area, between the flashing of FAA hazard lights.

Figure 2B. Blocked background artificial light viewed eastward at rotor-height through the Altamont Pass Wind Resource Area, coinciding with the flashing of FAA hazard lights.