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Relating Bat Passage Rates to Wind Turbine Fatalities

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Received: 31 December 2019; Accepted: 20 February 2020; Published: 22 February 2020

Abstract: Wind energy siting to minimize impacts to bats would benefit from impact predictions following pre-construction surveys, but whether pre- or even post-construction activity patterns can predict fatalities remains unknown. We tested whether bat passage rates through rotor-swept airspace differ between groups of wind turbines where bat fatalities were found and not found during next-morning dog searches for fatalities. Passage rates differed significantly and averaged four times higher where freshly killed bats were found in next-morning fatality searches. Rates of near misses and risky flight behaviors also differed significantly between groups of turbines where bats were found and not found, and rate of near misses averaged eight times higher where bat fatalities were found in next-morning searches. Hours of turbine operation averaged significantly higher, winds averaged more westerly, and the moon averaged more visible among turbines where and when bat fatalities were found. Although dogs found only one of four bats seen colliding with turbine blades, they found many more bat fatalities than did human-only searchers at the same wind projects, and our fatality estimates were considerably higher. Our rates of observed bat collisions, adjusted for the rates of unseen collisions, would predict four to seven times the fresh fatalities we found using dogs between two wind projects. Despite markedly improved carcass detection through use of dogs, best estimates of bat fatalities might still be biased low due to crippling bias and search radius bias.

Keywords: bats; detection trials; fatality estimates; passage rates; thermal-imaging; wind turbines

1. Introduction

Based on wind turbine-caused bat fatalities reported over 12 years through 2011, 196,190 to 395,886 bat fatalities were predicted at US and Canadian wind projects in 2012 [1]. Based on another year of fatality monitoring reports and the installed wind energy capacity of 51,630 MW in 2012, syntheses of available fatality reports yielded estimates of 683,910 [2] to 888,036 (90% CI: 384,643–1,391,428) bat fatalities [3]. With the near doubling of installed wind energy capacity to 100,125 MW by September 2019 [4], and if annual bat fatalities are proportional to installed capacity and the number of bats vulnerable to collision undiminished, then extrapolating from a 2012 estimate [3] would predict >1.7 million bat fatalities in the USA in 2019 (95% CI: 746,207–2,699,370). If we restrict mean fatality rates to those estimated from fatality search intervals < 10 days, which increased bat fatality estimates over the overall mean fatality rate [5,6], then estimated annual fatalities in 2019 would have increased to 3,719,043 bats (95% CI: 1,770,510 to 5,667,676). Either of these 2019 fatality estimates number many more than the estimated nationwide mortality caused by white nose syndrome—a fungal disease estimated to have killed about 600,000 bats per year since 2007 [7]. As wind energy continues to expand, it is imperative that scientists learn whether pre-construction surveys can predict wind turbine impacts on bats [8]. It needs to be determined whether pre-construction activity levels or passage rates through planned rotor-swept airspace correlate with post-construction fatality rates. It also needs to be determined whether the methods we use are adequate for estimating and comparing bat activity levels and bat fatalities. Accurate fatality rate predictions are needed to decide whether particular wind project sites would cause unreasonable impacts, and to inform micro-siting decisions [5,9], operational curtailment strategies [10–13], or deterrent strategies [14] to minimize or reduce impacts.

Predicting bat fatality rates has not been successful, neither from pre-construction surveys nor post-construction surveys concurrent with fatality monitoring. Nor has perceived risk to bats prior to construction proven more than marginally predictive of post-construction fatality finds in Europe [15]. Measured across multiple wind projects in Canada and the USA, bat fatality rates did not correlate significantly with pre-construction activity levels measured by bat acoustic detectors [16]. Among 48 wind turbines in the Solano Wind Resource Area, California, fatality rates of bats measured from daily searches did not correlate significantly with the previous night's nocturnal activity measured by marine radar, acoustic bat detectors, and thermal-imaging goggles [17]. Activity rates and fatality rates measured more closely in time would more likely reveal a correlation, if one exists, than would pre-construction activity levels compared to post-construction fatalities. Nevertheless, substantial biases and potentially large sources of error loom large when relating fatality rates to activity rates.

Pre-construction activity levels and passage rates can be measured using radar, acoustic detectors, or thermal imaging cameras, but no matter how they were derived, pre-construction activity rates carry error and potential biases. For pre-construction activity to be predictive, the error and bias in the predictor variable must not obscure the predictor variable's relationship with variation in post-construction fatality rates, which carry their own error and biases [3,18–21]. Furthermore, activity patterns measured before construction must persist after construction to be predictive. Inter-annual variation in activity patterns could impinge on prediction accuracy, and so could any attraction effects of bats to wind turbines.

Activity rates can be biased by placement of acoustic detectors due to limited range caused by sound attenuation [22], by variation in activities by height above ground among bat species [23,24], and by reduced echolocation output under certain circumstances [25,26]. Ground-mounted detectors will miss bats flying at rotor height and nacelle-mounted detectors will miss bats flying through the outer two-thirds of a modern turbine's rotor-swept airspace (or pre-construction equivalent) [22]. Detector range also varies by model, atmospheric conditions, and inter-specific variation in call frequencies [22]. Performance of thermal-imaging cameras can also vary by model and atmospheric conditions, and by distance between subject and camera. For both radar and thermal imaging, identifying targets to bats, birds, and insects requires accurate assumptions about size, flight speed and behavior.

As noted earlier, fatality estimates are also prone to biases and large sources of error. Whether fatality searchers consisted of humans or dogs can determine whether entire species of bats were represented in fatality estimates, because human detection of bat carcasses is usually very low. Fatality estimates can be further biased by whether carcass persistence was measured as proportion of carcasses remaining or mean days to carcass removal [21], and by mean search interval [19], maximum search radius [3], and monitoring duration [27]. Detecting more of the available fatalities can increase estimation accuracy [19,21] and precision [28]. Both the error and bias in adjustments for the proportion of fatalities not found can be reduced by integrating carcass detection trials into fatality monitoring rather than performing searcher detection and carcass persistence trials separately [21]. For fatality estimation of bats, crippling bias, representing the proportion of mortally injured bats that leave the fatality search area under their own volition [18], remains unquantified and potentially a large source of error and bias.

To accurately predict fatality rates from pre-construction activity of bats, the investigator would need accurate estimates of both fatalities and pre-construction activity, as well as either a persistent or a predictive relationship between pre- and post-construction activity patterns of bats. To determine whether any chance exists for accurately predicting bat fatalities from pre-construction activity patterns, we first determined whether we could detect a relationship between bat activity and fatality finds among operational wind turbines. To do this, we maximized our detection of fatalities by using scent-detection dogs [29–31] and linked those fatalities to activity patterns observed only the night before each fatality search. We also worked harder at detecting fatalities before vertebrate scavengers had time to find and remove them [31,32]. We maximized our observations of bat activity by using a thermal imaging camera to view all parts of the rotor-swept plane, including its outer edge where nacelle-mounted acoustic detectors would fail to detect bat passages [33]. We also performed these surveys during the bat migration through the Altamont Pass Wind Resource Area (APWRA), California, and during the first three hours of each night when bat activity is highest [17,34].

Our study was founded on considerable experience with thermal imaging surveys in the APWRA since 2012. Thermal imaging enables the observer to see heat distribution across the body, wing flaps, and even among dangling legs of some insects. The distribution of heat, along with body size and movement patterns such as speed, wing flaps, and turning angles, help identify subjects as bats, birds or insects. Wind turbines serve as frames of reference that facilitate estimation of a subject's body size and distance from wind turbine. Thermal imaging can reveal behavior patterns that can be inferred as reactions to wind turbines, to prey, and to other bats or birds. Certain behaviors observable through thermal imaging might be more predictive of collision fatalities than simple passage rates, such as hovering near operative rotors, interacting with other bats or birds, chasing blades, repeatedly diving through the rotor plane, passing through the rotor plane parallel rather than perpendicular to the rotor plane, or approaching portions of the rotor emitting more heat [8,35,36]. Whereas these types of behaviors are only observable post-construction, their topographic and environmental contexts might help interpret pre-construction survey results.

Our study was motivated by repowering of the APWRA, where bat fatalities were rarely discovered over decades of fatality monitoring until modern wind turbines began replacing the old-generation turbines. The question arose whether macro- and micro-siting of wind turbines might help minimize impacts on bats in the APWRA. Micro-siting reduced raptor fatalities at a repowered wind project [37] and could minimize impacts at proposed new wind projects [9]. However, as noted earlier, micro-siting for bats would require flight behavior data more closely tied to fatality finds than was necessary for raptors because bat carcasses are more quickly removed by scavengers than are raptor carcasses. As a first step toward macro- and micro-siting, fatality finds need to be compared to bat passage rates recorded over overlapping time periods to determine if a relationship exists.

We focused on whether post-construction fatality rates of bats can be estimated with sufficient accuracy to discover meaningful relationships with bat passage rates through wind turbine rotors. Our primary objective was to relate fatality finds to patterns of bat activity at wind turbines during the night preceding fatality searches. We aimed to more closely compare wind turbine fatalities to rates of passage, distracting behaviors, and near misses with the rotor blades observed the night before each fatality search. To meet our objective, we followed each night's observations at specific wind turbines with next-morning fatality searches using scent-detection dogs. Our second objective was to estimate fatalities from our observed collision rate among the nocturnally sampled wind turbines and time periods, and to compare this estimate with an estimate based on fatality searches.

2. Materials and Methods

2.1. Study Area

Our study comprised 2 wind projects 8 km apart in the Altamont Pass Wind Resource Area (APWRA), California. 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 of which were accessible to us on privately held land in Alameda County. Two Mitsubishi turbines were on 45 m towers, 27 on 55 m towers, and 2 on 65 m towers. All GE turbines were on 80 m towers. Both projects were on steeply rolling hills covered by cattle-grazed annual grasses. Elevations ranged 41–280 m at Buena Vista and 115–477 m at Golden Hills.

2.2. Field Methods

To achieve our goal of comparing bat passage rates to fatalities, we sought to maximize our variation in observed bat activity and fatality finds by conducting fieldwork before, during, and after the seasonal peak of bat activity and previously documented fatalities in the APWRA. Bat activity peaks during the last week of September and first week of October, which also happens to generally coincide with a peak in nocturnal flights of small birds through the APWRA [33]. Using a FLIR T620 thermal imaging camera with 307,200 (640 × 480) pixel resolution and a frame rate of 30 Hz, and fitted with an 88.8 mm telephoto lens (FLIR Systems, Inc., Wilsonville, OR, USA), we surveyed for bats and small birds from 4 September through 15 November 2017, 5 days per week (Table 1). We mounted the camera on a tripod, which we weighted with a 2.3 kg sandbag to stabilize against wind.

Table 1. Nocturnal survey dates and start times (Pacific Standard Time) and the number and operational status of wind turbines surveyed.

Station	Date	Start Time	Turbines Surveyed	Status on Survey Date		Next-Morning Fatality Searcher
				Golden Hills	Buena Vista	
12	9/4/2017	19:51	4	Operable		Human
3	9/5/2017	19:53	5		Operable	Human
89	9/7/2017	19:55	3	Operable		Human
91	9/8/2017	19:52	5		Operable	Human
85	9/10/2017	19:54	2	Operable		Human
93	9/12/2017	19:52	5		Operable	Human
92	9/14/2017	19:48	5		Operable	Dog
66	9/15/2017	20:02	2	Operable		Dog
95	9/17/2017	19:45	3		Operable	Dog
61	9/18/2017	19:38	3	Operable		Dog
97	9/19/2017	19:48	2	Operable		Dog
64	9/21/2017	19:37	3	Operable		Dog
96	9/22/2017	19:29	4		Operable	Dog
3	9/24/2017	19:29	5		Operable	Dog
86	9/25/2017	19:21	4	Operable		Dog
91	9/26/2017	19:20	4		Operable	Dog
94	9/28/2017	19:22	3		Operable	Dog
89	9/29/2017	19:23	2	Operable		Dog
93	10/1/2017	19:15	4		Operable	Dog
90	10/2/2017	19:14	2	Operable		Dog
71	10/3/2017	19:14	4		Inoperable	Dog
12	10/5/2017	19:07	2	Operable		Dog
95	10/6/2017	19:04	3		Inoperable	Dog
85	10/8/2017	19:03	4	Operable		Dog
92	10/9/2017	19:02	4		Inoperable	Dog
66	10/10/2017	19:03	2	Operable		Dog
61	10/12/2017	18:54	2	Operable		Dog
96	10/13/2017	18:57	3		Inoperable	Dog
97	10/15/2017	18:52	3	Operable		Dog
94	10/16/2017	18:51	3		Inoperable	Dog
64	10/17/2017	18:55	2	Operable		Dog
92	10/19/2017	19:02	4		Inoperable	Dog
86	10/20/2017	18:46	2	Operable		Dog
63	10/22/2017	18:55	2	Operable		Dog
3	10/23/2017	18:50	4		Inoperable	Dog
90	10/24/2017	18:42	2	Operable		Dog
93	10/26/2017	18:40	4		Inoperable	Dog
12	10/27/2017	18:48	2	Operable		Dog
89	10/29/2017	18:45	2	Operable		Dog

Table 1. *Cont.*

Station	Date	Start Time	Turbines Surveyed	Status on Survey Date		Next-Morning Fatality Searcher
				Golden Hills	Buena Vista	
91	10/30/2017	18:48	5		Inoperable	Dog
85	10/31/2017	18:40	3	Operable		Dog
95	11/2/2017	18:37	3		Inoperable	Dog
98	11/3/2017	18:30	2	Operable		Dog
88	11/5/2017	18:40	3	Operable		Dog
92	11/6/2017	18:43	4		Inoperable	Dog
70	11/7/2017	18:33	3	Operable		Dog
68	11/9/2017	18:36	2	Operable		Dog
96	11/10/2017	18:35	4		Inoperable	Dog
94	11/12/2017	18:35	3		Inoperable	Dog
69	11/13/2017	18:24	2	Operable		Dog
61	11/14/2017	18:35	3	Operable		Dog

Each night's nocturnal survey lasted 3 h and comprised a series of timed scans that we rotated among 2 to 5 wind turbines (Figure 1). We typically scanned 3 to 5 wind turbines per night at Buena Vista where 1 MW wind turbines were arranged closer together, and we scanned 2 to 4 wind turbines per night at Golden Hills where 1.79 MW wind turbines were farther apart and required larger fatality search areas. The number of turbines surveyed varied by condition of our dog team, which had to search for fatalities around every surveyed turbine the following morning. Each night, we sent a cell phone text message to the dog handlers to inform them of which turbines to search in the morning. To decide how many turbines to survey each night, we conferred with the dog handlers daily to assess the physical condition of both dogs and handlers.

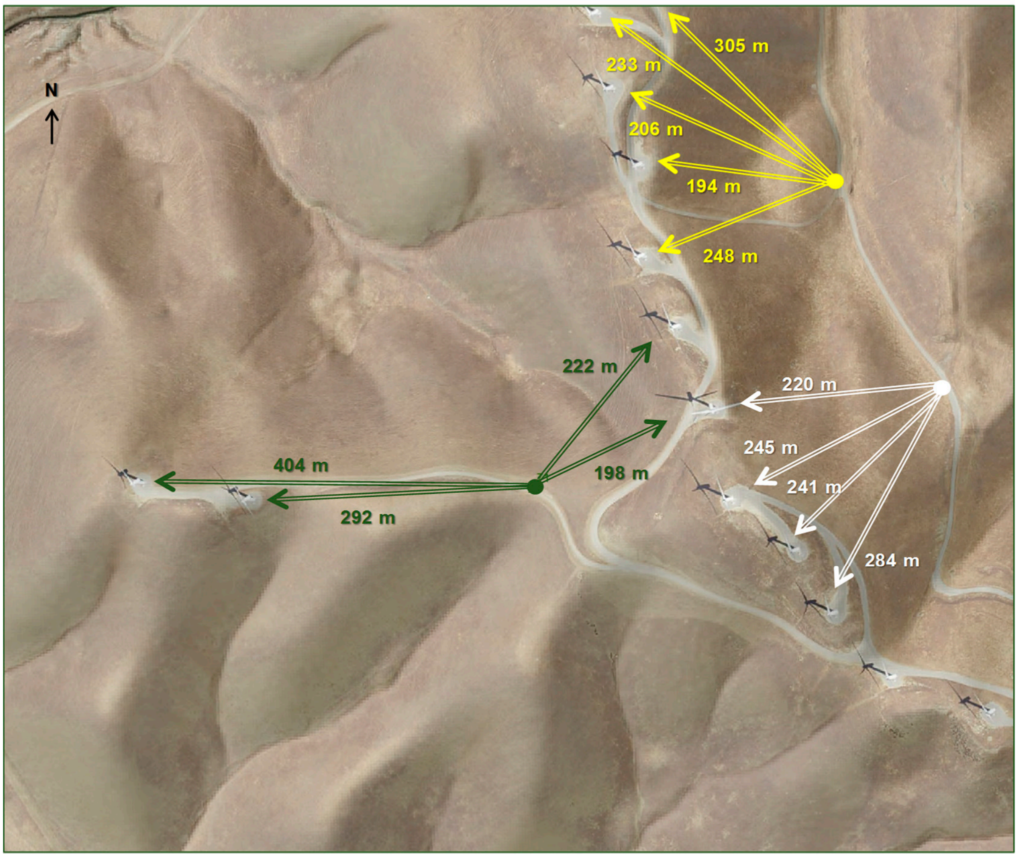

Figure 1. Buena Vista wind turbines viewed (arrows) from 3 survey stations (yellow, white and green circles) during nocturnal surveys in Fall 2017.

Terrain also influenced the number of wind turbines surveyed on a given night. We surveyed fewer turbines where terrain was more difficult to search by our dog team. Another factor was our targeted range of distances between the survey station and wind turbines. We positioned our survey stations at a mean distance of 297 m (SD = 90 m, range 132 m to 569 m) from wind turbines, a distance that Smallwood determined from earlier surveys was far enough away to efficiently view a modern wind turbine's rotor plane and to pan the camera to track flying bats within or near the rotor plane, but close enough to readily detect heat signatures of bats, small birds, and insects. At these distances, however, only a portion of a wind turbine's rotor-swept plane could be seen within the frame of the camera. To equitably view the entirety of the rotor plane during each passage-rate scan, we slowly swiveled the camera from top to bottom and side to side of the rotor plane (Figure 2). Distances between the observation station and wind turbines were also determined by where views of wind turbine rotor planes were unobscured by terrain.

Figure 2. Example thermal-imaging camera frame views (white squares) from nocturnal survey station as views shifted while slowly swiveling camera mounted on tripod. During actual surveys, the sky was completely dark.

We performed nocturnal thermal imaging surveys between dusk (see Table 1 for actual start times) and 3 h after dusk, which is the time period corresponding with most bat activity [17,34]. At the start of each survey, and at the end of hours 1, 2, and 3, we recorded each wind turbine's operational status, percent visibility of the moon, and we used a Kestrel wind meter to record air temperature (C), wind direction (°), and wind speed (m/s).

Each night's survey included at least 1 rotation of 5 to 10 min passage-rate scans per turbine per hour. During timed passage rate surveys, we recorded observations into a digital audio recorder for later transcription to an electronic spreadsheet. We recorded an estimate of the proportion of the rotor-swept plane that we could see within the frame of the camera at any given time; we later converted these proportions to vertical ha of visible rotor plane. We recorded time into the survey when subjects were first and last seen, size and number of subjects, origins and directions of flights, encounters with each other or with the wind turbine (Figure 3), and near misses (Figure 4) and flight disruptions caused by the turbulence of blade-sweeps or rotor wakes. We also video-recorded each timed passage rate survey to later verify observations, assess degree of confidence in observed collisions, and to capture any missed bat passages upon later viewing of the video. At intervals between timed passage rate surveys, we surveyed for individual bats and birds, which upon detection were tracked by panning the thermal camera to keep pace with the bat or bird to determine whether it targeted one or more wind turbines.

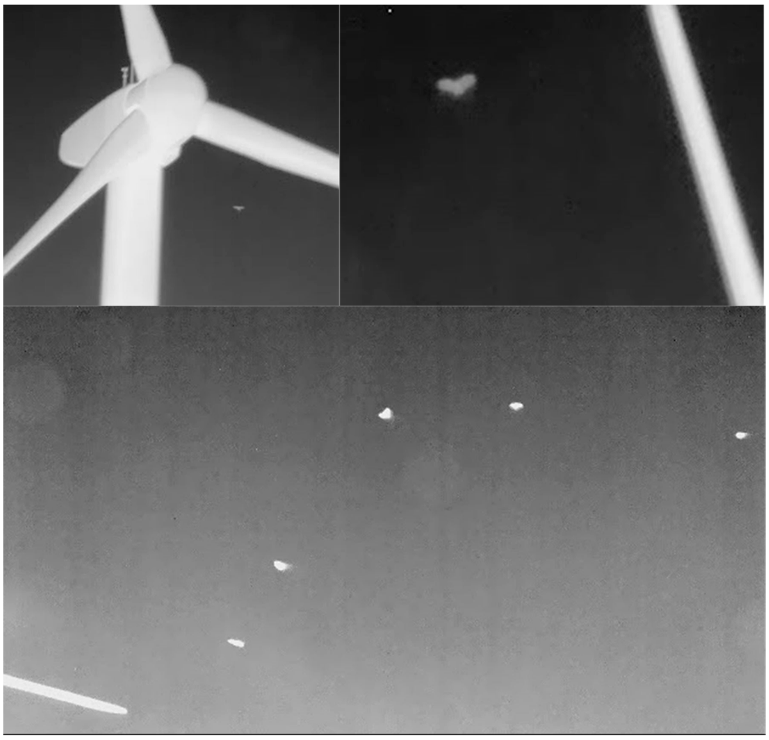

Figure 3. Bats observed near wind turbines, all of which we assumed were hoary bats based on size, behavior, and frequent discovery of hoary bat fatalities at Buena Vista and Golden Hills Wind Energy projects in California. The lower photo shows 5 hoary bats approaching a 1 MW Mitsubishi wind turbine.

Working with dogs, we searched for fatalities at the same turbines the following morning after each nocturnal thermal imaging survey. Skilled dog handler Collette Yee and handler-in-training Skye Standish searched for fatalities using one of two scent-detection dogs at a time (Figure 5). The dogs—Captain and Jack—were trained by Conservation Canines with the Center of Conservation Biology, University of Washington. The dogs were tested on 95 bat carcasses that we placed in 132 detection trials during this study (some bats were redeployed in second trials). Our dogs achieved a detection rate of 95% [31].

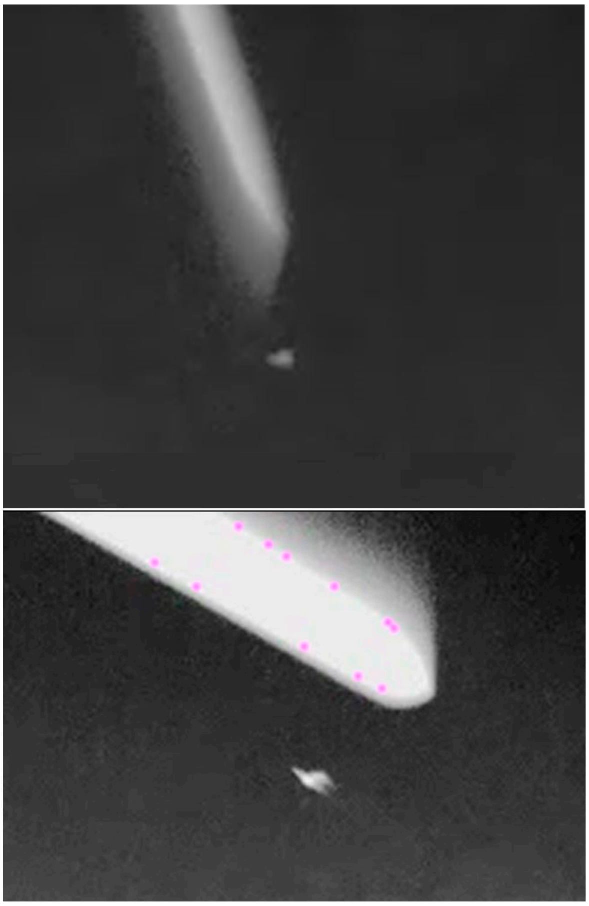

Figure 4. Examples of near misses of bats and moving wind turbine blades.

Figure 5. Jack leads handler Collette Yee and data collector/orienteer Skye Standish in a fatality search at Buena Vista Wind Energy project, California.

We searched mornings when conditions were optimal for scent detection. Each dog was given turns searching, then rested as the other dog took a turn. Search areas extended to 75 m from the 1 MW wind turbines at the Buena Vista Wind Energy project and to 105 m from the 1.79 MW wind turbines at the Golden Hills Wind Energy project. Daily searches covered 3 to 5 turbines at Buena Vista and 2 to 4 turbines at Golden Hills. Dogs were guided by leash along transects oriented perpendicular to the wind and separated by 10 m over most of the search area. Because few bat fatalities are found upwind of wind turbines [33,37], we allowed dogs off leash for a more cursory search within a 90° arc between 210° and 300° from the turbine, which corresponds to prevailing upwind directions in the APWRA. Within the intensive search areas, we navigated transects using GPS and a Locus Map application on a cell phone along with visible flagging as needed. We tracked dogs using a Keychain Finder Transystem 860e GPS data logger. Standish mapped and photographed fatality finds using a Trimble GeoExplorer 6000 GPS and identified carcasses to species.

We performed 151 fatality searches at 63 wind turbines from 4 September through 15 November 2017. A human searcher performed the first 20 searches through 13 September, and dogs guided by 2 handlers performed the last 131 searches thereafter (Table 1). Our dogs performed 83 searches at operable wind turbines, totaling 55 at Golden Hills and 28 at Buena Vista before it underwent a project-wide maintenance shutdown from 06:00 hours, 2 October, through the end of our study.

We related whether bat fatalities were found to the previous night's passages through the rotor plane of wind turbines, having also noted the wind turbine's operational status at the time of each passage. We defined passage as either a flight through the rotor plane or within 1 m of the rotor plane while flying parallel to the rotor axis, and we defined passage rate as the number of passages per hour per ha of rotor plane that was visible within the frame of the camera. Additionally, we related whether bat fatalities were found to passage rates that included near collisions with a blade, referred to as "near misses," or were displaced or jostled by a blade sweep, referred to as "disrupted flights," or additionally exhibited dangerous or "risky" behaviors such as chasing blades, investigating blades, interacting with other volant animals, fleeing, chasing or foraging for prey items, or other distracted behaviors. We also related whether bat fatalities were found due to observed collisions, in which bats came into contact with a turbine, were seen to have become dismembered, or observed to have fallen without flight control all the way to the ground.

We used Pearson's correlation test to relate bat fatality counts/ha to the previous night's passage rates through rotor-swept airspace. We used independent samples t-tests to test whether means of measured variables differed significantly between groups of wind turbines where bat fatalities were found and not found between 15 September and 26 October, which was a period that more closely covered the fall bat migration [37]. Measured variables included the various types of passage rates defined earlier, as well as number of hours each wind turbine operated during the survey, ambient air temperature, wind direction, and percent of the moon that was visible. We measured wind speed, but we decided hours of operability better reflected wind speed than did our measurements made at survey-station ground level. We also note that visibility of the moon was affected by both the lunar cycle and cloud cover—overcast sky reduced moon visibility to 0%.

Because passage rates and environmental variables were measured for a specific night whereas fatalities could have occurred on any night since the previous fatality search, we performed t-tests of bat fatalities estimated to have died within 3 days, 7 days, and 30 days. Based on our experience with monitoring 134 bat carcasses in detection trials in an earlier study [37], in which we compared searcher estimates of time since death against our known time since thawing of fresh-frozen bat carcasses at time of placement, we felt these ranges minimized the effects of error on estimates of time since death. A bat that died within 3 days is unlikely to be mistaken for a bat that has been dead longer than a week. These separate tests allowed us to assess whether a previous night's passage rates could predict fatalities that occurred within the preceding several nights, preceding week, or preceding month.

2.3. Fatality Estimation

We estimated fatalities from our study for two purposes—the first to estimate annual fatalities from our limited monitoring period, and the second to estimate the number of fresh carcasses our dogs should have found based on observed collision rates. Both of our estimation approaches were intended to further explore bat fatality estimates at wind projects, and neither was expected to be as accurate as yearlong monitoring of all available wind turbines. We compared our estimates to those made at Golden Hills [38], which was monitored concurrently with our study, and Buena Vista in 2008–2011 [39]. At Golden Hills, humans searched 32 wind turbines monthly, and these were the same turbines made available for our concurrent dog searches. The human searchers and our dog searchers searched at nearly equal intervals and over the same plots. A separate dog team [38] searched 16 randomly selected turbines weekly, but their dogs were unleashed and our dogs never searched the same turbines as theirs. At Buena Vista, humans searched the same plots we searched 6–8 years later, and at the same search interval.

We estimated bat fatalities/MW from found carcasses, $\hat{F}_c$, using a derivation of the Smallwood estimator [3]:

$$\hat{F}_c = \frac{F_c}{R_C \times S \times d \times P}, \tag{1}$$

where F_c was number of fatalities found per MW (megawatts) of rated wind energy capacity, R_C was mean daily proportion of trial carcasses persisting at a time interval corresponding with the average search interval in days, S was searcher detection or proportion of trial carcasses detected upon the next search following carcass placement, d was proportion of fatalities detected within the maximum search radius, and P was the proportion of annual fatalities found by the Golden Hills fatality monitor's [38] scent-detection dogs during the time period matching our dog team searches.

The Golden Hills monitor's dogs searched for fatalities at weekly intervals throughout the year at 16 randomly selected Golden Hills turbines. The monitor's scent-detection dogs at Golden Hills found 47.5% of their annual total bat fatalities between the dates of 15 September and 15 November, which covered the time period when our dog team also searched for fatalities at Golden Hills. The Golden Hills monitor's dogs also found 33% of their total annual bat fatalities between the dates of 18 September and 2 October, which covered the time period when our dogs searched for fatalities at Buena Vista. Therefore, P = 0.475 at Golden Hills and P = 0.33 at Buena Vista. Except for P, which we treated as a constant, we carried error through the fatality adjustments using the Delta Method to estimate $SE(\hat{F}_c)$, which we multiplied against the appropriate t-value from a t-distribution to estimate 95% CI.

Based on observed collisions, and only those we were certain of bats falling to the ground, we estimated bat fatalities/MW, $\hat{F}_o$, using the following estimator:

$$\hat{F}_o = \frac{F_o}{\left(\frac{w}{W}\right)}, \tag{2}$$

where F_o was number of observed collisions during nocturnal surveys, w was cumulative rotor-swept area expressed as a rotor's ha-hours (ha rotor plane viewed within the lens frame of the thermal-imaging camera × hours of thermal-imaging scan), and W was cumulative rotor-swept area (ha-hours) among the project's operable wind turbines during the study.

Ha were measured as m^2 of rotor-swept plane ÷ 10,000 m^2. We constrained measurement of W to the first 3 h per night, the period that we surveyed to observe the highest nightly bat activity [17,34], which we assumed was when most bat collisions occurred. At Golden Hills and Buena Vista, respectively, W was 3359.5 and 337.4 ha-hours, w totaled 11.29 and 1.85 ha-hours, and $\frac{w}{W}$ was 0.00336 and 0.0055. We measured SE ($\hat{F}_o$) from nightly variation in F (SE = 0.10 at Buena Vista and 0.06 at Golden Hills).

3. Results

Nightly counts of bats peaked with the waxing moon, rising temperatures, diminishing wind speeds, and a shift in winds to more westerly origin (Figure 6). Counts also peaked with small birds migrating through our study areas (Figure 6). Using dogs in next-morning searches of wind turbines, we found 24 bat fatalities at Buena Vista and 71 at Golden Hills that we estimated to have died during our study period, and another nine bats that we estimated had died prior to our study. We estimated 6 bats (6%) died within 3 days prior to discovery, 14 bats (15%) died between 3 and 7 days prior, 59 bats (63%) died between 7 and 30 days prior, and 25 bats (24%) died > 30 days prior but still within our study period. We found 38 Mexican free-tailed bats (*Tadarida brasiliensis*), 16 hoary bats (*Lasiurus cinereus*), 5 western red bats (*Lasiurus blossevillii*), 1 myotine bat (*Myotis* sp.), and 44 bats unidentified to species.

3.1. Daily Comparison of Passage Rates and Fatality Finds

Relating thermal imaging surveys to next-day fatality searches, nightly bat passes through operable wind turbine rotors correlated significantly with next-day counts of fatalities/ha of bats ≤ 3 days since death ($r = 0.44$, $P < 0.05$) and of bats ≤ 7 days since death ($r = 0.35$, $P < 0.05$), but we found no correlation for bats > 7 days since death.

Bat passage rates averaged four times higher where fatalities were found and differed significantly between groups of wind turbines where bats ≤ 3 days since death were found or not found during the next morning's fatality search (Table 2). The difference was not significant for bats ≤ 7 days since death, but it was significant for bats ≤ 30 days since death.

Table 2. Independent sample t-tests to determine whether means of measured variables differed between fatality searches at which bat fatalities were found and not found by scent-detection dogs, and where bats found were estimated to have died within 3 days, 7 days, or 30 days ago, inclusive.

Days Since Death	Variable Measured the Night before Search	Fatalities Not Found		Fatalities Found		t-Test (DF = 1,65)	
		$\bar{x}$	95% CI	$\bar{x}$	95% CI	t	*P*
≤3	Passages/hr/ha of rotor	22.3	9–37	88.2	0–240	−2.304	0.024
≤3	Near misses/hr/ha [a]	8.2	1–15	64.7	0–175	−3.574	0.001
≤3	Risky behavior/hr/ha [b]	20.0	8–32	72.9	0–202	−2.102	0.039
≤3	Operative time (h)	0.27	0.19–0.35	0.59	0.33–0.85	−2.084	0.041
≤3	Temperature (C)	19.1	18.1–20.1	19.2	13.9–24.5	−0.065	0.948
≤3	Wind direction (°)	215	208–223	265	177–352	−3.201	0.002
≤3	Visible moon (%)	15	10–20	53	12–94	−3.514	0.001
≤7	Passages/hr/ha of rotor	23.3	9–37	48.1	0–112	−1.152	0.253
≤7	Near misses/hr/ha [a]	8.7	1–16	32.7	0–80	−1.952	0.055
≤7	Risky behavior/hr/ha [b]	21.3	9–34	36.8	0–92	−0.818	0.416
≤7	Operative time (h)	0.24	0.17–0.32	0.59	0.34–0.84	−3.126	0.003
≤7	Temperature (C)	19.1	18.1–20.2	18.6	15.7–21.5	0.366	0.716
≤7	Wind direction (°)	215	208–223	240	202–278	−2.115	0.038
≤7	Visible moon (%)	15	10–21	33	6–60	−2.156	0.035
≤30	Passages/hr/ha of rotor	18.8	6–32	52.1	6–98	−2.029	0.047
≤30	Near misses/hr/ha [a]	8.2	0–16	23.1	0–47	−1.536	0.129
≤30	Risky behavior/hr/ha [b]	21.3	7–35	29.6	2–57	−0.558	0.578
≤30	Operative time (h)	0.22	0.14–0.30	0.52	0.36–0.68	−3.594	0.001
≤30	Temperature (C)	19.4	18.4–20.5	17.8	16.0–19.6	1.492	0.141
≤30	Wind direction (°)	213	205–220	238	216–260	−2.820	0.006
≤30	Visible moon (%)	14	9–20	27	10–44	−2.008	0.049

[a] Near misses included flights disrupted by rotor wake turbulence or pressure waves of passing blades. [b] Risky behaviors included chasing blades, investigating blades, interacting with other volant animals, fleeing, chasing or foraging for prey items, or other distracted behaviors.

Rates of near misses and disrupted flights averaged eight times higher where fatalities were found, and differed significantly between groups of wind turbines where bats ≤ 3 days since death were found or not found during the next morning's fatality search (Table 2). Differences were not significant for bats > 3 days since death.

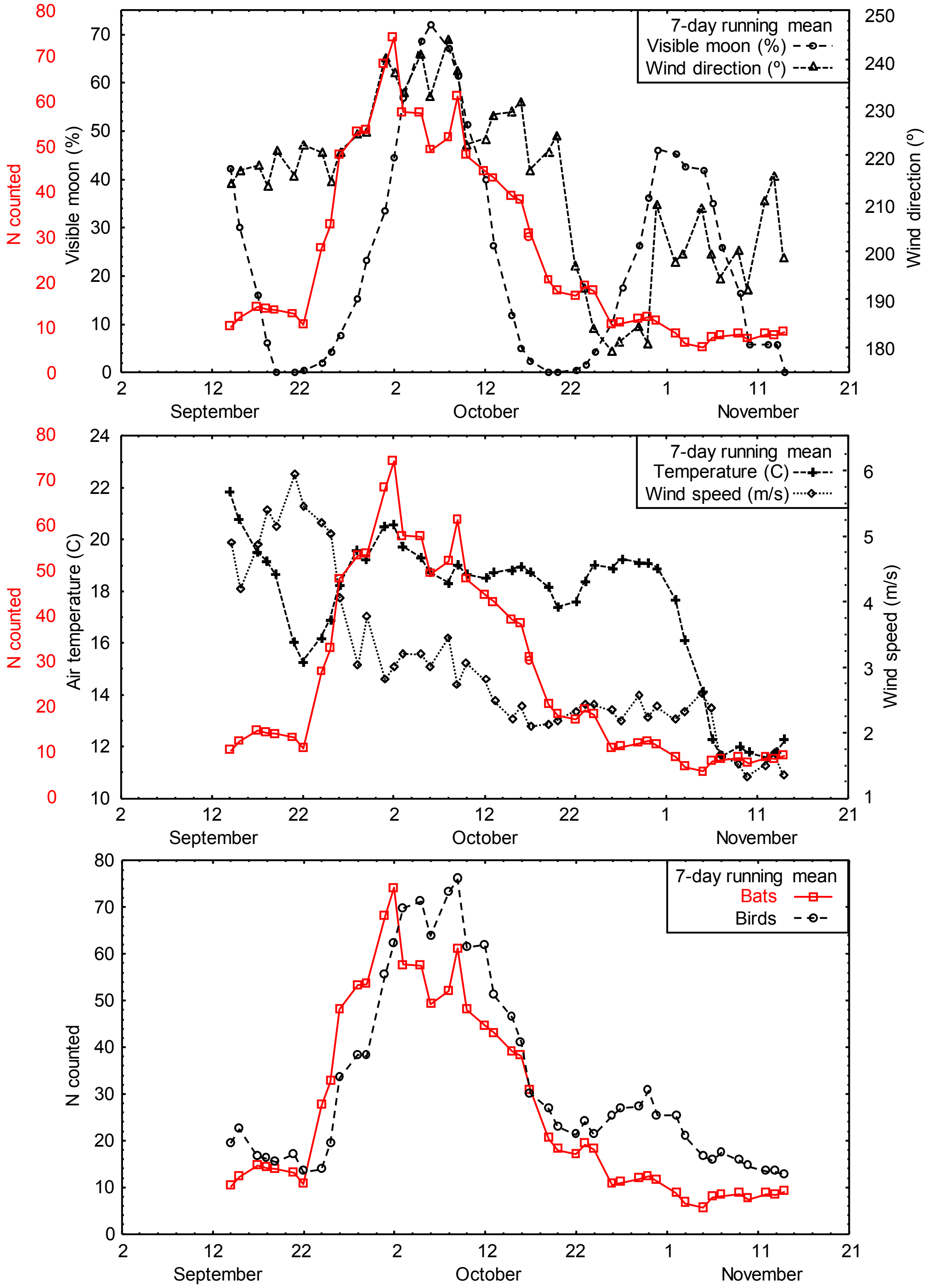

Figure 6. Running means (7 days) of visible moon and wind direction (top graph), air temperature (C) and wind speed (m/s) at ground level (middle graph), and nightly counts of all bats and birds observed flying (bottom graph) during surveys in the Altamont Pass Wind Resource Area, California, 4 September through 14 November 2017.

Rates of risky flight behaviors averaged 3.6 times higher where fatalities were found and differed significantly between groups of wind turbines where bats ≤ 3 days since death were found or not found during the next morning's fatality search (Table 2). Differences were not significant for bats > 3 days since death.

The operative time of surveyed turbines averaged more than twice as long where fatalities were found and differed significantly between groups of wind turbines where bats ≤ of any time since death were found or not found during the next morning's fatality search (Table 2).

Temperature did not differ significantly between groups of wind turbines where bat fatalities were found or not found during the next morning's search, but wind direction and visible moon did (Table 2). Regardless of carcass age, wind directions were significantly more westerly among turbines where fatalities were found during the next morning's search. Visible moon (%) averaged 3.5 times higher at wind turbines where bats ≤ 3 days since death were found the next morning. Although still significant, the magnitude of the difference in visible moon diminished to twice as high among turbines where next-morning searches detected bat carcass older than 3 days (Table 2).

3.2. Daily Comparison of Passage Rates and Fatality Finds by Wind Turbine

Throughout the study, we found bat fatalities that we judged to have died ≤ 7 days earlier (Figure 7). During the same portion of the study period when we were seeing most of the near misses and turbine-disrupted passage flights of bats, we found bat fatalities ≤ 7 days since death (Figure 7). Most passages through operative rotors, including most of the near misses and disrupted flights, spanned the early portion of the bat migration peak when the waxing moon was < 50% visible and winds were shifted to more westerly origin.

3.3. Fatality Estimates

Based on our fatality surveys, we estimated that 288 (95% CI: 107–469) bat fatalities occurred over 61 days at Golden Hills, and 70 (95% CI: 20–120) bat fatalities occurred over 18 days at Buena Vista while it was operational. Adjusting these estimates for P, the proportion of bat fatalities found by the project monitor's [38] dogs over the same periods at Golden Hills, we estimated 606 (95% CI: 225–987) annual bat fatalities, or 7.05 (95% CI:2.62–11.49) bat fatalities/MW/yr at Golden Hills, and 213 (90% CI: 61–364) annual bat fatalities, or 5.61 (95% CI: 1.61–9.58) bat fatalities/MW/yr at Buena Vista. Our estimate for Golden Hills was 25% higher than that of the first two years of fatality monitoring (overlapping our survey effort in time) based on weekly searches using dogs [38]. Our estimate for Buena Vista was nearly 11 times greater than the 3 year average based on human searches at 15 day intervals during the period 2008–2011 at the same project [39]. It was also 1.7× the upper end and 5.3× the lower end of the predicted range of annual fatalities for Buena Vista in the planning phase [40].

3.4. Fatality Estimates from Observed Collisions

Based on one observed collision at Buena Vista—the only one with high certainty—we estimated 18.2 (95% CI: 5.1–31.3) project-wide fatalities/night over the 10 nights we surveyed operable turbines. Based on three observed collisions at Golden Hills, we estimated 31.8 (95% CI: 25.0–38.75) project-wide fatalities/night over the 28 nights we surveyed. These estimates translate to 0.479 (95% CI: 0.134–0.824) bat fatalities/MW/night at Buena Vista and 0.371 (95% CI: 0.291–0.451) bat fatalities/MW/night at Golden Hills during our respective monitoring periods. When we expanded these rates from observed collisions to fatality search efforts and after we adjusted them for proportions of carcasses not found (Buena Vista: 1 MW × 28 searches; d = 0.96, R_C = 0.9, S = 0.93; Golden Hills: 1.79 MW × 55 searches; d = 0.86, R_C = 0.9, S = 1.00), we estimated we should have found 10.8 (95% CI: 3–18.5) fresh bat fatalities at Buena Vista and 28.3 (95% CI: 22.2–34.4) fresh bat fatalities at Golden Hills. We actually found two fresh bat fatalities at Buena Vista and 4 at Golden Hills (by "fresh" we mean bats estimated to have died within 3 days). We found 19% and 14% of the fresh bat fatalities that eye-witnessed collisions predicted we should have found at Buena Vista and Golden Hills, respectively.

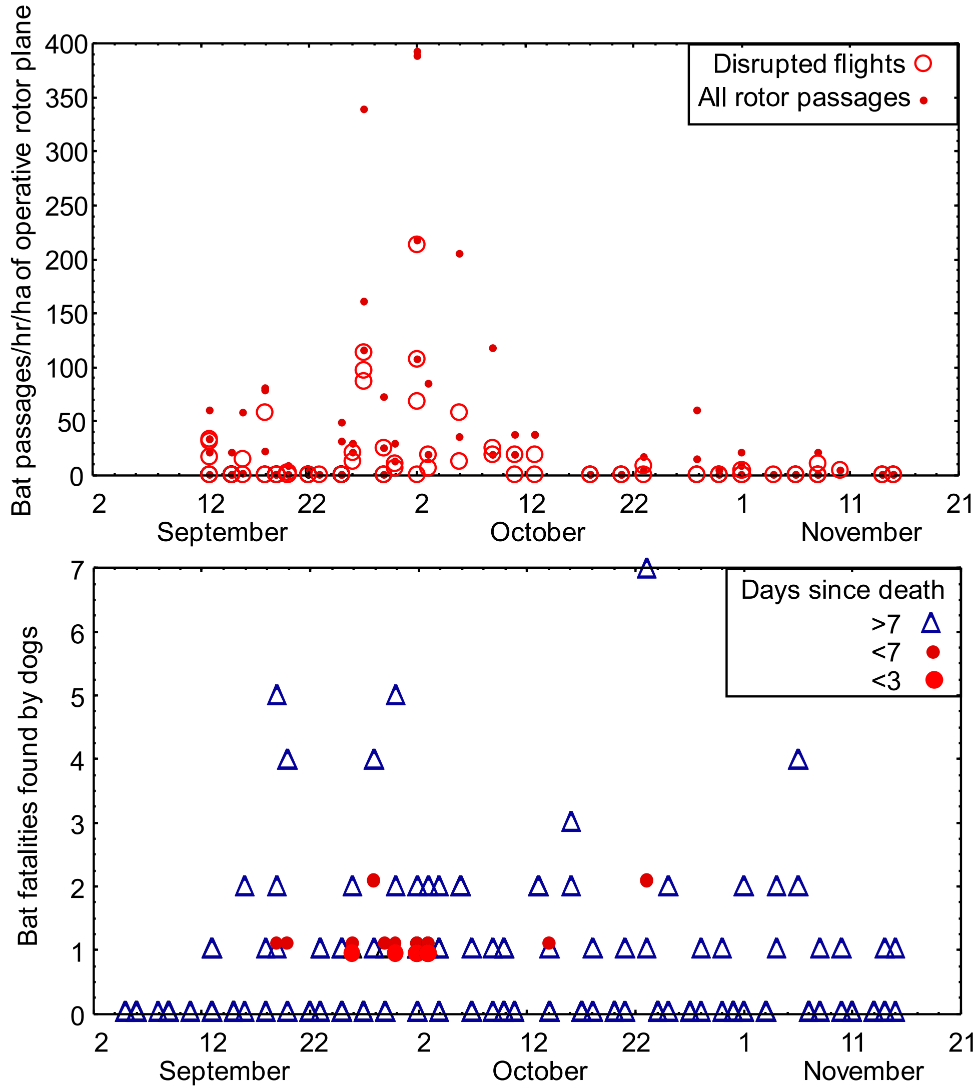

Figure 7. Bat passage rates through operative wind turbine rotors (top) corresponded with next-day fatalities of bats estimated to have died within a week (bottom) in 2017 in the Golden Hills and Buena Vista Wind Projects, Contra Costa and Alameda Counties, California.

4. Discussion

4.1. Predicting Fatality Finds from Passage Rates

Passage rates can predict which wind turbines will have deposited bats killed within 3 days, but they are less predictive of which wind turbines deposited bats > 3 days since death. Considering the larger mean difference in near misses between wind turbines where bats were found and not found the next morning, observed near misses are even more predictive of which turbines deposited bats ≤ 3 days since death. Passage rates of bats can be used to predict next-day availability of fatalities, and predictions would increase in accuracy when passage rates are defined by near misses. Wind direction and moon visibility can also predict next-day fatalities. Because we can predict fatalities at wind turbines that were already installed and operative, our findings might eventually increase the accuracy or efficiency of fatality monitoring, or they might contribute to an operational curtailment strategy.

Based on our findings, passage rates probably will not consistently predict where fatalities will be found in searches performed more than a few days later. Although passage rates were significantly higher at wind turbines where we found fatalities of bats ≤ 3 days, and even of bats ≤ 30 days since death, they were not significantly higher at turbines where we found fatalities of bats ≤ 7 days since death. Further, although rates of near misses and risky behaviors were significantly higher at turbines where we found fatalities of bats ≤ 3 days since death, the same was not true for bats that had been dead longer than 3 days. Overall, our most predictive period of time between measured bat activity and finding bats as fatalities appears to have been only a few days.

Pre-construction passage rates through planned rotor-swept airspace probably will not predict post-construction fatalities. The months and years intervening pre-construction surveys and post-construction fatality monitoring would probably generate no relationship useful for micro-siting to minimize bat impacts. Near misses, which were more predictive than passage rates, cannot be recorded during pre-construction surveys. Passage rates probably cannot predict collision risk based on wind project locations, and therefore are probably of little use for macro-siting. Substantiating our conclusions is evidence that bats target wind turbines by altering flight trajectories to pass through or near operating wind turbine rotors on foraging runs [41] or for other reasons [8,36].

4.2. Fatality Estimates

Searching daily with scent-detection dogs guided by leash, we discovered that bat fatality rates exceeded the estimate based on off-leash dogs searching weekly during concurrent monitoring at Golden Hills [38], and far exceeded the estimate based on humans searching every two weeks at Buena Vista 6–8 years earlier. Our findings reveal that unless high inter-annual variation in fatality rates was the reason for our much higher fatality rate at Buena Vista, changes to field methods can substantially affect fatality estimates. If using dogs instead of human searchers can make this large a difference at Buena Vista, then it is conceivable that many reported fatality estimates of bats could be biased low.

Although our sample size of observed collisions was small, the rates of collisions we witnessed during nocturnal surveys suggest that even our intense fatality monitoring with high carcass detection rates might have underestimated bat impacts. Our dogs found fewer fresh fatalities than our observed collisions suggest they should have found, and yet our dogs performed near perfectly at finding bat carcasses in detection trials. The dogs even found all 34 baby bats placed in trials, and nearly all of the bats that had already decayed for days in the field before being redeployed in trials [31]. Nevertheless, despite their exemplary performance in detection trials, of the four bat collisions we witnessed at turbines to be searched the next morning, dogs found only one of them. Immediately following the standard search for one of the observed collision victims at Golden Hills turbine 26, Smallwood directed the dog team to the area of the turbine's pad where he saw the bat fall, and the dogs performed a second intensive search without detecting the bat. The deficit of fresh bat detections suggested by observed collision rates was confirmed by our dogs finding only 25% of the bats we witnessed to have collided with wind turbines the night before the searches.

The bat we saw fall to the pad of turbine 26 could have been scavenged during the hours between its collision at 19:24 hours and the next morning's fatality search. It was unlikely that this bat left the site after falling to the ground because the video record clearly showed a piece of the bat falling separately to the ground. The bat could have found refuge in one of the many available fossorial mammal burrows, or in cracks within the dried, clay soil of the turbine pad. It also could have left the site on its own volition, most likely to die outside the search radius. These last two possibilities would never apply to bat carcasses deployed in detection trials, but they certainly could apply to injured bats capable of moving on the ground. This type of bias is what is referred to as crippling bias [18].

According to our detection trials [31], only 6% of placed bats are removed by scavengers within 1 day, but these bats were frozen and thawed prior to placement in trials. In our experience, freshly killed bats are much more odiferous than frozen and thawed bat carcasses, and so scavengers relying on olfactory perception might remove freshly killed bats quicker than they remove detection trial carcasses. Coyotes (*Canis latrans*) rely on olfactory perception for foraging and are known to patrol wind turbines for food during the night [33]. We have often observed common ravens (*Corvus corax*) —a bird that relies on both olfactory and visual perception for foraging [42]—patrolling wind turbines in the mornings. On a study area adjacent to Buena Vista, coyotes and common ravens were also the leading removers of detection trial carcasses placed before event-triggered cameras, which captured a coyote swallowing a California quail (*Callipepla californica*) whole and a common raven carrying off a northern pygmy-owl (*Glaucidium gnoma*), neither leaving a trace of evidence of the trial carcasses they removed [32]. It is conceivable that the scavenger guild could be finding and removing fresh-killed bats faster than our detection trials indicate.

It is also conceivable that injured bats evade detection by either entering fossorial mammal burrows or cracks in the dried soil or leaving the fatality search area prior to the next search. We found a live, injured Mexican free-tailed bat under the lip of a concrete pad supporting an electrical transformer box and a dead bat wedged within a soil crack. Both of these bats sought shelter after falling to the ground. Our dogs strongly indicated on a ground squirrel burrow, which we believe included a bat, and the dogs indicated on other burrows as well. Bats might often survive wind turbine injuries long enough to find cover within or outside the area searched by dogs. Some injured bats might also flush from scavengers, flying far enough away to evade detection by searchers (Figure 8).

Figure 8. This Mexican free-tailed bat (*Tadarida brasiliensis*) was found by Smallwood as depicted, face-down under a Golden Hills wind turbine. Assuming the bat was dead, but checking to make certain, Smallwood nudged the bat with a boot. The bat flew up to hover near Smallwood's face for a few seconds, and then flew 50 m away before dropping to the ground.

Insufficient search area could also explain the deficit of fresh bats found by skilled detection dogs. Wind turbine blades sometimes dismember bats. In high winds dismembered parts can drift far from the impact site, especially when the impact site is at the blade's 12:00 position (Smallwood unpublished data). We conclude that crippling bias [18] and maximum search radius bias [3] might often result in underestimation of bat fatalities.

5. Conclusions

Although measured pre-construction activity levels of bats might eventually facilitate decisions over the appropriateness of a proposed wind energy project [15], they will likely never support micro-siting decisions. What might prove more instructive for micro-siting is discernment of spatial and temporal patterns of passage rates, near misses, and disrupted flights through the rotor-swept airspace of existing wind turbines. To this end, thermal imaging enables investigators to see bat and bird interactions with the entirety of wind turbine rotors, as well as flight behaviors and reactions. Thermal imaging also enables counts of insect passages. Combined with nacelle-mounted bat acoustic detectors, some of the bats observed via thermal-imaging camera could be identified to species, which would further elucidate the roles of terrain and location in passage rates, near misses and disrupted flights.

Our fatality estimates based on searches by leashed dogs exceeded those of unleashed dogs and far exceeded those of human searchers who monitored the same turbines 6–8 years earlier. Conventional adjustments for carcass persistence and searcher detection could not fully account for the proportion of carcasses not found by fatality searchers. Our results indicate that substantial improvements in accuracy of fatality estimation are yet to be gained by searching harder for fatalities.

Lastly, our observed collisions predicted we should have found four to seven times the number of bat fatalities than our dogs actually found at Buena Vista and Golden Hills, respectively. Substantial improvements in accuracy of fatality estimation might yet be gained by detecting collisions as they happen and by understanding the fates of collision victims that fatality searchers are unable to detect. The possibility exists that our best estimates of bat fatalities are biased low by search radius bias and crippling bias, either through the volitional departure of searchable areas by injured bats or their seeking refuge when grounded.

Author Contributions: Both K.S.S. and D.A.B. conceived of the study, developed the methods, and acquired funding. K.S.S. performed nocturnal surveys, supervised fatality monitoring, and performed analyses. Both K.S.S. and D.A.B. substantially contributed to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the Gordon and Betty Moore Foundation and the East Bay Regional Park District. The Gordon and Betty Moore Foundation grant was administered through the East Contra Costa County Habitat Conservancy Science and Research Grant Program (Conservancy Contract 2016-03).

Acknowledgments: We are grateful to the Gordon and Betty Moore Foundation and the East Bay Regional Park District for financial support. We also thank East Bay Regional Park District for helping with access to the Buena Vista Wind Energy project. We thank Bryan Maddock and Leeward Renewable Energy LLC for access and assistance at the Buena Vista Wind Energy project, and Renee Culver and NextEra Energy Resources for access and assistance at Golden Hills Wind Energy project. We thank Heath Smith, Collette Yee and Skye Standish of Conservation Canines, Center of Conservation Biology, University of Washington, for their highly skilled dog handling. We also thank Jeff Smith and H.T. Harvey & Associates for assistance at Golden Hills. Our study would not have been possible without the generous donations of bird carcasses by Native Songbird Care and bat carcasses by Deborah Cottrell at West End Animal Hospital. Use of animal carcasses was authorized under permits from the U.S. Fish and Wildlife Service (MB135520-0) and the California Department of Fish and Wildlife (SC-00737). We thank Jennifer Brown of the former agency and Carie Battistone, Esther Burkett, Justin Garcia and Scott Osborn of the latter agency, for assistance with permitting. We are indebted to Debbie Woollett for working with us to train a dog we ended up not using, but this effort was important to our development. We are also greatly indebted to Karen Swaim for her generous donation of living space for our dog handler and detection dogs throughout this study. We also thank three anonymous reviewers for their helpful comments on an earlier draft of this paper. Lastly, we are grateful to the spirited efforts given us by Captain and Jack in the face of high temperatures, rugged terrain, and rattlesnakes.

Conflicts of Interest: The authors declare no conflict of interest.

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