The Journal of Wildlife Management 84(5):852–864; 2020; DOI: 10.1002/jwmg.21863

Research Article

Dogs Detect Larger Wind Energy Effects on Bats and Birds

K. SHAWN SMALLWOOD,[1] *3108 Finch Street, Davis, CA 95616, USA*
DOUGLAS A. BELL, *East Bay Regional Park District, 2950 Peralta Oaks Court, Oakland, CA 94605, USA*
SKYE STANDISH, *Standish Ecological Services, 156 Franklin Street, Santa Cruz, CA 95060, USA*

ABSTRACT As wind turbine-caused mortality of birds and bats increases with increasing wind energy capacity, accurate fatality estimates are needed to assess effects, identify collision factors, and formulate mitigation. Finding a larger proportion of collision victims reduces the magnitude of adjustment for the proportion not found, thus reducing opportunities for bias. We tested detection dogs in trials of bat and small-bird carcasses placed randomly in routine fatality monitoring at the Buena Vista and Golden Hills Wind Energy projects, California, USA, 2017. Of trial carcasses placed and confirmed available before next-day fatality searches, dogs detected 96% of bats and 90% of small birds, whereas humans at a neighboring wind project detected 6% of bats and 30% of small birds. At Golden Hills dogs found 71 bat fatalities in 55 searches compared to 1 bat found by humans in 69 searches within the same search plots over the same season. Dog detection rates of trial carcasses remained unchanged with distance from turbine, and dogs found more fatalities than did humans at greater distances from turbines. Patterns of fatalities found by dogs within search plots indicated 20% of birds and 4–14% of bats remained undetected outside search plots at Buena Vista and Golden Hills. Dogs also increased estimates of carcass persistence by finding detection trial carcasses that the trial administrator had erroneously concluded were removed. Compared to human searches, dog searches resulted in fatality estimates up to 6.4 and 2.7 times higher for bats and small birds, respectively, along with higher relative precision and >90% lower cost per fatality detection. © 2020 The Authors. The *Journal of Wildlife Management* published by Wiley Periodicals, Inc. on behalf of The Wildlife Society.

KEY WORDS Altamont Pass, bats, carcass detection trials, detection dogs, fatality monitoring, small birds, wind farm.

As wind energy expands worldwide, a potential bat mortality crisis lurks behind available estimates of fatality rates from collisions at wind farms (Kunz et al. 2007). Based on bat fatalities reported over 12 years through 2011, Arnett and Baerwald (2013) predicted 196,190–395,886 bat fatalities at wind projects in 2012 in the United States and Canada. With an installed wind energy capacity of 51,630 MW in 2012, the estimate of annual wind turbine-caused bat fatalities in the United States was 600,000 (Hayes 2013) to 888,000 bats (90% CI = 384,643–1,391,428; Smallwood 2013). By 2019, installed capacity had increased to 100,125 MW (https://www.awea.org/wind-101/basics-of-wind-energy/wind-facts-at-a-glance, accessed 6 Dec 2019). If vulnerability of bats to wind turbine collision increased linearly with this increased wind energy capacity, if mean fatality rates are restricted to those estimated from fatality search intervals <10 days (Smallwood and Neher 2017), and if we assume that monitored wind projects reasonably sampled regional variation in installed capacity across the United States (Smallwood 2013, Allison and Butryn 2018), then estimated annual fatalities in 2019 would have increased to >3 million bats, or more than the estimated nationwide mortality caused by white-nose syndrome, a fungal disease estimated to have killed about 600,000 bats/year since 2007 (Hopkins and Soileau 2018). The nationwide estimates cited above were based on using human searchers at wind turbines, an approach prone to large biases and sources of uncertainty due to variation in fatality monitoring methods and poor detection of bat carcasses (Smallwood 2007; Smallwood et al. 2010, 2013). Given the potential magnitude of wind turbine effects on bats and their possible contribution to regional population declines (Rodhouse et al. 2019), it is important to improve estimates of bat fatality rates to formulate realistic mitigation measures.

North America's avifauna has declined 29% in 48 years (Rosenberg et al. 2019), and the magnitude of bird mortality at wind farms is less clear, partly because of high uncertainty in estimates based on human searchers and varying methods to monitor fatalities (Smallwood 2007, 2013). The estimates of wind turbine-caused bird fatalities in the United States in 2012 were 214,000–368,000 (Erickson et al. 2014), 234,000 (Loss et al. 2013), and 573,000 birds (Smallwood 2013).

Received: 26 March 2019; Accepted: 21 February 2020

[1]*E-mail: puma@dcn.org*

Projecting the estimates of Erickson et al. (2014) and Smallwood (2013) to the 100,125 MW of installed wind energy capacity in 2019 yields annual tolls of 415,010–713,662 and 1,111,219 birds, respectively. Whether this range of fatalities qualifies as a crisis for birds depends on the accuracy of the estimates of Erickson et al. (2014) and Smallwood (2013), their spatial representation of the 2012 wind energy capacity in the United States, and the extent to which wind energy-related mortality threatens particular species or contributes cumulatively to other mortality factors.

Sources used to estimate nationwide bat and bird fatalities are confounded by low carcass detection rates of human searchers combined with relatively long intervals between searches, 2 attributes typical of older studies. In a study of 2 overlapping fatality monitoring teams whose methods differed only in average search interval, the team with the shorter search interval of 5 days yielded a small-bird fatality estimate numbering 2.3 times higher than the other team using a search interval of 39 days (Smallwood 2017). Considering the effect of long search interval alone, nationwide bird fatalities estimated by Erickson et al. (2014) could be nearly doubled.

The accuracy of fatality estimates depends largely on detecting as many of the available fatalities as possible, and accurately adjusting for the proportion of fatalities not found (Smallwood et al. 2018). Finding more of the actual fatalities decreases the proportion of unfound fatalities, thereby minimizing inaccuracy caused by biases and error in the adjustment. Multiple steps can be taken to detect more of the available fatalities, including searching to a maximum radius around wind turbines that includes the majority of deposited carcasses, searching along transects spaced closer together, searching more frequently, and searching with skilled detection dogs instead of only humans. Homan et al. (2001), Arnett (2006), Paula et al. (2011), and Matthews et al. (2013) reported that using skilled dogs greatly increased carcass detection rates over human searchers, and Reyes et al. (2016) reported that dogs improved searcher efficiency and were more likely to detect fatalities of rarely represented species.

Detecting as many fatalities as possible caused by a wind turbine includes incorporating an appropriate maximum search radius around the turbine, yet the scientific basis for deciding on a maximum search radius has been scarce. Hull and Muir (2010) proposed a method based on ballistics. However, ballistics cannot account for the collider's premortem contribution to deposition distance, including staying aloft until farther from the turbine or continued movement on the ground post-deposition. An injured mobile bat can defy predictions of deposition patterns based on ballistics. Another approach is to observe the pattern of outcomes: where bat carcasses finally wind up within the wind project. Smallwood (2013) proposed such an outcomes method based on modeling the pattern of carcass deposition within previously searched areas but warned the observed pattern might shift with increasing maximum search radius. Huso and Dalthorp (2014) and Huso et al. (2017) also proposed modeling the pattern of carcass deposition, but the proposed metric consisted of the density of carcasses (carcasses/m^2) as opposed to Smallwood's (2013) cumulative number of carcasses with increasing distance from the turbine. Huso and Dalthorp (2014) and Huso et al. (2016) further proposed that monitoring can be more efficient by concentrating efforts near the turbine tower where carcass densities were higher at one cited project site. Both the Smallwood (2013) and Huso and Dalthorp (2014) and Huso et al. (2017) approaches are also vulnerable to a potential bias caused by human searchers finding fewer of the available fatalities farther from the wind turbines, a pattern that can result from decreasing ground visibility, searchers struggling to remain on the intended transect, and searchers shifting attention to navigating more difficult terrain farther from the turbine. If use of dogs greatly improves carcass detection (Arnett 2006, Mathews et al. 2013), then dogs might reveal truer patterns of carcass deposition within the maximum search radius around wind turbines.

Our objectives were to compare dog versus human searchers at wind turbines for their detection rates of volitionally placed trial carcasses of bats and small birds; patterns of found fatalities around wind turbines; and cost-effectiveness. To further test the efficacy of using skilled dogs relative to human searchers to find available fatalities, our fourth objective was to test whether factors documented to affect human detection rates of bat and small-bird carcasses also affect dog detection rates, including number of days since trial carcass placement, relative visual occlusion of trial carcass by ground conditions, and carcass size. We also examined conditions associated with trial carcasses that dogs did not detect.

STUDY AREA

Our study involving dogs included 2 wind projects 8 km apart in the Altamont Pass Wind Resource Area (APWRA), California, USA, 2017. 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 the East Bay Regional Park District, Contra Costa County. Two Mitsubishi turbines were on 45-m towers, 2 on 65-m towers, and 27 on 55-m towers. The Golden Hills Wind Energy project (Golden Hills) consisted of 48 1.79-MW General Electric (GE) wind turbines (GE, Boston, MA, USA), 32 of which were accessible to us on privately held land in Alameda County. All GE turbines were on 80-m towers. Relying on data from Brown et al. (2016), we compared the pattern of fatalities reported by human searchers with distance from the wind turbine at Vasco Winds Energy Project (Vasco Winds) to the pattern found by dogs at Buena Vista and Golden Hills. Vasco Winds neighbored Buena Vista in Contra Costa County, and consisted of 34 2.3-MW Siemens turbines (Siemens, Munich, Germany) on 80-m towers. All 3 projects were on steeply rolling hills covered by cattle-grazed annual grasses. California ground squirrel (*Otospermophilus beecheyi*) is a keystone species of wildlife in the APWRA, supporting coyotes (*Canis latrans*), American badgers (*Taxidea taxus*), golden eagles (*Aquila chrysaetos*), and many other species of mammalian Carnivora and raptors. Bats and small birds migrate through APWRA with a distinct peak in nocturnal flight activity in late September and early October (Smallwood and Bell 2020). Elevations ranged 41–280 m at Buena Vista, 115–477 m at Golden Hills, and 54–402 m at Vasco Winds.

METHODS

Carcass Detection Rates

We sought to maximize bat and small-bird fatality finds by performing dog searches for fatalities through fall migration from 15 September through 15 November 2017, a period of peak activity in our study area identified by nocturnal surveys using a thermal-imaging camera since 2012 (Smallwood 2016). During daylight morning hours 5 days/week, dogs searched within 105 m of 2–3 turbines/day at Golden Hills, and within 75 m of 3–5 turbines/day at Buena Vista, completing 55 turbine-searches at Golden Hills and 76 at Buena Vista. Dogs searched within the same search boundary that were searched by humans in 2008–2011 at Buena Vista (Insignia 2011) and concurrent with our study at Golden Hills (H. T. Harvey & Associates 2018*a*, *b*). We note that our reference to dogs includes human handlers as part of a dog-human fatality detection team. 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).

Conservation Canines from the Center of Conservation Biology, University of Washington, carefully selected dogs from animal rescue facilities for their health, athleticism, keenness to play with toys, and willingness to work with human handlers. Conservation Canines trained dogs for ≥2 weeks before handling them in our study. Two dogs worked 1 at a time with a trained handler and a data collector. The handler, who used global positioning system (GPS) and a Locus Map application on a phone to track location, guided dogs by leash along transects oriented perpendicular to the wind and separated by 10 m over most of each search area (Fig. 1). Dogs selected their paths within 5 m on either side of the transect, air-scenting for carcasses along the way. Although dogs could detect scent far beyond the transect, they were usually constrained from indicating a carcass location until a transect intersected the carcass. Within a 90° arc between 210° and 300° from the turbine, which corresponds to prevailing upwind directions in the APWRA, we allowed dogs off leash for a more cursory search because in our experience few bat and small-bird fatalities are found upwind of wind turbines (Brown et al. 2016, Smallwood 2016). We mapped and photographed fatality finds using a Trimble GeoExplorer 6000 GPS unit (Trimble, Sunnyvale, CA, USA), and identified carcasses to species. Searches and carcass data collection lasted about 2 hours/2.3-MW turbine and 1.5 hours/1-MW turbine, and each dog was limited to working about 2.5 hours/day to maintain health and vigor.

We integrated carcass detection trials into fatality monitoring, similar to Smallwood et al. (2018). The day before each fatality search, our detection trial administrator (KSS) deposited trial carcasses of bats and small birds at randomized locations, nearly all within intensively searched areas downwind of wind turbines (Table 1). Carcasses had been frozen immediately post-mortem. We weighed trial carcasses prior to placements, removed 1 foot from bats, and clipped off tips of flight feathers of birds. Human members of our dog teams, who were blind to trials, reported found trial carcasses in the same manner as turbine-caused

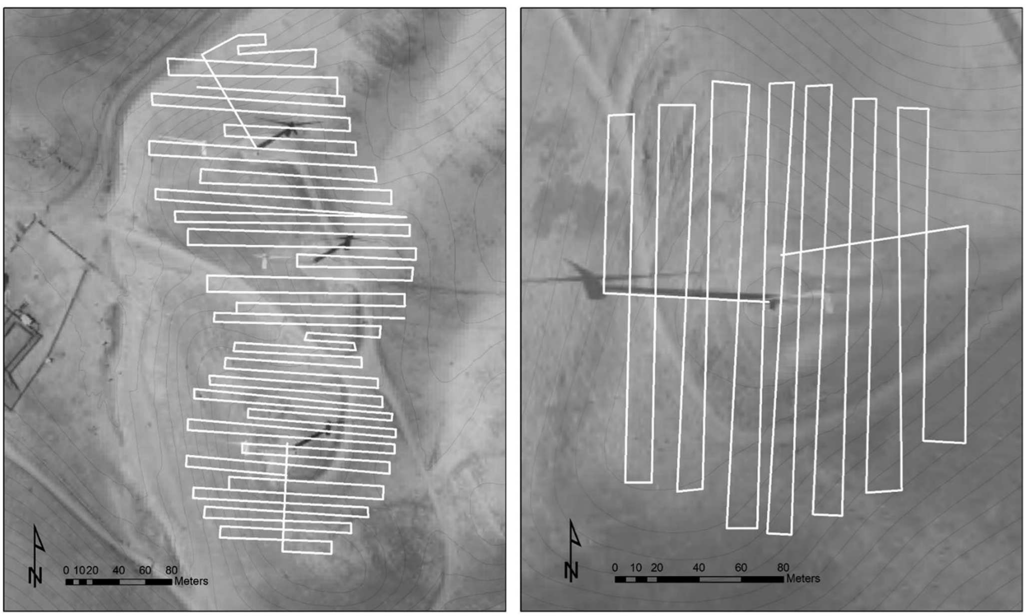

Figure 1. Examples of fatality search transects followed by dogs on particular days (white lines) around 3 wind turbines at the Buena Vista Energy Project (left) and around 1 turbine at the Golden Hills Wind Energy Project (right) in Contra Costa and Alameda Counties, California, USA, 2017. Wind turbines appear as white, and their shadows are dark. Transect directions indicate wind was blowing from the south or north on the day of the depicted survey at Buena Vista, and from the west on the day of the survey at Golden Hills (east winds are rare in fall).

Table 1. Carcasses placed in detection trials at Golden Hills and Buena Vista Wind Projects, Alameda and Contra Costa Counties, California, USA, 5 September–15 November 2017. Bat species are listed in order of number placed, then birds. Sample sizes were n_1 for placements of fresh-frozen and thawed carcasses the day before the search, n_2 for placements on randomized days within 2 weeks of the search, and n_3 for relocations of carcasses from Golden Hills to Buena Vista the day before the search.

	Placed			Body mass (g)		
Species	n_1	n_2	n_3	$\bar{x}$	Low	High
Mexican free-tailed bat (*Tadarida brasiliensis*)	71		17	7.5	1.9	15.6
Evening bat (*Nycticeius humeralis*)	25		11	6.0	1.7	11.4
Little brown bat (*Myotis lucifugus*)	6		5	2.2	1.0	3.5
Seminole bat (*Lasiurus seminolus*)	3		1	15.1	9.1	19.8
Eastern pipistrelle (*Pipistrellus subvlafus*)	2			5.2	4.6	5.8
Cliff swallow (*Hirundo pyrrhonota*)	12	1		15.1	10.7	19.0
Oak titmouse (*Parus inornatus*)	8	1		12.0	6.9	15.6
House finch (*Carpodacus mexicanus*)	5	4		19.9	15.6	23.9
Anna's hummingbird (*Calypte anna*)	5	3		3.6	2.5	5.7
Northern mockingbird (*Mimus polyglottos*)	4	3		38.0	32.2	47.0
Bushtit (*Psaltriparus minimus*)	4	3		4.3	3.7	5.0
Vaux's swift (*Chaetura vauxi*)	4	2		12.5	11.1	14.9
Wilson's warbler (*Wilsonia pusilla*)	3	2		5.9	4.9	7.7
Bewick's wren (*Thryomanes bewickii*)	5			7.4	3.7	8.6
Swainson's thrush (*Catharus ustulatus*)	3	2		54.0	38.1	69.0
Western bluebird (*Sialia Mexicana*)	3	1		20.6	17.8	25.5
Black-headed grosbeak (*Pheucticus melanocephalus*)	3	1		39.7	34.2	50.8
Violet-green swallow (*Tachycineta thalassina*)	2	2		14.2	11.6	18.0
Barn swallow (*Hirundo rustica*)	2	2		16.4	14.4	18.3
Western scrub-jay (*Aphelocoma coerulescens*)	2	1		59.2	55.5	64.9
American robin (*Turdus migratorius*)	2	1		61.0	49.6	70.3
Black phoebe (*Sayornis nigricans*)	1	2		15.8	14.5	17.9
Eurasian collared-dove (*Streptopelia decaocto*)	3	1		73.3	44.3	90.0
Cedar waxwing (*Bombycilla cedrorum*)	3			24.6	23.7	26.3
White-breasted nuthatch (*Sitta carolinensis*)	2			14.0	13.6	14.3
Hooded oriole (*Icterus cucullatus*)	2			16.4	15.5	17.2
Golden-crowned sparrow (*Zonotrichia atricapilla*)	2			14.9	7.7	22.0
California towhee (*Piplio fuscus*)	2			35.8	28.0	43.6
Acorn woodpecker (*Melanerpes formicivorus*)	2			69.3	57.6	81.0
Say's phoebe (*Sayornis saya*)	2			25.3	4.9	45.6
Chestnut-backed chickadee (*Parus rufescens*)	2			5.4	5.4	5.4
Prairie falcon (*Falco mexicanus*)	1			57.4	57.4	57.4
Budgerigar (*Melopsittacus undulatus*)	0	1		20.3	20.3	20.3
American goldfinch (*Carduelis tristis*)	0	1		9.4	9.4	9.4
Mountain bluebird (*Sialia currucoides*)	0	1		26.0	26.0	26.0
Western flycatcher (*Empidonax difficilis*)	1			9.7	9.7	9.7
Hermit thrush (*Catharus guttatus*)	0	1		17.4	17.4	17.4
American crow (*Corvus brachyrhynchos*)	1			179.8	179.8	179.8
Mourning dove (*Zenaida macroura*)	1			107.9	107.9	107.9
White-crowned sparrow (*Zonotrichia leucophrys*)	1			20.4	20.4	20.4
California quail (*Callipepla californica*)	1			184.5	184.5	184.5
Northern rough-winged swallow (*Stelgidopteryx serripennis*)	1			13.9	13.9	13.9
Spotted towhee (*Piplio erythrophthalmus*)	1			27.8	27.8	27.8
Brewer's blackbird (*Euphagus cyanocephalus*)	1					

fatalities except for additionally reporting carcasses that were marked by removed foot or clipped flight feathers. At Buena Vista, KSS checked trial carcass status as long as carcasses persisted. At Golden Hills, KSS removed carcasses of bats but not birds following the dog team's next search, as required by the wind company.

We informed the Golden Hills monitor of our trial carcass placements, but the monitor's human searchers and our dog team were blind to each other's fatality finds until the end of our study. Human searchers at Golden Hills removed carcasses they found, except for our trial carcasses, but we left dog-detected carcasses in place to potentially be discovered by human searchers. From 15 September through 15 November 2017, we performed 55 searches with dogs at the same 32 turbines where human searchers working without dogs performed 69 searches. We later compared fatality finds and estimated fatalities/MW between human searchers and our dog team.

Patterns of Fatalities around Wind Turbines

Fatality rates are less comparable between wind projects unless one accounts for the proportion of fatalities not found because they were located beyond the search boundary. This proportion (d), which can be estimated (see below), varies among wind projects with tower height, rotor diameter, wind speed, flight direction, body mass of species flying through the project, slope steepness around wind turbines, and maximum fatality search radius (Hull and Muir 2010, Kitano and Shiraki 2013, Loss et al. 2013, Smallwood 2013). Also contributing to variation in carcass distribution are pre-mortem movements of mortally injured animals from initial deposition sites and post-mortem translocation of carcasses by vertebrate scavengers. Given the variety of factors that can affect carcass location, Smallwood (2013) asserted that, other than searching farther from the turbine to find more of the available fatalities beyond the typical maximum search radius, inferences drawn from the spatial distribution of found fatalities within the maximum search radius, an outcomes-based approach, should be more accurate than a ballistics approach for predicting d. Smallwood (2013) also warned that declining detection rates with distance from the turbine could bias predictions of d. We quantified trial carcass detection rates with distance from the turbine to reveal whether detection rates change with distance for humans or dogs, and we compared the pattern of human- and dog-found fatalities around wind turbines.

Human searchers found insufficient bat fatalities at Golden Hills for characterizing spatial pattern, so as a surrogate we used data from 3 years of fatality monitoring, May 2012–May 2015, at 34 turbines at Vasco Winds, where 80-m tower heights, 105-m maximum search radius, and 10-m transect spacing equaled those at Golden Hills, and where the detection trial protocol was similar. We used Vasco Winds data to quantify searcher detection rates of trial carcasses and fatality finds by distance from the turbine, and we compared these human searcher-derived spatial patterns to those derived from dogs at Golden Hills.

We fit logistic models to the cumulative number of found fatalities (C) with distance from the turbine to predict number of fatalities within an estimated asymptotic distance (u) beyond which no more fatalities would likely be found, and from which the actual fatality count can be subtracted to estimate the proportion of undetected fatalities due to an insufficient maximum search radius (Smallwood 2013):

$$C = \frac{1}{\left(\frac{1}{u} + a \times b^{X}\right)},$$

where u was the best-fit upper bound value of the cumulative number of found fatalities, X was carcass distance from the wind turbine within 10-m increments, and a and b were best-fit coefficients. We divided C by u to obtain proportions of cumulative fatalities within 10-m distance increments from the turbine (d).

Cost-Effectiveness of Dogs

We compared the monitoring cost per hectare searched to fatalities found, number of species represented by found fatalities, and to the magnitude and precision of fatality estimates. We measured these metrics from fatality searches using dogs from 15 September through 15 November at Golden Hills and Buena Vista in 2017, and from human searchers over the same time period at Golden Hills (H. T. Harvey & Associates 2018*a*, *b*). We also assessed these metrics based on human searches and averaged yearly within these same dates 2008–2011 at Buena Vista (Insignia 2011) and 2012–2015 at Vasco Winds (Brown et al. 2016).

We estimated fatalities/MW ($\hat{F}$) of bats and birds using the Smallwood (2013) estimator:

$$\hat{F} = \frac{F}{R_C \times S \times d},$$

where F was number of fatalities found per MW, R_C was mean daily proportion of trial carcasses persisting at a time interval corresponding with the average search interval in days, and S was searcher detection or proportion of trial carcasses detected upon the next search following carcass placement. We used 28-day R_C values to represent first searches, and our average 27-day R_C values to represent subsequent searches. We carried error through the fatality adjustments using the delta method:

$$SE(\hat{F}) = \sqrt{\left(\begin{array}{l}\left(\left(\frac{1}{S \times R_C \times d}\right) \times SE(F)\right)^2 + \left(\left(\frac{F}{S \times d} \times \left(\frac{-1}{{R_C}^2}\right)\right) \times SE(R_C)\right)^2 + \left(\left(\frac{F}{R_C \times d} \times \left(\frac{-1}{p^2}\right)\right) \times SE(S)\right)^2 \\ + \left(\left(\frac{F}{R_C \times S} \times \left(\frac{-1}{d^2}\right)\right) \times SE(d)\right)^2\end{array}\right)},$$

which we multiplied against the appropriate t-value from a t-distribution to estimate 95% confidence intervals. We curtailed the lower bound of the confidence interval at 0. We measured relative precision as the coefficient of variation.

Factors Affecting Human Search Detection of Bat and Bird Carcasses

Human searcher detection of wind turbine fatalities has been documented to decline with smaller carcass size, time since trial carcass placement, and reduced visibility of carcasses on the ground (Smallwood et al. 2018). To test whether dog searcher detection declined similarly, we tested detection rates of dogs on carcass size. We transformed measured body mass of placed carcasses to $\log_{10}$ scale, which was the measurement scale used in Smallwood et al. (2018), and we deliberately placed 30 juvenile bats and 15 flightless bird chicks to increase the size range of bats and small birds used in the tests. To test whether dogs detect fewer older carcasses, we deliberately placed older carcasses in some trials. Because we were required to remove bat trial carcasses from Golden Hills after our next search following placement, we also relocated persisting carcasses to Buena Vista to test dogs on carcasses that had endured an extra 1–4 days in the field (Table 1). We also placed fresh-frozen and thawed bird carcasses on randomized days up to 2 weeks prior to the next fatality search At Buena Vista, thereby introducing controlled variation in time between placement and the next search. To test whether visual occlusion of carcasses reduces dog detections, we related detection rates to an index of carcass visibility to searchers, which we measured as distances to trial carcass occlusion (no longer visible) from 3 standardized directions. Upon trial placement we counted paces in 3 directions from each carcass until the carcass was occluded because of vegetation or terrain, and we related detection outcomes to mean number of paces to carcass occlusion. One pacing direction was directly away from the turbine, and the other 2 directions were perpendicular to the first direction.

RESULTS

From 15 September through 15 November 2017, dogs found 24 bats and 26 birds during 76 turbine searches at Buena Vista, and 71 bats and 63 birds during 55 turbine searches at Golden Hills (Table 2). Based on carcass decay, we estimated that 9 of those bats and 43 birds had died prior to our study (Table 2). At Golden Hills, human searchers found 0 of 71 bats found by dogs and left in place to be potentially found again, and they found 11 (17%) of 63 bird fatalities found by dogs. Some of the bats missed by humans were likely removed by scavengers in the time between our dogs finding them and the next human search ($\bar{x} = 15$ days; range = 1–28 days), but with 25% more turbine searches over the same time period of our study, human searchers had 25% more opportunities to find bat and bird fatalities than did dog searchers.

Carcass Detection Rates

Of 278 trial carcass placements at Buena Vista and Golden Hills, 214 were available to be found by dogs during ≥1 search. Of carcasses placed before next-day fatality searches and confirmed available, dogs detected 96% of bats and 90% of birds. Dogs found 100% of 41 bats placed at Golden Hills and 93% of 54 bats placed at Buena Vista. They found 84% of 56 small birds placed at Golden Hills and 91% of 32 small birds placed at Buena Vista. Of all searcher exposures to placed carcasses, whether just placed

Table 2. Fatalities found by dogs at Buena Vista (BV) and Golden Hills (GH) Wind Energy Projects, Alameda and Contra Costa Counties, California, USA, fall 2017, where old fatalities were judged to have pre-dated our fatality searches, and new fatalities happened during the study.

Species name (scientific name)	Old fatalities	New fatalities	
		BV	GH
Western red bat (*Lasiurus blossevillii*)	0	4	1
Myotis (*Myotis* spp.)	0	0	1
Mexican free-tailed bat (*Tadarida brasiliensis*)	3	6	29
Hoary bat (*Lasiurus cinereus*)	1	2	13
Bat spp.	5	12	27
Mallard (*Anas platyrhynchos*)	0	0	1
Grebe (Podicipedidae)	1	0	1
Turkey vulture (*Cathartes aura*)	2	0	2
Northern harrier (*Circus cyaneus*)	1	1	0
White-tailed kite (*Elanus leucurus*)	1	1	0
Red-tailed hawk (*Buteo jamaicensis*)	0	0	3
Large raptor	1	0	1
American kestrel (*Falco sparverius*)	2	4	1
Prairie falcon (*Falco mexicanus*)	1	1	0
Rock pigeon (*Columba livia*)	1	1	0
Barn owl (*Tyto alba*)	0	1	0
Burrowing owl (*Athene cunicularia*)	1	0	4
White-throated swift (*Aeronautes saxatalis*)	1	1	0
Pacific-slope flycatcher (*Empidonax difficilis*)	0	1	0
Horned lark (*Eremophila alpestris*)	10	2	10
Northern rough-winged swallow (*Stelgidopteryx serripennis*)	0	0	2
Bewick's wren (*Thryomanes bewickii*)	0	0	1
House wren (*Troglodytes aedon*)	0	0	1
Ruby-crowned kinglet (*Regulus calendula*)	0	0	2
American pipit (*Anthus rubescens*)	1	0	2
Warbler (Parulidae)	0	0	1
Black-throated gray warbler (*Dendroica nigrescens*)	1	0	1
Townsend's warbler (*Dendroica townsendi*)	0	1	0
Lincoln's sparrow (*Melospiza lincolnii*)	0	0	1
Dark-eyed junco (*Junco hyemalis*)	0	0	1
Blackbird (Icteridae)	1	0	1
Western meadowlark (*Sturnella neglecta*)	6	7	7
Brown-headed cowbird (*Molothrus ater*)	1	0	1
Large bird	8	2	8
Small bird	3	3	11
All bats	9	24	71
All small birds	27	19	47
All large birds	16	7	16
All birds	43	26	63

or persisting through multiple searches, dogs found 95% of 132 bat trials and 91% of 101 bird trials between both projects. To adjust the number of bats found for the proportion not found because of searcher detection error, the number of bat fatalities found by dogs required multiplication factors of 1 and 1.075 at Golden Hills and Buena Vista, respectively, whereas those found by humans at Vasco Winds required a multiplication factor of 17.2. To adjust the number of small birds found for the proportion not found because of searcher detection error, the number of small-bird fatalities found by dogs required multiplication factors of 1.16 and 1.09 at Golden Hills and Buena Vista, respectively, whereas those found by humans at Vasco Winds required a multiplication factor of 3.37.

Predicted mean daily carcass persistence rates (R_C) were similar between bats and small birds when based solely on trial administrator status checks (Fig. 2). Our best-fit models for daily carcass persistence based solely on trial administrator status checks were $R_C\,[Bats] = 1.0185 \times 0.8998^{days}$ ($r^2 = 0.98$, root mean square error [RMSE] = 0.11), and $R_C\,[Small\ birds] = 1 - 3.0732 \times (1 - e^{-0.0996 \times \log(days+1)})$ ($r^2 = 0.99$, RMSE = 0.04), where *days* represented number of days into the carcass persistence trial. Bat carcass persistence was higher for bats placed immediately after thawing, and it was higher for birds and bats when relying on dog detections instead of only the trial administrator's status checks (Fig. 2) because dogs found remains of trial carcasses the trial administrator erroneously determined had been removed. Compared to a trial administrator checking on old carcasses typical of those found during monitoring and redeployed in detection trials, dog detections combined with trial administrator checks of fresh-frozen and thawed carcasses at times of placement reduced adjusted bat fatality rates by 28%, 40%, and 44% at 7-, 14-, and 28-day search intervals, respectively (Fig. 2). Adding dog searches to trial administrator carcass checks reduced the adjusted bird fatality rates by 16%, 20%, and 24% at 7-, 14-, and 28-day search intervals, respectively (Fig. 2).

Patterns of Carcass Detections around Wind Turbines

Regardless of distance from turbine, dogs found more of the available trial carcasses at Golden Hills than did humans at Vasco Winds, especially bat carcasses (Fig. 3; Table 3). Neither dog nor human searcher detection rates (*S*) changed significantly with increasing distance from the turbine, but human searcher detection rates of birds tended to decline with increasing distance (Fig. 3).

Human searchers at Golden Hills found 1 bat and 21 bird fatalities during our study, so we could not infer a spatial pattern of bat fatalities from human searches at Golden Hills. To quantify the pattern of human-found bat fatalities around wind turbines, which served as our basis for predicting the proportion of fatalities occurring within the search area, we used 3 years of fatality searches by humans at Vasco Winds. Logistic models fit to the pattern of fatalities found by humans predicted that 100% of bat fatalities and 92% of bird fatalities were located within the maximum search radius of 105 m. Logistic models fit to the pattern of fatalities found by dogs predicted that 86% of bat fatalities and 80% of bird fatalities were located within the maximum search radius of 105 m (Table 4). For dog and human searchers, logistic models fit to the same fatality data found within 3 different maximum search radii predicted 3 different asymptotic distances beyond which no more fatalities should be found, and therefore different values for *d* used to adjust fatality rates (Fig. 4). Numbers of fatalities found to the 105-m search radius confirmed that models fit to curtailed maximum search radii of 50 m and 80 m inaccurately predicted distance asymptotes; the most inaccurate predictions were based on fatality data within the curtailed 50-m radius. For example, the pattern of 30 bat fatalities

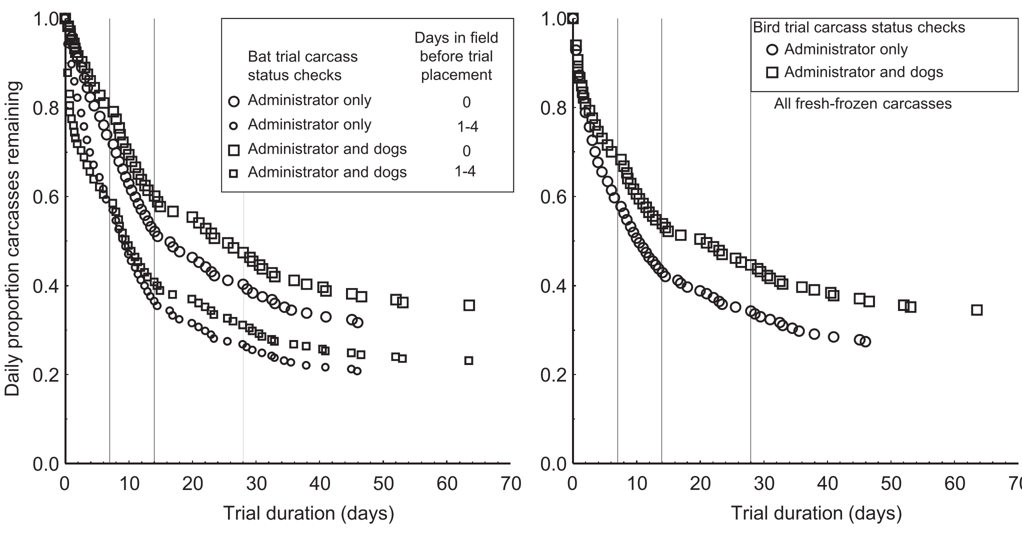

Figure 2. Mean daily carcass persistence for bats (left) and small birds (right) and as determined by the trial administrator's carcass checks (circles) and both the trial administrator's carcass checks and fatality searches using dogs (squares) for carcasses defrosted just before placement (large symbols) and those having already persisted in the field 1–4 days (small symbols) at Golden Hills Wind Energy Project and Buena Vista Wind Energy Project in the Altamont Pass Wind Resource Area, California, USA, fall 2017. Also shown are typical fatality search intervals of 7, 14, and 28 days for reference (vertical lines).

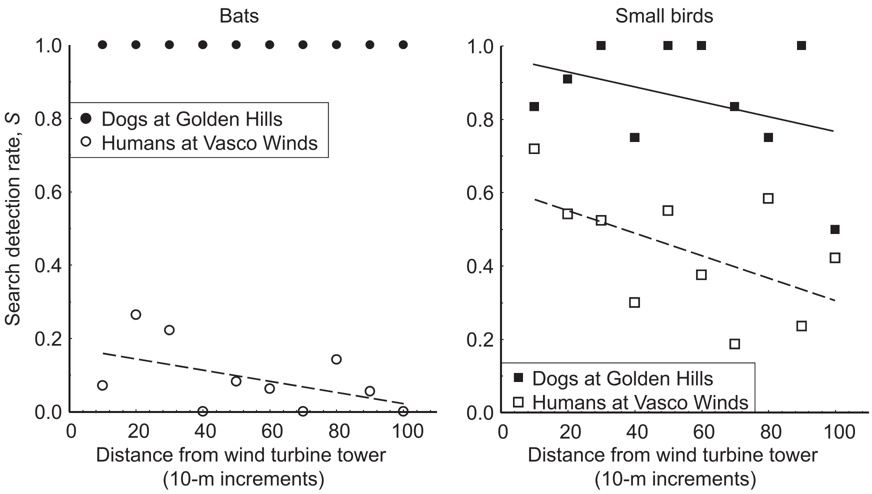

Figure 3. Searcher detection rates of bats (left) and birds (right) did not change significantly with increasing distance from the wind turbine whether the searchers were humans or dogs at Vasco Winds Energy Project or Golden Hills Wind Energy Project, respectively, in the Altamont Pass Wind Resource Area, California, USA, fall 2017. Searcher detection using dogs was higher than using humans for trial bird carcasses and higher for trial bat carcasses.

Table 3. Searcher detection rate (S) regressed on increasing 10-m distance increments from wind turbine for the dog team at Golden Hills Wind Energy Project (fall 2017) and for humans at the Vasco Winds Energy Project (2012–2015), Altamont Pass Wind Resource Area, California, USA, where $S = a + bX$, and X represents distance (m).

		Model coefficients				
Searcher	**Trials**	***a***	***b***	r^2	**SE**	***P***
Dog team	Bats	1.000	−0.0000	0.00	0.00	1.00
Dog team	Birds	0.970	−0.0020	0.04	0.16	0.28
Humans	Bats	0.174	−0.0015	0.16	0.08	0.14
Humans	Birds	0.612	−0.0031	0.21	0.15	0.10

found after 3 years of human searches within the curtailed 50-m radius at Vasco Winds resulted in a logistic model prediction of 30.5 total available bats, 1.5 of which were predicted outside the search radius. But 49 were found within 100 m, so the model prediction based on the fatality pattern within 50 m was 38% too low. For dog searches at Golden Hills, the model fit to fatality finds within 50 m predicted a total available number of bat fatalities that was 53% too low, as confirmed by dog searches within the entire 105-m radius.

Cost-Effectiveness of Dogs

Dogs finding more of the available fatalities than human searchers translated into higher fatality estimates. Estimated bat fatalities/MW were 6.4 times higher based on dog searchers than on human searchers at Golden Hills, and 4.2 times higher at Buena Vista (Table 5). Estimated bird fatalities/MW were 1.6 times higher based on dog searchers than on human searchers at Golden Hills, and 2.7 times higher at Buena Vista (Table 5).

Relative precision of fatality estimates was higher when based on dog searches. At Golden Hills and Buena Vista, respectively, estimates of coefficient of variation from dog searches were 28% and 30% of those estimated from human

Table 4. Logistic models of cumulative fatalities found in 10-m distance increments from wind turbines to the maximum search radius at Vasco Winds (VW), Golden Hills (GH), and Buena Vista (BV) Energy Projects, Altamont Pass Wind Resource Area, California, USA, fall 2017: $C = \frac{1}{\left(\frac{1}{u} + a \times b^X\right)}$, where u was the best-fit upper bound value of the cumulative number of found fatalities, X was carcass distance from the wind turbine within 10-m increments, and a and b were best-fit coefficients. From the model we also predicted proportion of fatalities to occur within the maximum search radius: $d = \frac{C}{u}$.

				Model coefficients					Logistic model prediction	
Searcher	**Site**	**Radius (m)**	**Taxon**	***u***	***a***	***b***	r^2	**SE**	***d***	**Distance (m) to 99% of *u***
Human	VW	105	Bats	45.39	0.29	0.937	0.96	0.012	1.00	99
Human	BV	75	Bats	14.27	1.34	0.925	1.00	0.003	0.98	98
Human	VW	105	Small birds	84.58	0.15	0.957	0.99	0.023	0.89	159
Human	VW	105	Large birds	60.43	0.12	0.966	0.97	0.023	0.84	173
Human	VW	105	All birds	155.05	0.06	0.964	0.99	0.005	0.84	189
Human	GH	105	All birds	21.90	0.61	0.953	0.98	0.023	0.92	119
Human	BV	75	All birds	63.82	0.21	0.947	0.99	0.004	0.88	132
Dog	GH	105	Bats	78.86	0.16	0.962	0.98	0.018	0.86	177
Dog	BV	75	Bats	25.96	1.22	0.915	0.99	0.008	0.96	76
Dog	GH	105	Small birds	52.15	0.58	0.954	0.99	0.009	0.86	156
Dog	BV	75	Small birds	21.63	3.36	0.936	1.00	0.001	0.74	110
Dog	GH	105	Large birds	17.93	9.18	0.942	0.98	0.022	0.79	120
Dog	BV	75	Large birds	7.91	18.74	0.917	0.98	0.018	0.89	80
Dog	GH	105	All birds	73.89	0.48	0.956	0.99	0.009	0.80	173
Dog	BV	75	All birds	28.79	3.13	0.929	1.00	0.006	0.80	108

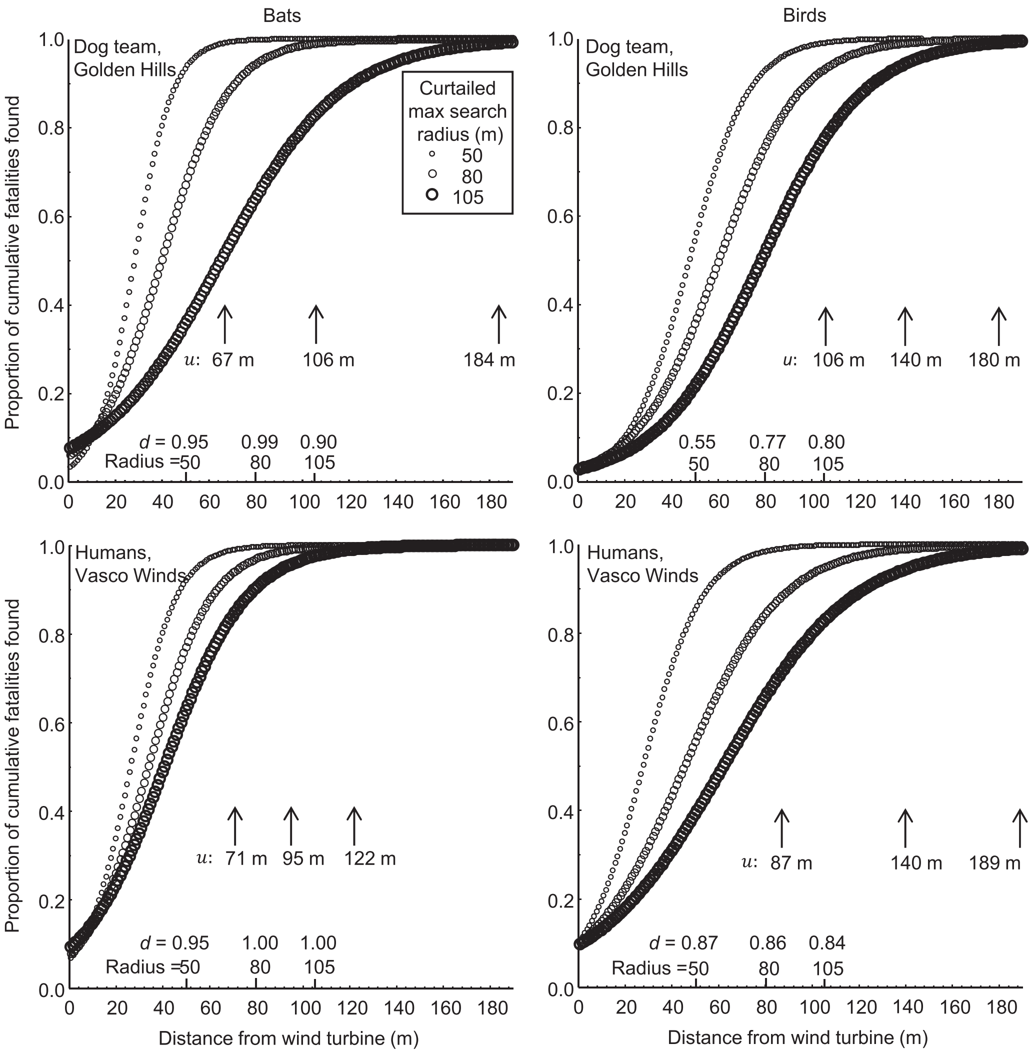

Figure 4. Proportions of bat (left graph) and bird (right graph) fatalities found within increasing 10-m distance increments from the turbine at Golden Hills Wind Energy Project, Alameda County, California, USA, fall 2017, based on dog (top graphs) and human (bottom graphs) searchers covering maximum search radii curtailed to 50 m and 80 m and to the full extent of 80 m (symbolized by radius and extended tics). We calculated proportions of fatalities as cumulative numbers of fatalities divided by the fatality asymptote (u) both of which were predicted from logistic models fit to the data. Also shown are the distances corresponding to 99% of u along with arrows pointing to u, and estimated proportions of carcasses found within each search radius (d).

Table 5. Estimated fatalities/MW ($\hat{F}$) of bats and small birds killed by wind turbines during our fall 2017 study at operational wind turbines in the Buena Vista (BV) and Golden Hills (GH) projects in the Altamont Pass Wind Resource Area, California, USA, where we divided the number of carcasses/MW found (F) by carcass persistence rate (R_C), searcher detection rate (S), and maximum search radius bias (d), and calculated standard errors using the delta method.

				Adjustments						
				R_C		S		d		
Taxa	Site	Searcher	$\bar{F}$ (SE)	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	$\hat{F}$ (95% CI)
Bats	BV	Humans	0.01 (0.01)	0.43	0.11	0.06[a]	0.025	0.97	0.325	0.44 (0.00–1.50)
Bats	BV	Dogs	0.71 (0.17)	0.43	0.11	0.93	0.001	0.96	0.008	1.85 (0.53–3.17)
Bats	GH	Humans	0.03 (0.03)	0.58	0.06	0.06[a]	0.025	1.00[b]	0.214	0.52 (0.00–1.68)
Bats	GH	Dogs	2.22 (0.38)	0.43	0.11	1.00	0.000	0.86	0.018	3.35 (1.24–5.46)
Small birds	BV	Humans	0.03 (0.02)	0.45	0.04	0.30[a]	0.038	0.86	0.230	0.28 (0.00–0.65)
Small birds	BV	Dogs	0.23 (0.12)	0.45	0.04	0.91	0.002	0.74	0.004	0.75 (0.00–1.57)
Small birds	GH	Humans	0.38 (0.13)	0.45	0.06	0.30[a]	0.038	0.89	0.023	1.76 (0.31–3.21)
Small birds	GH	Dogs	1.63 (0.30)	0.45	0.04	0.84	0.001	0.86	0.009	2.79 (1.61–3.97)

[a] Estimated at Vasco Winds (Brown et al. 2016), where methods of human searches for fatalities were the same as at Golden Hills. No human searcher detection trials were reported in H. T. Harvey & Associates (2018).

[b] Estimated at Vasco Winds, where methods of human searches for fatalities were the same as at Golden Hills. We could not estimate d from a single fatality find.

searches for bats, and were 51% and 84% of those estimated from human searches for small birds.

Our dog team searched 298.22 ha at Golden Hills and Buena Vista from 15 September through 15 November 2017, and human monitors searched 238.74 ha at Golden Hills. Humans searched 619.34 ha between the same dates in each of 3 years, 2012–2015 at Vasco Winds. Our dog team averaged US \$99.95/ha, whereas human searchers at Vasco Winds averaged \$62.68/ha, a rate that would also apply to human searchers at Golden Hills and Buena Vista assuming they were paid about the same rate. On a per-fatality detection basis, dogs averaged \$314/bat, \$335/bird, and \$162/fatality of birds and bats pooled together, whereas humans averaged \$5,545/bat, \$4,014/bird, and \$2,329/fatality of birds and bats pooled together at Vasco Winds, \$14,964/bat, \$680/bird, and \$651/fatality of birds and bats pooled together at Golden Hills, and \$16,555/bat, \$5,519/bird, and \$4,140/fatality of birds and bats pooled together at Buena Vista. Per fatality detection, dogs cost 7% of humans at Vasco Winds, 25% of humans at Golden Hills, and 4% of humans at Buena Vista.

Assuming our dogs would have detected the 1 golden eagle and 1 ferruginous hawk (*Buteo regalis*) that had been found and removed by the Golden Hills monitor prior to dog searches, dogs cost \$827/species of birds and bats detected as fatalities (19 bird and 4 bat species) at Golden Hills and \$770/species (11 bird and 3 bat species) at Buena Vista. Human searchers cost \$1,247/species of birds and bats detected as fatalities (11 bird and 1 bat species) at Golden Hills, and \$3,311/species of birds and bats (8 bird and 2 bat species) detected as fatalities at Buena Vista. Human searchers cost more per species detected as fatalities and discovered only half the species in fatality detections, which imposed a greater cost in lost information that would have been critical for impact assessment.

Factors Affecting Search Detection of Bat and Bird Carcasses

Whereas dogs found nearly all of the trial bat carcasses confirmed available to them at Buena Vista and Golden Hills, human searchers found none of the bats weighting $\leq$5 g but found increasingly higher proportions of bats in larger weight categories (Fig. 5). Bird fatality finds were skewed towards larger birds among human searchers, whereas dogs discovered most of the small birds (Fig. 5). For bats, birds, and bats and birds pooled together, dog detection trial outcomes did not differ significantly by mean $\log_{10}$ body mass (t-tests, $P > 0.05$).

Of 24 trial bat carcasses that we placed at Buena Vista that had already persisted 1–4 days at Golden Hills (Table 1), and of which we confirmed available for detection, dogs detected 87.5%, or only 5.5% lower than the fresh bat detection rate at Buena Vista. Of the 36 bird carcasses we placed on randomized days at Buena Vista to vary the days since placement by up to 2 weeks (Table 1), dogs detected 36%, but they detected 100% of the 13 that persisted through the next fatality search. The 64% that were undetected had not persisted until the next search, likely because scavengers removed them. For bats, birds, and bats and birds pooled together, dog detection trial outcomes did not differ significantly by mean distance to carcass occlusion (t-tests, $P > 0.05$).

Of 7 bats missed by dogs, 3 had been relocated from Golden Hills to Buena Vista to test dogs on older carcasses. Dogs missed 3 bats on 31 October 2017. Dogs missed 1 bat on a gravel turbine pad, 1 on a gravel access road, 1 in restored grassland, and 4 in established grassland. Two of the missed bats were near the edge of the maximum search radius.

Dogs missed 8 birds ranging in size from a 3.7-g Bewick's wren (*Thryomanes bewickii*) to an 87.6-g Eurasian collared-dove

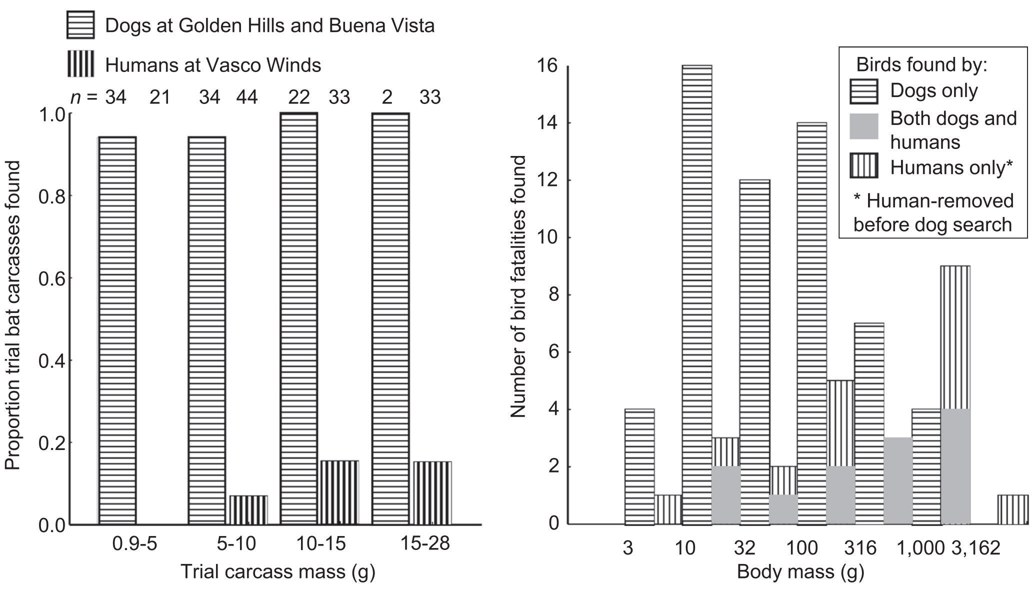

Figure 5. Proportions of trial bat carcasses that were confirmed available by carcass status checks (n) and found by body mass category based on dogs at Golden Hills and Buena Vista Wind Energy Projects and on humans at Vasco Winds Energy Project (left graph), and bird fatality finds by $\log_{10}$ 0.5 g-increments based on dog and human searchers during concurrent monitoring efforts (right graph) at Golden Hills, Altamont Pass Wind Resource Area, California, USA, fall 2017.

(*Streptopelia decaocto*). Dogs missed 2 birds on 23 October 2017, and 3 more on 13 November 2017. Dogs missed 2 birds on the non-gravel portions of turbine pads, 3 in reclaimed grassland, and 3 in established grassland. Four were on very steep slopes, and 2 were at the edge of the maximum search radius.

Of the 15 missed bat and bird trial carcasses, 4 bats and 6 birds (67% of misses) were missed on 8 (18%) search days when the dog team was accompanied by the dog handler's supervisor or a photographer. The misses occurred on such days of distraction (i.e., addition of a supervisor or photographer) nearly 4 times more often other than expected. Another bat trial carcass was missed during the dogs' first search of the study.

DISCUSSION

Skilled scent-detection dogs found 95% of placed bats and 91% of placed birds, despite our deliberate placements of carcasses of immature bats and birds, mostly small-bodied species, and some old carcasses, and despite inadvertent placement of some carcasses beyond the search radius. Dogs found 22 of 23 available immature bats averaging 3.46 g, and a desiccated bat carcass of only 1 g. Dogs found most of the relocated bats that had already decayed in the field for ≤4 days, and they found bats that disappeared into tall grass when dropped from shoulder-height, bats that human searchers probably would not have found. Among birds, dogs found hummingbirds and many chicks of various songbird species. Dogs found all available birds placed ≤2 weeks prior to their next search. Overall, dogs found the majority of trial carcasses, giving us confidence that they can find the majority of available carcasses representing wind turbine fatalities.

Our results were consistent with others who have used scent-detection dogs for fatality searches. At 2 wind projects, dogs found 71% and 81% of trial bat carcasses, whereas humans found 42% and 14%, respectively (Arnett 2006). At other wind projects, dogs found 96% of trial common quail (*Coturnix coturnix*) carcasses compared to 9% found by humans (Paula et al. 2011), and 73% of trial bat carcasses compared to 20% found by humans (Mathews et al. 2013). In another study using untrained dogs, dogs found 92% of trial house sparrow (*Passer domesticus*) carcasses compared to 45% found by humans (Homan et al. 2001). Our findings were similar to earlier comparisons between dogs and humans, although we note the disparity between dog and human detection rates increased with smaller-bodied animals. Where 55 of our dog searches overlapped 69 human searches at the same wind turbines, our dogs found 71 bat fatalities, whereas human searchers found 1; our dogs found 47 small birds, whereas human searchers found 11; and our dogs found 16 large birds, whereas humans found 10 (4 were found by both dogs and humans). The 71-fold difference in found bats and 4-fold difference in found small birds represented substantial differences in searcher detection between dogs and humans, differences that were measured in actual concurrent fatality monitoring rather than in separate trials. Our findings at Buena Vista also differed largely from human searches over the same season 6 to 9 years earlier. Over only 17 days of surveys at operable turbines, our dogs found more bat fatalities than Insignia's (2011) human searchers found in 3 years, amounting to a 66-fold difference in bats found per year.

Dogs finding more of the available fatalities translated into fatality estimates up to 6.4 times higher for bats and up to 2.7 times higher for small birds; it also resulted in twice the number of species represented in fatality estimates and higher relative precision. Fatality estimates based on dog searches also include more of the small-sized species of bats and birds that human searchers are prone to miss. Increased fatality detection using dogs accounted for most of the improvements in fatality estimation and cost-effectiveness, but the increased detection was not measured only in *S*. Whereas human search detection tended to decline with increasing distance from the turbine, dog detection of fatalities did not. Therefore, so long as the maximum search radius truly encompasses the majority of available fatalities, the spatial pattern of fatalities discovered by dogs should result in more accurate predictions of how many were undetected beyond the search radius. Increased detection also reduced error in detection trial administration. Dogs revealed that our trial administrator, even knowing exactly where he placed carcasses, nevertheless falsely determined removals of 8.9% (11 of 123) of bird trial carcasses and 2.9% (3 of 105) of bat trial carcasses. This type of error is difficult to avoid because wind and animals move and diminish carcass remains and some of the remains will be small and hidden in vegetation. Finding feathers and bones a month or 2 after a trial carcass was reported to have been removed can result in erroneously counting trial remains as a fatality. Acknowledging the potential error associated with incomplete removals and false removal determinations, Brown et al. (2016) and Smallwood et al. (2018) left carcasses where found and relied on fatality photos and on tracking when and where remains were found to prevent errors. Dogs, however, find almost all remains, including small pieces of bat wing or a few feathers of a small bird, and thus nearly eliminate detection trial administration error so long as the remains are identifiable or located where trial carcasses were placed.

Even with the improvements to fatality monitoring using skilled dogs, more research is needed to quantify the undetected portion of fatalities beyond the maximum search radius. The most obvious method for satisfactorily quantifying the undetected portion of fatalities occurring outsides the search radius would be to extend dog searches well beyond the conventional search radius. Also, crippling bias (Smallwood 2007) remains unquantified without detecting collisions in some way other than searches within plots. Background mortality also remains insufficiently quantified.

Scent-detection dogs would more effectively test hypotheses related to impact assessments and mitigation efficacy by detecting more of the available bat and bird fatalities. They would be more likely than human searchers to reveal whether pre-construction bat activity patterns can predict post-construction effects (Hein et al. 2013), and they should find enough of the available bats to develop micro-siting strategies consistent with those developed for raptors (Smallwood et al. 2017) and for testing operational curtailment strategies in appropriate experimental designs (Sinclair and DeGeorge 2016). Dogs could also facilitate evidence of absence methods used for estimating the probability of fatalities of particular species (Huso et al. 2015).

We concur with Paula et al. (2011) and Mathews et al. (2013) that fatality monitoring at wind turbines should be performed using scent-detection dogs and trained handlers, and we further concur that dogs should be carefully selected for the task (Beebe et al. 2016). Unlike humans, skilled dogs find almost all of the available carcasses. Some of our findings suggest that a skilled dog team might find even more of the available carcasses if the dog team is left undisturbed by colleagues. The much more accurate fatality estimates generated from dog searches can usually lead to more cost-effective monitoring and to insight about causal factors of collisions and reasonable solutions. Cost-effectiveness of using dogs might prove lower than what we report where dogs perform less effectively in higher heat or on certain ground covers, and where costs are higher because of unavailability of dog teams, lack of appropriate lodging, or increased need for treatment of injuries or parasitic infections. Where dogs can search for fatalities at reasonable cost, monitoring and mitigation solutions can be arrived at much more rapidly with the vastly superior data that dogs and their handlers can collect at wind energy projects.

MANAGEMENT IMPLICATIONS

Many of the available fatality monitoring reports likely underestimated bat and small-bird fatalities in North America because they relied on human searchers. The accuracy and precision of fatality estimates at wind projects would greatly improve by using scent-detection dogs guided by trained handlers and applied to larger search areas than typically used. Dog search teams should consider using leashed dogs for greater precision of areal searches, and should minimize distractions to the dogs. Dog searches can reveal spatial and temporal patterns of fatalities that can better support hypothesis-testing of causal factors and wind turbine micro-siting strategies.

ACKNOWLEDGMENTS

We thank B. Maddock and Leeward Renewable Energy for access and assistance at the Buena Vista Wind Energy project, and R. C. Culver and NextEra Energy Resources for access and assistance at Golden Hills Wind Energy project. We thank H. Smith and C. Yee for their skilled dog handling. We also thank J. 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 D. Cottrell. We thank J. Brown, C. Battistone, E. Burkett, J. Garcia and S. Osborn for assistance with permitting. We are indebted to D. 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 K. Swaim for her generous donation of living space for our dog handler and detection dogs throughout this study. We thank 2 anonymous reviewers of previous drafts of this manuscript. Lastly, we are grateful to the spirited efforts given us by Captain and Jack. This research was funded in part by the Gordon and Betty Moore Foundation, which was administered through the East Contra Costa County Habitat Conservancy Science and Research Grant Program (Conservancy Contract 2016-03). We thank these 2 organizations and also the East Bay Regional Park District for additional funding and for assistance with access to the Buena Vista Wind Energy project located on its property.

LITERATURE CITED

Allison, T. D., and R. Butryn. 2018. AWWI technical report: a summary of bat fatality data in a nationwide database. American Wind and Wildlife Institute, Washington, D.C., USA.

Arnett, E. 2006. A preliminary evaluation on the use of dogs to recover bat fatalities at wind energy facilities. Wildlife Society Bulletin 34:1440–1445.

Arnett, E. B., and E. F. Baerwald. 2013. Impacts of wind energy development on bats; implications for conservation. Pages 435–456 *in* R. A. Adams and S. C. Pedersen, editors. Bat evolution, ecology, and conservation. Springer, New York, New York, USA.

Beebe, S. C., T. J. Howell, and P. C. Bennett. 2016. Using scent detection dogs in conservation settings: a review of scientific literature regarding their selection. Frontiers in Veterinary Science 3(96):1–13.

Brown, K., K. S. Smallwood, J. Szewczak, and B. Karas. 2016. Final 2012–2015 Report Avian and Bat Monitoring Project Vasco Winds, LLC. Prepared for NextEra Energy Resources, Livermore, California, USA.

Erickson, W. P., M. M. Wolfe, K. J. Bay, D. H. Johnson, and J. L. Gehring. 2014. A comprehensive analysis of small-passerine fatalities from collision with turbines at wind energy facilities. PLoS ONE 9(9):e107491.

Hayes, M. A. 2013. Bats killed in large numbers at United States wind energy facilities. BioScience 63:975–979.

Hein, C., W. Erickson, J. Gruver, K. Bay, and E. B. Arnett. 2013. Relating pre-construction bat activity and post-construction fatality to predict risk at wind energy facilities. A report submitted to the National Renewable Energy Laboratory. Bat Conservation International, Austin, Texas, USA.

Homan, H. J., G. M. Linz, and B. D. Peer. 2001. Dogs increase recovery of passerine carcasses in dense vegetation. Wildlife Society Bulletin 29:292–296.

Hopkins, M. C., and S. C. Soileau. 2018. U.S. Geological Survey response to white-nose syndrome in bats: U.S. Geological Survey Fact Sheet 2018–3020, Reston, Virginia, USA.

H. T. Harvey & Associates. 2018*a*. Golden Hills Wind Energy Center post-construction fatality monitoring report: year 1. Prepared for Golden Hills Wind, LLC, Livermore, California, USA.

H. T. Harvey & Associates. 2018*b*. Golden Hills Wind Energy Center post-construction fatality monitoring report: year 2. Prepared for Golden Hills Wind, LLC, Livermore, California, USA.

Hull, C. L., and S. Muir. 2010. Search areas for monitoring bird and bat carcasses at wind farms using a Monte-Carlo model. Australian Journal of Environmental Management 17:77–87.

Huso, M. M. P., and D. Dalthorp. 2014. Accounting for unsearched areas in estimating wind turbine-caused fatality. Journal of Wildlife Management 78:347–358.

Huso, M. M. P., D. Dalthorp, D. Dail, and L. Madsen. 2015. Estimating wind-turbine-caused bird and bat fatality when zero carcasses are observed. Ecological Applications 25:1213–1225.

Huso, M. M. P., D. Dalthorp, and F. Korner-Nievergelt. 2017. Statistical principles of post-construction fatality monitoring. Pages 84–102 *in* M. Perrow, editor. Wildlife and wind farms—conflicts and solutions, volume 2. Pelagic Publishing, Exeter, United Kingdom.

Huso, M. M. P., D. Dalthorp, T. J. Miller, and D. Bruns. 2016. Wind energy development: methods to assess bird and bat fatality rates post-construction. Human–Wildlife Interactions 10:62–70.

Insignia Environmental. 2011. Draft Final Report for the Buena Vista Avian and Bat Monitoring Project. Report to County of Contra Costa, Martinez, California, USA.

Kitano, M., and S. Shiraki. 2013. Estimation of bird fatalities at wind farms with complex topography and vegetation in Hokkaido, Japan. Wildlife Society Bulletin 37:41–48.

Kunz, T. H., E. B. Arnett, W. P. Erickson, A. R. Hoar, G. D. Johnson, R. P. Larkin, M. D. Strickland, R. W. Thresher, and M. D. Tuttle. 2007. Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. Frontiers in Ecology and the Environment 5:315–324.

Loss, S. R., T. Will, and P. P. Marra. 2013. Estimates of bird collision mortality at wind facilities in the contiguous United States. Biological Conservation 168:201–209.

Mathews, F., M. Swindells, R. Goodhead, T. A. August, P. Hardman, D. M. Linton, and D. J. Hosken. 2013. Effectiveness of search dogs compared with human observers in locating bat carcasses at wind-turbine sites: a blinded randomized trial. Wildlife Society Bulletin 37:34–40.

Paula, J., M. C. Leal, M. J. Silva, R. Mascarenhas, H. Costa, and M. Mascarenhas. 2011. Dogs as a tool to improve bird-strike mortality estimates at wind farms. Journal for Nature Conservation 19:202–208.

Reyes, G. A., M. J. Rodriguez, K. T. Lindke, K. L. Ayres, M. D. Halterman, B. R. Boroski, and D. S. Johnston. 2016. Searcher efficiency and survey coverage affect precision of fatality estimates. Journal of Wildlife Management 80:1488–1496.

Rodhouse, T. J., R. M. Rodriguez, K. M. Banner, P. C. Ormsbee, J. Barnett, and K. M. Irvine. 2019. Evidence of regionwide bat population decline from long-term monitoring and Bayesian occupancy models with empirically informed priors. Ecology and Evolution 9:11078–11088.

Rosenberg, K. V., A. M. Dokter, P. J. Blancher, J. R. Sauer, A. C. Smith, P. A. Smith, J. C. Stanton, A. Panjabi, L. Helft, M. Parr, and P. P. Marra. 2019. Decline of the North American avifauna. Science 366(6461):120–124.

Sinclair, K., and E. DeGeorge. 2016. Framework for testing the effectiveness of bat and eagle impact-reduction strategies at wind energy projects. Technical Report NREL/TP-5000-65624. National Renewable Energy Laboratory, Golden, Colorado, USA.

Smallwood, K. S. 2007. Estimating wind turbine-caused bird mortality. Journal of Wildlife Management 71:2781–2791.

Smallwood, K. S. 2013. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. Wildlife Society Bulletin 37:19–33.

Smallwood, K. S. 2016. Bird and bat impacts and behaviors at old wind turbines at Forebay, Altamont Pass Wind Resource Area. Report CEC-500-2016-066. California Energy Commission Public Interest Energy Research program, Sacramento, USA.

Smallwood, K. S. 2017. Long search intervals under-estimate bird and bat fatalities caused by wind turbines. Wildlife Society Bulletin 41:224–230.

Smallwood, K. S., and D. A. Bell. 2020. Relating bat passage rates to wind turbine fatalities. Diversity 12(2):84.

Smallwood, K. S., D. A. Bell, B. Karas, and S. A. Snyder. 2013. Response to Huso and Erickson comments on novel scavenger removal trials. Journal of Wildlife Management 77:216–225.

Smallwood, K. S., D. A. Bell, S. A. Snyder, and J. E. DiDonato. 2010. Novel scavenger removal trials increase estimates of wind turbine-caused avian fatality rates. Journal of Wildlife Management 74:1089–1097.

Smallwood, K. S., D. A. Bell, E. L. Walther, E. Leyvas, S. Standish, J. Mount, and B. Karas. 2018. Estimating wind turbine fatalities using integrated detection trials. Journal of Wildlife Management 82:1169–1184.

Smallwood, K. S., and L. Neher. 2017. Comparing bird and bat use data for siting new wind power generation. Report CEC-500-2017-019. California Energy Commission Public Interest Energy Research program, Sacramento, USA.

Smallwood, K. S., L. Neher, and D. A. Bell. 2017. Siting to minimize raptor collisions: an example from the Repowering Altamont Pass Wind Resource Area. Pages 145–166 *in* M. Perrow, editor. Wildlife and wind farms—conflicts and solutions, volume 2. Pelagic Publishing, Exeter, United Kingdom.

Associate Editor: David King.