



Research Article

Effects of Wind Turbine Curtailment on Bird and Bat Fatalities

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ABSTRACT Bird and bat fatalities increase with wind energy expansion and the only effective fatality-reduction measure has been operational curtailment, which has been documented for bats but not for birds. We performed opportune before-after, control-impact (BACI) experiments of curtailment effects on bird and bat fatalities and nocturnal passage rates during fall migration at 2 wind projects, where 1 continued operating and the other shut down from peak migration to the study's end (study 1). We also performed BACI experiments during a 3-year study of curtailment and operational effects on bird fatalities among wind turbines of varying operational status (study 2). In study 1, wind turbine curtailment significantly reduced near-misses and rotor-disrupted flights of bats, and it significantly reduced fatalities of bats but not of birds. In study 2, converting wind turbines from inoperable to operable status did not significantly increase bird fatalities, and bird species of hole or sheltered-ledge nesters or roosters on human-made structures died in substantial numbers at vacant towers. Of bird species represented by fatalities in study 2, 79% were found at inoperable wind turbines. Because the migration season is relatively brief, seasonal curtailment would greatly reduce bat fatalities for a slight loss in annual energy generation, but it might not benefit many bird species. © 2020 The Authors. The *Journal of Wildlife Management* published by Wiley Periodicals, Inc. on behalf of The Wildlife Society.

KEY WORDS bat fatalities, bird fatalities, collision risk, mitigation, operational curtailment, wind turbine operability.

Wind energy development has expanded rapidly over the last 3 decades and wildlife ecologists have pursued mitigation strategies to minimize and reduce bird and bat fatalities caused by collisions with wind turbine blades. In the United States, for example, wind energy generation in 2012 was estimated to have killed 600,000 (Hayes 2013) to 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. Because installed wind energy capacity in the United States doubled from 2012 to 2020, bird and bat fatalities likely also increased. Whereas multiple mitigation measures have been proposed, promised, or required in conditional use permits in earlier wind projects, efficacy was poor or unquantified because of a 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 (i.e., the siting of wind turbines within a project based on specific flight behavior patterns) contributed to reduced fatality rates in re-powered wind projects for select raptor species but might have

inadvertently increased fatalities of other birds and bats (Brown et al. 2016, Smallwood et al. 2017). Operational curtailment showed promise for reducing bat fatalities (Arnett et al. 2011, 2013; Behr et al. 2017; Hayes et al. 2019), whereas a decade of seasonal curtailment did not appear to reduce bird fatalities in the Altamont Pass Wind Resource Area (APWRA) (Smallwood and Neher 2017).

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). Evidence is lacking for any attraction to operating 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 zero fatalities following an action to reduce fatalities is difficult to interpret outside the context of a suitably designed experiment, such as a before-after, control-impact (BACI) experiment, and without knowing how many animals were normally killed by wind turbines prior to the action (Sinclair and DeGeorge 2016). Furthermore, finding zero fatalities might mean that none occurred or that fatalities occurred but none were found. Compared to measuring experimental treatment effects applied to animals the size of griffon vultures, measuring a treatment effect for small birds and bats is made even more difficult by low fatality detection rates owing 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)

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and use of scent-detection dogs (Arnett 2006, Mathews et al. 2013) have improved fatality detection.

Bat fatalities have emerged as a substantial issue with re-powering from old-generation wind turbines to modern wind turbines in the APWRA. We therefore sought to determine whether operational curtailment can reduce bat fatalities in the APWRA and whether this mitigation measure could also reduce bird collision fatalities. High fatality detection rates in 2 recent studies enabled us to test the effects of operational curtailment on reducing fatalities of volant wildlife. Study 1 used scent-detection dogs at Buena Vista and Golden Hills Wind Energy Projects (K. S. Smallwood, independent researcher, unpublished data). Study 2 used human searchers averaging 5-day intervals between searches at Sand Hill Energy Project (Smallwood et al. 2018). Our first objective was to test whether wind turbine curtailment, and conversely, conversion of wind turbines from inoperable to operable, affected fatality rates of birds and bats. Our second objective was to test whether wind turbine curtailment affected nocturnal bird and bat passage rates through wind turbine rotors, where we measured passage rates as the hourly number of subjects passing through or within 1 m of the rotor plane. Our third objective was to test whether wind turbine curtailment altered the rates of nocturnal bird and bat near-miss collisions, turbine-disrupted flights caused by factors such as rotor wake turbulence, or flights exhibiting potential distraction to external factors such as other volant wildlife.

STUDY AREA

Our studies included 3 wind projects averaging 4.2 km apart in the APWRA, Contra Costa and Alameda counties, California, USA. The APWRA was situated in the Inner Coast Range geomorphic province, bordering the Central Valley province. All 3 projects were situated on steep rolling hills with elevations that ranged 41–280 m over 1,012 ha at Buena Vista, 115–477 m over 1,822 ha at Golden Hills, and 61–179 m over 354 ha at Sandhill. The cattle-grazed California Annual Grassland was dominated by nonnative annuals such as rye grass (*Lolium multiflorum*), wild oat (*Avena fatua*), and soft chess (*Bromus hordeaceus*). Climate was Mediterranean, consisting of dry summers averaging 31.5°C during July–August, and mild winters averaging 13–16°C during December–February with peak precipitation during November–March (<https://www.usclimatedata.com>, accessed Feb 2020). California ground squirrel (*Otospermophilus*

beecheyi) serves as one of APWRA's keystone wildlife species, colonies of which focus activity of many other species. Birds and bats also migrate through the APWRA in spring and fall.

The Buena Vista project was composed of 1-MW wind turbines spaced about 90 m apart in 3 rows (Table 1). Buena Vista became operational in January 2007 but underwent a project-wide shutdown for circuit repairs that began at 0600 on 2 October 2017 and lasted through 14 November 2017. Golden Hills was composed of 1.79-MW turbines spaced ≥ 265 m apart. Golden Hills became operational in December 2015 and remained operable throughout the Buena Vista shutdown. Sand Hill was composed of hundreds of wind turbines varying in manufacturer, tubular versus lattice tower structure, rated capacity from 40 KW to 109 KW, and spacing of about 40–50 m apart in rows. Sand Hill began operating in the early 1980s. By the time of our study, turbine operability had deteriorated; of the 157 turbines investigated, 6% never worked, 16% always worked in windy conditions, and 78% varied in operability because of mechanical and circuit failures, often remaining inoperable for months at a time. All Sand Hill turbines were shut down with rotors locked to prevent motion for 3.5 months each winter (1 Nov–15 Feb) to mitigate raptor fatalities.

METHODS

We performed 7 BACI experiments during 2 studies to test whether wind turbine curtailment affected nocturnal passage rates and fatality rates of birds and bats (Table 1). In study 1, which used dogs as fatality searchers, we performed 4 paired-site BACI experiments at all wind turbines available to us in the Buena Vista and Golden Hills projects from 15 September through 15 November 2017. Because the entire Buena Vista project was shut down beginning 2 October 2017 through the end of our study, we capitalized on the opportune BACI design, using Golden Hills as our experimental control because its turbines remained operational. Based on monitoring 5 days/week and a high fatality detection rate using dogs (K. S. Smallwood, unpublished data), we measured shutdown effects on nocturnal passage rates through the rotor planes of wind turbines and estimated fatality rates (see below).

In study 2, we performed 3 BACI experiments at the Sand Hill project, which involved human searches for fatalities at an average of 5-day intervals between searches at 151 Sand Hill turbines monitored from April 2012 through March 2015

Table 1. Attributes of wind turbines and monitoring used for relating collision fatalities to turbine operability at Golden Hills and Buena Vista Wind Energy Projects in fall 2017 (study 1), and at Sand Hill Wind Energy Project in 2012–2015 (study 2), Alameda and Contra Costa counties, California, USA.

Project	Turbine model	MW	Hub height (m)	<i>n</i> turbines		Monitoring		Searches	
				In project	In study	Duration (yr)	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
Sand Hill	Enertech	0.040	18.5	144	63	3.00	Humans	11,857	40.6
Sand Hill	Micon	0.065	24.6	221	85	3.00	Humans	15,702	52.5
Sand Hill	Windmatic	0.065	18.5	26	16	3.00	Humans	2,936	35.7
Sand Hill	Polenko	0.109	24.4	12	11	3.00	Humans	1,985	34.9

(Smallwood et al. 2018). Besides undergoing project-wide shutdowns for 15 weeks each winter to mitigate raptor fatalities, mechanical and circuit failures at all but 16% of these old turbines resulted in frequent forced shutdowns lasting up to the 1,086-day duration of our study. We regularly searched for fatalities at all wind turbines initially selected for the study regardless of operational status. Of the turbine-searches at inoperable turbines, we performed 60.7% during winter shutdown periods and searched the rest during periods of shutdown caused by turbine malfunctions through spring, summer, and fall seasons when the turbines were intended to be operable. For inclusion in any of our BACI experiments at Sand Hill, an operable turbine must have been determined operable for $\geq 90\%$ of any contiguous span of spring, summer, and fall seasons when the turbines were allowed to operate outside the winter shutdown, and an inoperable turbine never operated during these seasons. In 2 BACI experiments, we assigned the preceding year's operable seasons as the before phase and the subsequent year's operable seasons as the after phase (Table 2). In the first of these experiments, we assigned those turbines that remained operable through both years as the control treatment and those that were operable the previous year and inoperable the next year as the impact treatment. In the second of these experiments, we assigned those turbines that remained inoperable through both years as the control treatment and those turbines that were inoperable the previous year but operable the next year as the impact treatment. In the third experiment we assigned winter shutdowns as the before phase and subsequent spring-fall seasons as the after phase, and we assigned those turbines that remained inoperable through the operable seasons as the control treatment and those turbines that were operable through the operable season as the impact treatment (Table 2). In all 3 Sand Hill experiments composing study 2, turbines that were operable or inoperable during operable seasons varied annually and were spatially interspersed. We omitted the third and final winter shutdown and fourth and final operable season from BACI experiments because our monitoring of the final operable season spanned only 44 days (16 Feb–31 Mar).

For both studies 1 and 2, we were certain that wind turbines were inoperative (not moving) during inoperable periods but uncertain about how long wind turbines operated during operable periods. Operable wind turbines operate only when wind speed exceeds the turbine's cut-in speed, which varies by turbine model seasonally and even by the minute. Fatalities attributed to inoperable periods could be assumed to have collided with the

stationary structures of a wind turbine, including with towers and unmoving blades, whereas fatalities attributed to operable periods could have collided with either stationary portions of the turbine or with the moving blades of the turbine's rotor. Unlike fatality finds, however, we were certain whether a turbine was operative or inoperative when we recorded nocturnal passages through the turbine's rotor plane in study 1.

Passage Rate Surveys at Study 1: Buena Vista and Golden Hills

Using a FLIR T620 thermal imaging camera with an 88.9-mm telephoto lens (FLIR Systems, Wilsonville, OR, USA), we performed 3 hours of nocturnal survey each night, 5 nights per week from 14 September through 14 November 2017. Nocturnal surveys began at dusk, and included ≥ 1 round of 5–10-minute scans per turbine per hour, covering 2–3 wind turbines per night at Golden Hills and 3–5 turbines per night at Buena Vista. During each timed scan we recorded when each turbine transitioned from operative to inoperative status and vice versa. 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 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 3).

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; mobbing, harassing, chasing, following or fleeing other volant animals; hovering ≤ 1 m

Table 2. Number of fatality searches, wind turbine-years, and MW-years per operational treatment contributing to before-after, control-impact (BACI) treatments in 3 experiments in study 2 at the Sand Hill Wind Energy Project, Alameda County, California, USA, 2012–2015, including during operable seasons (1 Apr–31 Oct 2012, 16 Feb–31 Oct 2013, 16 Feb–31 Oct 2014) and winter shutdowns (1 Nov 2012–15 Feb 2013, 1 Nov 2013–15 Feb 2014).

BACI	Before period	After period	Turbine searches		Wind turbine-years	
			Before	After	<i>n</i>	MW
1	Previous spring-fall operable	Subsequent spring-fall operable	5,115	5,707	117	7.045
1	Previous spring-fall operable	Subsequent spring-fall inoperable	246	215	5	0.225
2	Previous spring-fall inoperable	Subsequent spring-fall inoperable	1,024	861	23	1.503
2	Previous spring-fall inoperable	Subsequent spring-fall operable	328	394	8	0.439
3	Previous winter inoperable	Subsequent spring-fall inoperable	907	1,506	41	2.724
3	Previous winter inoperable	Subsequent spring-fall operable	3,806	9,216	173	10.453

Table 3. Nocturnal survey effort in study 1, using a 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, USA, fall 2017.

Survey effort	Golden Hills		Buena Vista		Both projects	
	Before	After	Before	After	Before	After
Survey hrs	11.25	34.14	15.58	23.36	26.83	57.50
Survey hrs at operative turbine	10.84	26.57	11.34	0.00	22.18	26.57
Survey hrs 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

from rotor sweeps or diving into airspace ahead of blade sweeps; or chasing, approaching, or following along blades. We classified some distracted flights also as disrupted flights, near misses, or collisions, and some disrupted flights were also near misses, but we did not classify any collisions as near misses or disrupted flights.

Dog Searches for Fatalities at Study 1: Buena Vista and Golden Hills

The morning after each nocturnal survey at Buena Vista and Golden Hills, we used scent-detection dogs to search for bat and bird fatalities 5 days a week, 15 September through 15 November 2017. Our dog team consisted of a trained handler, an orienteer-data collector, and 1 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 (Brown et al. 2016, Smallwood 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 we marked 88 bird carcasses by clipping flight feathers and 95 bat carcasses by removing 1 foot (Smallwood et al. 2018). Use of animal carcasses was authorized under permits from the United States Fish and Wildlife Service (MB135520-0) and the California Department of Fish and Wildlife (SC-00737). Placed 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 trial carcasses 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 turbine searches (14 turbines) at Golden Hills prior to the Buena Vista shutdown, and 41 turbine searches (31 turbines) afterwards.

Human Searches for Fatalities at Study 2: Sand Hill

Experienced fatality searchers walked parallel transects at 4–6-m intervals to a maximum search radius of 50 m,

averaging 5 days between searches from April 2012 through March 2015. 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 that we applied to typical body masses of species represented by found fatalities (Smallwood et al. 2018).

Upon each fatality search, fatality searchers recorded whether each turbine could operate. Searchers assumed a wind turbine was operable when it was intact and its rotor was free to spin, whereas they recorded it as inoperable during winter shutdown, if ≥ 1 blade was broken or missing, or if the rotor was tied down to prevent it from spinning. We also conferred with the wind company regarding wind turbine operability because turbines appearing intact could be rendered inoperable by an internally broken part or bad circuit. 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.

Analytical Methods

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 expressed fatality rate as fatalities/MW/search in study 1 at Golden Hills and Buena Vista because the experimental time periods were too brief for expressing the metric as fatalities/MW/year as we did in study 2 at Sand Hill.

To test for wind turbine shutdown effects on nocturnal passage rates and fatality rates of birds and bats in study 1, or for the effects of changes in turbine operability between time periods in study 2, we used 2-factor analysis of variance with interest only in the significance of the interaction effect between time period (BA) and treatment (CI) of each BACI experiment. Whereas main effects represent differences between time periods and between sites such as

terrain, wind turbine hub height, and wind turbine model, the interaction effect represents the effect of an action, which in our studies could have been the project-wide shutdown of wind turbines at Buena Vista or the resumption of operations of turbines following the winter shutdown at Sand Hill, as examples. A before-after change in passage rates or collision fatalities in 1 treatment group relative to the other composed the interaction effect so long as the only before-after change in treatment groups was wind turbine operability. In our studies, nothing about the wind turbines changed between before and after phases other than operability.

We note that inter-turbine contamination of fatalities was possible, in which a fatality is attributed to a wind turbine that did not cause the fatality. Also, because estimating time since death is prone to error (Smallwood et al. 2018), we might have assigned a small number of fatalities to the wrong treatment period even though we omitted fatalities whose estimated time since death introduced the possibility of such error. We assert that these errors, if they occurred, were slight and of little consequence to our results. Another source of error was the small sample of study units assigned to the impact treatments associated with consecutive operable seasons as before and after phases in study 2 at Sand Hill. Mitigating these small sample sizes, however, was the spatial interspersed of study units at Sand Hill and the large sample size associated with the winter shutdowns serving as the before phase.

RESULTS

Study 1: Buena Vista and Golden Hills BACI

Experiments

Hourly bat passes per vertical hectare of rotor plane were greater at Buena Vista than at Golden Hill across all experiments. Bat passes averaged 6 times higher at Buena Vista than at Golden Hills prior to the Buena Vista shutdown, and

nearly 2 times higher during the after phase at Buena Vista compared to the after phase at Golden Hills (Table 4).

The shutdown effect (BA × CI interaction) on bat passes per hour per vertical hectare of rotor plane was significant among wind turbines that were otherwise operative but not among wind turbines that had been inoperative at both Golden Hills and Buena Vista before and after the Buena Vista shutdown (Table 5; Fig. 1). Based on passage rates through otherwise operative turbine rotors, we counted zero bat passes/hour/ha instead of the expected 77 passes/hour/ha at Buena Vista after the shutdown (Fig. 1). Relying on our passage rate of near-miss collisions and rotor-disrupted flights, we counted zero instead of the expected 26 passes/hour/ha through shutdown Buena Vista turbine rotors. We found no significant wind turbine shutdown effect on bird passage rates (Table 5).

Bat fatalities found before and after the Buena Vista shutdown numbered 37 and 27 at Golden Hills, and 22 and 0 at Buena Vista, respectively. Mean bat fatalities/MW/search were nearly equal between projects before the Buena Vista shutdown, and they were nearly equal at Golden Hills before and after the Buena Vista shutdown, but the 0 bat fatalities/MW/search instead of the expected 0.39 bat fatalities/MW/search at Buena Vista after the shutdown revealed a significant BA × CI interaction effect (Table 5 [test 4]; Fig. 2).

Bird fatalities found before and after the Buena Vista shutdown numbered 16 and 17 at Golden Hills, and 8 and 5 at Buena Vista. Mean bird fatalities/MW/year, which consisted mostly of small birds, did not differ between projects or between before and after phases; the BA × CI interaction effect was not significant (Table 5 [test 4]; Fig. 2). The birds we found as fatalities at Buena Vista after the shutdown were 4 western meadowlarks (*Sturnella neglecta*) and 1 unidentified small bird (Table 6). After the Buena Vista shutdown, we continued to find western meadowlark and red-tailed hawk (*Buteo jamaicensis*) fatalities at Golden Hills, where we also found fatalities of

Table 4. Mean (and 95% CI) nocturnal passes/hour/ha of rotor plane in before-after, control-impact paired-site experimental design in study 1 at Golden Hills (GH) and Buena Vista (BV) Wind Energy Projects, Alameda and Contra Costa counties, California, USA, fall 2017.

Taxa	Passage type	Passes/hr/ha of rotor plane							
		GH before		GH after		BV before		BV after	
		\bar{x}	95% CI	\bar{x}	95% CI	\bar{x}	95% CI	\bar{x}	95% CI
Bats	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
	Operative rotor	9.4	1.6–17.2	18.5	7.3–29.7	68.0	28.7–107.2	0.0	
	Inoperative rotor	18.0	0.0–246.8	9.0	0.2–17.8	24.0	0.0–55.1	32.7	2.2–63.0
	Collided	0.0		0.8	0.0–1.8	0.5	0.0–1.5	0.0	
	Near miss or disrupted flight ^a	4.2	1.0–7.5	5.3	2.6–8.0	24.5	8.4–40.6	0.0	
	Near miss, disrupted flight, or distracted ^b	6.5	0.6–12.3	6.4	3.4–9.4	34.8	14.9–54.7	8.1	0.0–18.2
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
	Operative rotor	4.9	0.0–13.1	1.7	0.3–3.0	5.0	0.4–9.5	0.0	
	Inoperative rotor	0.0		2.5	0.0–7.8	4.2	0.0–13.5	1.9	0.0–5.3
	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	
	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

^a 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.

^b Distracting flights included interactions with volant animals such as prey; mobbing, harassing, chasing, following, or fleeing other volant animals; hovering ≤ 1 m from rotor sweeps; diving into airspace ahead of blade sweeps; or chasing, approaching, or following along blades.

Table 5. Before-after, control-impact (BACI) experiments, including a paired-site experiment in study 1 at the Golden Hills and Buena Vista Wind Energy Projects, California, USA, fall 2017 to test whether a project-wide shutdown of wind turbines at Buena Vista would reduce nocturnal passes/hour/ha of rotor plane (tests 1–3) and fatality rates (test 4) of bats and birds, and a multiple-site experiment in study 2 at Sand Hill over 2 years, 2012–2014, to test whether change in wind turbine operability from a previous period to a later period reduced or increased bird fatality rates (tests 5–7). We performed both experiments in Alameda and Contra Costa counties, California.

Test) metric	Treatment	Turbine status per period		BA × CI effect (<i>F</i>) ^a	
		Before	After	Bats	Birds
Study 1 (before = 15 Sep–1 Oct; after = 2 Oct–15 Nov; <i>F</i> _{1, 58})					
1a) Passes/hr/ha rotor plane	Control: Golden Hills	Operable	Operable		
	Impact: Buena Vista	Operable	Inoperable	3.52 ^f	0.72
1b) Passes/hr/ha rotor plane; near-miss or disrupted ^b	Control: Golden Hills	Operable	Operable		
	Impact: Buena Vista	Operable	Inoperable	14.57**	0.55
1c) Passes/hr/ha rotor plane; near-miss, disrupted or distracted ^c	Control: Golden Hills	Operable	Operable		
	Impact: Buena Vista	Operable	Inoperable	8.10*	0.68
2) Passes/hr/ha rotor plane	Control: Golden Hills	Operative	Operative		
	Impact: Buena Vista	Operative	Inoperative	24.19**	1.46
3) Passes/hr/ha rotor plane	Control: Golden Hills	Inoperative	Inoperative		
	Impact: Buena Vista	Inoperative	Inoperative	0.28	1.54
4) Fatalities/MW/search	Control: Golden Hills	Operable	Operable		
	Impact: Buena Vista	Operable	Inoperable	5.78*	0.70
Study 2 (Sand Hill; 2 yrs; before = previous spring-fall ^d ; after = subsequent spring-fall)					
5) Fatalities/MW/year (<i>F</i> _{1, 239})	Control	Operable	Operable		
	Impact	Operable	Inoperable		2.31
6) Fatalities/MW/year (<i>F</i> _{1, 59})	Control	Inoperable	Inoperable		
	Impact	Inoperable	Operable		1.02
7) Fatalities/MW/year ^d (<i>F</i> _{1, 451})	Control	Inoperable	Inoperable		
	Impact	Inoperable	Operable		0.69

^a *F* represents the *F*-ratio specific to the interaction term in 2-factor analysis of variance, where *t* denotes $0.10 > P > 0.05$, * denotes $P < 0.05$, and ** denotes $P < 0.001$.

^b 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.

^c Distracting flights included interactions with volant animals such as prey; mobbing, harassing, chasing, following, or fleeing other volant animals; hovering ≤1m from rotor sweeps; diving into airspace ahead of blade sweeps; or chasing, approaching, or following along blades.

^d For test 7: before = previous winter and after = subsequent spring-fall.

horned lark (*Eremophila alpestris*), northern rough-winged swallow (*Stelgidopteryx serripennis*), ruby-crowned kinglet (*Regulus calendula*), American pipit (*Anthus rubescens*), Lincoln's sparrow (*Melospiza lincolni*), and dark-eyed junco (*Junco hyemalis*). Fatality counts of individual species were too few for testing BACI effects at the species level.

Study 2: Sand Hill BACI Experiments

We could not compare bat fatality rates by wind turbine operability at Sand Hill because we recorded only a single bat fatality. In the BACI experiment in which the before phase consisted of wind turbines that were operable during the preceding operable season, bird fatalities/MW/year averaged 8.8 instead of the expected 54.1 among turbines that became inoperable the next year, but the associated BA × CI interaction effect was not significant (Table 5 [test 5]; Fig. 3). In the BACI experiment in which the before phase consisted of wind turbines that were inoperable during the preceding operable season, bird fatalities/MW/year averaged 37.7 instead of the expected zero among the turbines that became operational the next year, but the associated BA × CI interaction effect was not significant (Table 5 [test 6]; Fig. 3). In the BACI experiment in which the before phase consisted of wind turbines that were inoperable during the preceding winter shutdown, bird fatalities/MW/year averaged 31.3 instead of the expected 46.5 among the turbines that were

operable during the subsequent operable season, but the associated BA × CI interaction effect was not significant (Table 5 [test 7]; Fig. 3).

Although birds estimated to have died within 15 days of discovery averaged 43% more fatalities/MW/year at inoperable than they did at operable wind turbines, 95% confidence intervals largely overlapped (Table 7). Bird fatalities/MW/year at vacant towers averaged only 51% of those at operable wind turbines and 35% of those at inoperable wind turbines. Species represented by fatalities at vacant towers included American kestrel (*Falco sparverius*), rock pigeon (*Columba livia*), European starling (*Sturnus vulgaris*), and house finch (*Haemorrhous mexicanus*), all of which are hole or sheltered-ledge nesters that will use similar human-made structures for nesting or roosting. At empty pads, we found only 1 European starling fatality.

Seventy-nine percent of species represented by bird fatalities in study 1 were at inoperable wind turbines. All 6 red-tailed hawk fatalities were found at inoperable wind turbines. We found 1 of these red-tailed hawks directly under an inoperable wind turbine with its bill dislocated into its malar and cheek regions. Burrowing owls (*Athene cunicularia*), great horned owls (*Bubo virginianus*), mourning doves (*Zenaidura macroura*), western meadowlarks, and house finches died at inoperable turbines at about 2–3 times the rate as at operable turbines. Notable exceptions included American kestrels,

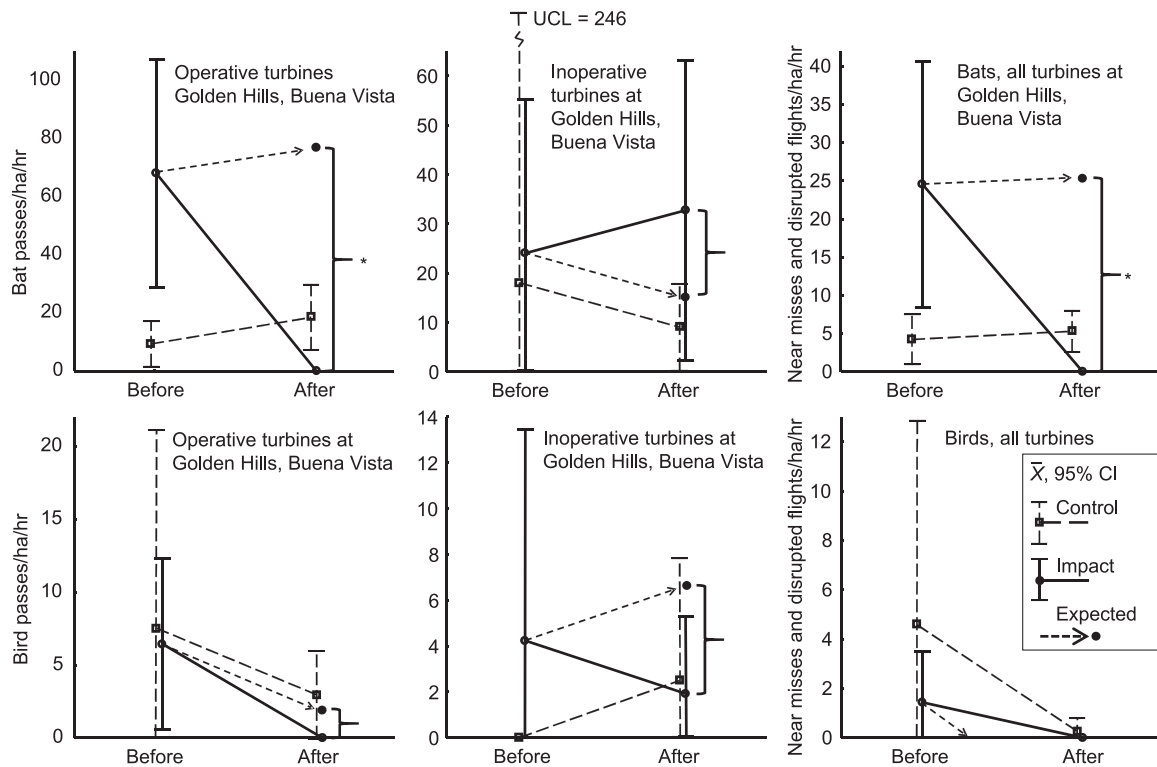


Figure 1. Before-after (BA) control-impact (CI) experiments of bat (top graphs) and bird (bottom graphs) passes/hour/ha of rotor plane and near misses and turbine-disrupted flights/hour/ha (right graphs) in study 1 at the Golden Hills and Buena Vista Wind Energy Projects before and after Buena Vista was shut down on 2 October 2017, Alameda and Contra Costa counties, California, USA. Left graphs indicate all turbines were operative during surveys before the shut down and only Buena Vista was inoperative after; middle graphs indicate all turbines were inoperative during surveys before and after the shutdown. Brackets denote the magnitude of the BA \times CI interaction effect and * denotes $P < 0.05$ in 2-factor analysis of variance.

which we found dead at operable turbines at more than twice the rate as at inoperable turbines, and northern flickers (*Colaptes auratus*) and 3 species of flycatcher, which we found dead only at operable wind turbines.

DISCUSSION

The Buena Vista shutdown in study 1 affected bat passage rates but not bird passage rates. After the shutdown, bats passed through Buena Vista's inoperative turbine rotors at

twice the rate other than expected, but this difference 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 no passages through shutdown turbine rotors instead of the expected 77/hour/ha of rotor plane. Comparing 47.3 (95% CI = 21–73.6) bat passages/hour/ha through operative turbines to 8.9 (95% CI = 3.3–14.5) passages/hour/ha

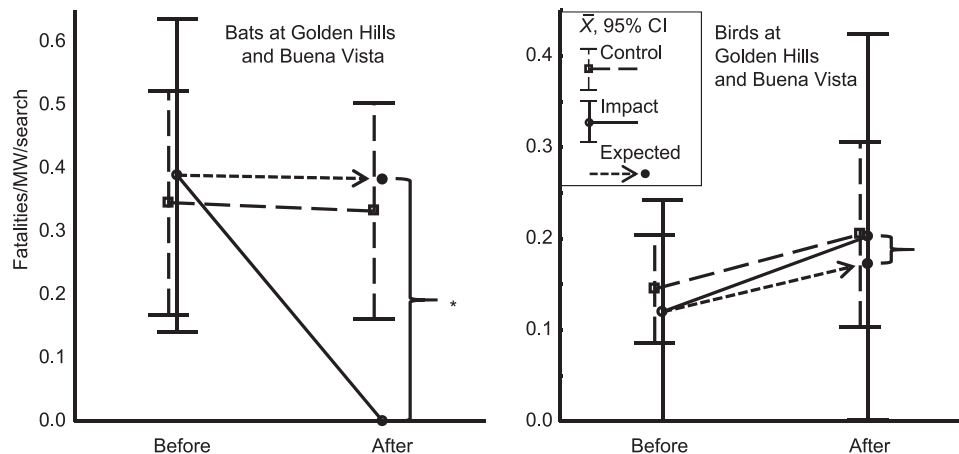


Figure 2. Before-after (BA) control-impact (CI) experiments of bat (left) and bird (right) fatalities/MW/search in study 1 at the Golden Hills and Buena Vista Wind Energy Projects before and after Buena Vista was shut down on 2 October 2017, Alameda and Contra Costa counties, California, USA, where brackets denote the magnitude of the BA \times CI interaction effect and * denotes $P < 0.05$ in 2-factor analysis of variance.

Table 6. Fatalities found by Conservation Canines' scent-detection dog teams in study 1 at Buena Vista and Golden Hills, California, USA, fall 2017, and fatalities/MW/search before and after the Buena Vista wind turbines were shut down on 2 October 2017.

Common name	Species name	Fatalities/MW/search			
		Golden Hills		Buena Vista	
		Before	After	Before	After
Western red bat	<i>Lasiurus blossevillii</i>	0.010	0.000	0.067	0.000
Myotis	<i>Myotis</i> spp.	0.010	0.000	0.000	0.000
Mexican free-tailed bat	<i>Tadarida brasiliensis</i>	0.155	0.115	0.106	0.000
Hoary bat	<i>Lasiurus cinereus</i>	0.059	0.077	0.039	0.000
Bat sp.		0.112	0.141	0.178	0.000
Mallard	<i>Anas platyrhynchos</i>	0.010	0.000	0.000	0.000
Red-tailed hawk	<i>Buteo jamaicensis</i>	0.016	0.008	0.000	0.000
American kestrel	<i>Falco sparverius</i>	0.007	0.000	0.033	0.000
Barn owl	<i>Tyto alba</i>	0.000	0.000	0.017	0.000
Burrowing owl	<i>Athene cucularia</i>	0.023	0.000	0.000	0.000
Pacific-slope flycatcher	<i>Empidonax difficilis</i>	0.000	0.000	0.013	0.000
Horned lark	<i>Eremophila alpestris</i>	0.010	0.013	0.000	0.000
Northern rough-winged swallow	<i>Stelgidopteryx serripennis</i>	0.000	0.026	0.000	0.000
Bewick's wren	<i>Thryomanes bewickii</i>	0.010	0.000	0.000	0.000
House wren	<i>Troglodytes aedon</i>	0.010	0.000	0.000	0.000
Ruby-crowned kinglet	<i>Regulus calendula</i>	0.000	0.026	0.000	0.000
American pipit	<i>Anthus rubescens</i>	0.000	0.013	0.000	0.000
Warbler	Parulidae	0.010	0.000	0.000	0.000
Townsend's warbler	<i>Setophaga townsendi</i>	0.000	0.000	0.013	0.000
Lincoln's sparrow	<i>Melospiza lincolni</i>	0.000	0.013	0.000	0.000
Dark-eyed junco	<i>Junco hyemalis</i>	0.000	0.013	0.000	0.000
Western meadowlark	<i>Sturnella neglecta</i>	0.000	0.026	0.030	0.155
Large bird		0.010	0.009	0.000	0.000
Small bird		0.040	0.060	0.013	0.048
All bats		0.346	0.332	0.389	0.000
All small birds		0.109	0.188	0.103	0.202
All large birds		0.036	0.017	0.017	0.000
All birds		0.145	0.205	0.120	0.202

through inoperative turbines between both projects before the Buena Vista shutdown suggests bats are twice as likely to pass through the rotor planes of operative versus inoperative turbines. Our finding that bats may be more strongly attracted to operating wind turbines tends to refute the roost attraction hypothesis during migration (Cryan and Barclay 2009) but could support hypotheses related to heat,

acoustic, or visual attraction (Long et al. 2009), insect attraction (Rydell et al. 2010), or the echolocation failure or electromagnetic disorientation hypotheses (Kunz et al. 2007). Most studies that attempt to test attraction hypotheses remain either inconclusive or non-exclusive (Barclay et al. 2017), and like other studies we cannot directly test any specific attraction hypothesis.

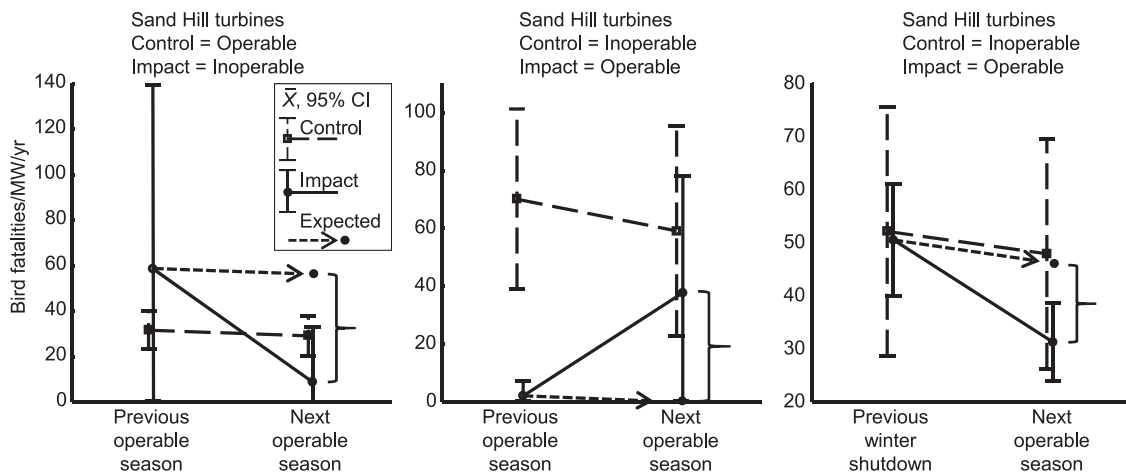


Figure 3. Before-after (BA) control-impact (CI) experiments of bird fatalities/MW/year in study 2 at Sand Hill Wind Energy Project, Alameda County, California, USA, in which the before phase consisted of operable wind turbines during the previous operable seasons and the impact consisted of inoperative turbines the next year (left graph), the before phase consisted of inoperative turbines during the previous operable season and the impact consisted of operable turbines the next year (middle graph), and the before phase consisted of inoperative turbines in the preceding winter shutdown and the impact consisted of operable turbines during the subsequent season (right graph). Brackets denote the magnitude of the BA × CI interaction effect and * denotes $P < 0.05$ in 2-factor analysis of variance.

Table 7. Estimates of fatalities/MW/year in study 2 among operable and inoperable wind turbines and vacant towers from April 2012 through March 2015 in the Sand Hill Energy Project, Alameda County, California, USA. 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. We adjusted fatality estimates for overall detection rates (Smallwood et al. 2018).

Common name	Species name	Estimated fatalities/MW/yr by wind turbine operational status					
		Operable ^a		Inoperable ^b		Vacant tower ^c	
		\bar{x}	95% CI	\bar{x}	95% CI	\bar{x}	95% CI
Mexican free-tailed bat	<i>Tadarida brasiliensis</i>	0.0		0.2	0.0–0.5	0.0	
Grebe	Podicipedidae	0.0		0.6	0.0–1.7	0.0	
American coot	<i>Fulica americana</i>	0.0		1.1	0.0–3.1	0.0	
Killdeer	<i>Charadrius vociferus</i>	0.4	0.0–1.1	0.6	0.0–1.6	0.0	
Spotted sandpiper	<i>Actitis macularis</i>	2.1	0.0–6.3	0.0		0.0	
Glaucous-winged gull	<i>Larus glaucescens</i>	0.3	0.0–1.0	0.0		0.0	
Herring gull	<i>Larus argentatus</i>	0.0		0.6	0.0–1.7	0.0	
Thayer's gull	<i>Larus thayeri</i>	0.0		0.2	0.0–0.6	0.0	
Gull	Laridae	0.6	0.0–1.4	0.9	0.0–2.1	0.0	
Ferruginous hawk	<i>Buteo regalis</i>	0.0		0.9	0.0–2.6	0.0	
Red-tailed hawk	<i>Buteo jamaicensis</i>	0.0		0.1	0.0–0.4	0.0	
American kestrel	<i>Falco sparverius</i>	3.4	0.0–7.0	1.4	0.0–3.8	5.1	0.0–15.2
Barn owl	<i>Tyto alba</i>	0.3	0.0–0.8	1.0	0.0–2.4	0.0	
Burrowing owl	<i>Athene cunicularia</i>	6.0	0.7–11.3	10.0	4.9–15.2	0.0	
Great horned owl	<i>Bubo virginianus</i>	0.3	0.0–0.8	0.8	0.0–1.8	0.0	
Mourning dove	<i>Zenaida macroura</i>	4.3	1.0–7.6	12.5	6.3–18.7	0.0	
Rock pigeon	<i>Columba livia</i>	50.6	37.0–64.1	48.1	35.1–61.0	14.2	0.0–32.6
Dove	Columbidae	0.3	0.0–2.9	1.6	0.0–4.2	0.0	
Common poorwill	<i>Phalanoptilus nuttallii</i>	0.0		1.0	0.0–2.9	0.0	
White-throated swift	<i>Aeronautes saxatalis</i>	0.0		1.1	0.0–3.3	0.0	
Northern flicker	<i>Colaptes auratus</i>	0.3	0.0–1.0	0.0		0.0	
Ash-throated flycatcher	<i>Myiarchus cinerascens</i>	1.0	0.0–3.0	0.0		0.0	
Pacific-slope flycatcher	<i>Empidonax difficilis</i>	1.6	0.0–4.8	0.0		0.0	
Say's phoebe	<i>Sayornis saya</i>	1.3	0.0–3.7	0.0		0.0	
Horned lark	<i>Eremophila alpestris</i>	0.0		1.0	0.0–3.0	0.0	
Common raven	<i>Corvus corax</i>	0.4	0.0–1.0	0.2	0.0–0.3	0.0	
American robin	<i>Turdus migratorius</i>	0.0		0.8	0.0–2.5	0.0	
European starling	<i>Sturnus vulgaris</i>	12.6	5.0–20.3	7.3	2.5–12.2	7.0	0.0–20.7
Yellow-rumped warbler	<i>Setophaga coronata</i>	0.0		3.3	0.0–7.8	0.0	
Lincoln's sparrow	<i>Melospiza lincolnii</i>	0.0		0.8	0.0–2.5	0.0	
Song sparrow	<i>Melospiza melodia</i>	0.0		0.2	0.0–0.6	0.0	
Sparrow	Emberizidae	0.0		8.7	0.0–25.7	0.0	
Red-winged blackbird	<i>Agelaius phoeniceus</i>	0.0		0.4	0.0–1.2	0.0	
Tricolored blackbird	<i>Aegolaius tricolor</i>	0.0		0.3	0.0–0.9	0.0	
Western meadowlark	<i>Sturnella neglecta</i>	3.3	0.0–6.6	6.5	2.0–10.9	0.0	
Blackbird	Icteridae	0.9	0.0–2.6	0.9	0.0–2.6	0.0	
House finch	<i>Haemorhous mexicanus</i>	0.6	0.0–1.8	1.9	0.0–4.7	22.6	0.0–66.7
Lesser goldfinch	<i>Spinus psaltria</i>	0.9	0.0–2.5	0.0		0.00	
Medium bird		1.9	0.0–4.5	1.7	0.0–3.7	0.00	
Small bird		2.6	0.0–6.6	21.4	10.1–32.6	0.00	
All birds		96.7	43.6–162.6	137.9	60.7–238.8	48.9	0.0–135.2

^a At operable turbines we performed 16,188 turbine-searches over 474 contiguous periods of operability averaging 170 days per period.

^b At inoperable turbines we performed 17,392 turbine-searches over 570 contiguous periods of operability averaging 146 days per period.

^c At vacant towers we performed 882 turbine-searches over 882 contiguous periods of operability averaging 494 days per period.

Our BACI experiment in study 1 at Buena Vista and Golden Hills suggests that shutting down wind turbines during bat migration curtails bat fatalities. Therefore, for bat species vulnerable to population-level effects caused by wind turbines, such as hoary bat (*Lasiurus cinereus*; Frick et al. 2017), a seasonal curtailment strategy might substantially improve population viability.

Wind turbine curtailment appeared ineffective at reducing fatalities of most bird species in both of our studies. And conversely, converting wind turbines from inoperable to operable did not significantly increase bird fatalities at Sand Hill. An annual winter shutdown, which was proposed as a

mitigation measure by the wind companies and endorsed by Smallwood (2008), and then implemented to varying degrees over the months of November–February at most of the APWRA's old-generation wind turbines during 2006–2014, was probably ineffective for reducing fatalities of many bird species. It remains unknown whether the winter shutdown reduced golden eagle (*Aquila chrysaetos*) fatalities, though historically fewer golden eagles have been found as fresh fatalities over the winter months (Nov–Feb) in the APWRA.

We found 1 golden eagle fatality at an operable turbine neighboring one of our selected study turbines, so we could



Figure 4. Blocked background artificial light viewed eastward at rotor-height through the Altamont Pass Wind Resource Area, California, USA, between (top) and during (bottom) the flashing of Federal Aviation Administration hazard lights, which flash red in true color.

not include it in our analyses. The golden eagle is a species for which the United States Fish and Wildlife Service recommends wind project developers obtain an eagle take permit and engage mitigation options (U.S. Fish and Wildlife Service 2013), and for which a detect-and-curtail strategy was under development (McClure et al. 2018). 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; thus, some form of turbine shutdown may serve a mitigation function. A few bird species, including American kestrel, are also more vulnerable to open interior spaces on towers or turbines, where they can become entrapped, covered in oil, or injured by heat or moving parts. An operational curtailment strategy might not reduce turbine-caused fatalities for all bird species.

Our study suggests that for many bird species, more of the collision risk might be in the above-ground structure of a wind turbine than in the turbine's moving blades, as suggested by collision risk modeling performed before our study began (R. H. Podolski, Ecology and Technology, personal communication). Furthermore, our results suggest that, for most bird species, vacant towers pose much lower collision risk than do inoperable turbines mounted on towers. The vacant towers in our Sand Hill study consisted of hollow tubes and sometimes empty nacelles within which cavity-nesting and cavity-roosting birds died from entrapment. We suspect that most of the risk of a mounted turbine is in the blades regardless of whether blades are moving. Although admittedly we are not birds, we have often found blades difficult to see because of 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. 4), or even the rising or setting of a lit moon. Also, a quarter of the turbines flash aviation hazard lights at night. Whether birds perceive these hazard cues remains unknown, but it could explain our lack of effect of turbine shutdown on birds.

Another implication of our findings relates to estimates of background mortality in wind projects. Surprisingly high background mortality was estimated over the winter months of 2014–2015 (ICF International 2015), but most of the fatality searches from which this estimate was based had 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.

MANAGEMENT IMPLICATIONS

Because the migration season is relatively brief and corresponds with reduced wind speeds, a seasonal curtailment strategy would greatly reduce bat fatalities without giving up a large proportion of a wind project's annual energy generation. The cost-effectiveness of such a migration-specific curtailment would improve if it could be narrowed to the first hour following dusk. Our findings also suggest that designing turbines without accessible interior spaces could reduce fatalities of cavity-nesting and cavity-roosting birds. Our findings suggest that fatality estimates based on proportion of time wind turbines operate, or those omitting the inoperable turbines from the fatality rate metric, 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 most birds because most birds are vulnerable to collision with stationary turbine parts and some are vulnerable to entrapment within interior spaces.

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