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Management and Conservation Article

Novel Scavenger Removal Trials Increase Wind Turbine–Caused Avian Fatality Estimates

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ABSTRACT For comparing impacts of bird and bat collisions with wind turbines, investigators estimate fatalities/megawatt (MW) of rated capacity/year, based on periodic carcass searches and trials used to estimate carcasses not found due to scavenger removal and searcher error. However, scavenger trials typically place ≥ 10 carcasses at once within small areas already supplying scavengers with carcasses deposited by wind turbines, so scavengers may be unable to process and remove all placed carcasses. To avoid scavenger swamping, which might bias fatality estimates low, we placed only 1–5 bird carcasses at a time amongst 52 wind turbines in our 249.7-ha study area, each carcass monitored by a motion-activated camera. Scavengers removed 50 of 63 carcasses, averaging 4.45 days to the first scavenging event. By 15 days, which corresponded with most of our search intervals, scavengers removed 0% and 67% of large-bodied raptors placed in winter and summer, respectively, and 15% and 71% of small birds placed in winter and summer, respectively. By 15 days, scavengers removed 42% of large raptors as compared to 15% removed in conventional trials, and scavengers removed 62% of small birds as compared to 52% removed in conventional trials. Based on our methodology, we estimated mean annual fatalities caused by 21.9 MW of wind turbines in Vasco Caves Regional Preserve (within Altamont Pass Wind Resource Area, California, USA) were 13 red-tailed hawks (*Buteo jamaicensis*), 12 barn owls (*Tyto alba*), 18 burrowing owls (*Athene cunicularia*), 48 total raptors, and 99 total birds. Compared to fatality rates estimated from conventional scavenger trials, our estimates were nearly 3 times higher for red-tailed hawk and barn owl, 68% higher for all raptors, and 67% higher for all birds. We also found that deaths/gigawatt-hour of power generation declined quickly with increasing capacity factor among wind turbines, indicating collision hazard increased with greater intermittency in turbine operations. Fatality monitoring at wind turbines might improve by using scavenger removal trials free of scavenger swamping and by relating fatality rates to power output data in addition to rated capacity (i.e., turbine size). The resulting greater precision in mortality estimates will assist wildlife managers to assess wind farm impacts and to more accurately measure the effects of mitigation measures implemented to lessen those impacts.

KEY WORDS bird fatalities, scavenger removal, scavenger swamping, Vasco Caves Regional Preserve, wind energy, wind turbine.

Wind energy generation has been expanding worldwide for 3 decades, but bird and bat impacts remain largely unknown at the population level and measures to minimize or reduce collisions with wind turbines unproven (Government Accountability Office 2005). Even in California's (USA) 580-megawatt (MW) Altamont Pass Wind Resource Area (APWRA), the world's first large wind farm and notorious for raptor fatalities, years of research has not contributed to detectable bird fatality reductions (Orloff and Flannery 1992, Howell 1997, Smallwood 2008, Smallwood and Karas 2009). Repowering the APWRA's aging, original wind turbines with modern turbines could provide opportunities to more carefully site and operate the new turbines based on lessons learned from past research. However, fatality rate estimates, which are necessary for assessing effectiveness of impact-reduction measures or repowering at wind resource areas worldwide, remain imprecise and potentially biased by common field methods (Smallwood 2007, Smallwood and Thelander 2008). Fatality rate estimates improve as biases are identified and either avoided or countered analytically.

A small repowering project has been proposed in Vasco Caves Regional Preserve, which is managed by East Bay Regional Park District (EBRPD) within the APWRA. The Preserve included 249.7 ha and 292.3 ha with and without wind turbines, respectively. It also supported a nesting population of burrowing owls (*Athene cunicularia*) and its large turbine-free area was intensively used by multiple other species of raptor. East Bay Regional Park District, facing a decision to renew wind farm leases and likely repowering, initiated fatality monitoring and related studies at existing wind turbines in June 2006 to assess ongoing impacts and possible repowering scenarios. Fatality monitoring was needed to estimate fatality rates, but fatality rates must be adjusted by estimates of scavenger removal rates to account for undetected fatalities during periodic fatality searches. Conventional scavenger removal trials might have produced biased estimates by placing groups of 10, 20, and more bird carcasses at once in open terrain study areas, exceeding the capacity of vertebrate scavengers to process and remove all evidence of the carcasses by trial's end (Smallwood 2007). This bias was termed scavenger swamping and can lead to low estimates of fatality rates (Smallwood 2007). We developed a novel scavenger removal trial that attempted to avoid scavenger swamping.

Our purpose was to accurately estimate fatality rates caused by wind turbines in our study area and to compare fatality rates adjusted by conventional scavenger removal rates and by those unbiased by scavenger swamping. Our objectives were to 1) avoid scavenger swamping by placing only 1–5 bird carcasses at a time at randomly chosen

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locations throughout the study area, 2) record scavenging events by placing each carcass in front of camera traps, 3) compare fatality rates adjusted by scavenger removal rates based on our novel trials and conventional trials, 4) compare fatality rates expressed as fatalities/MW of rated capacity and as fatalities/gigawatt-hour (GWh) of energy generated, and 5) test whether fatalities/GWh related to capacity factor, which is a measure of wind turbine efficiency (i.e., capacity factor = MW hr generation/(MW rated capacity)/hr available × 100%, where hr available are typically 8,760 hr/yr). Objectives 4 and 5 emerged toward the study's end, when Babcock and Brown Group supplied us with monthly wind-power generation totals for each of their wind turbines within Vasco Caves Regional Preserve, allowing us to test a hypothesis that less efficient turbines, characterized by more intermittent operations, could be more dangerous to birds and, hence, of highest priority for removal or repowering (Smallwood and Thelander 2004, 2008).

STUDY AREA

Our 249.7-ha study area was 6.4 km southwest of Byron, Contra Costa County, California, within the northern portion of the APWRA. In 2005 EBRPD acquired the property, which included leases to wind companies operating 62 wind turbines representing 21.9 MW of rated capacity. Babcock and Brown, Inc., owned 42 300-kilowatt (KW) Howden model turbines (James Howden and Company, Renfrew, Scotland) in the middle-to-western portions of the study area, and Northwind, Inc., owned 20 65-KW Nordtank model turbines (Nordtank Energy Group, Balle, Denmark) in the northeast portion. The study area included some existing easements for mitigation and conservation purposes and included habitat for San Joaquin kit fox (*Vulpes macrotis mutica*), burrowing owl, long-horned fairy shrimp (*Branchinecta longiantenna*), vernal pool fairy shrimp (*B. lynchi*), California tiger salamander (*Ambystoma californiense*), and California red-legged frog (*Rana aurora draytonii*).

Located in the Inner Coast Range geomorphic province and bordering the Central Valley province, elevations ranged 70 m to 300 m, and slopes were steep above several intermittent streams, springs, and stock ponds. Cattle grazed the study area for longer than a century before being replaced by sheep in late 2005. Soils were well-drained clays and silty clay loams. The major plant community was California Annual Grassland, dominated by nonnative annuals such as rye grass (*Lolium multiflorum*), wild oat (*Avena fatua*), soft chess (*Bromus hordeaceus*), and ripgut brome (*B. diandrus*). Native perennial grasses included creeping wild rye (*Leymus triticoides*), purple needlegrass (*Nassella pulchra*), and one-sided bluegrass (*Poa secunda*).

METHODS

Scavenger Removal Trial

We obtained avian carcasses for use in scavenger trials by salvaging carcasses resulting from bird collisions with automobiles, windows, and other manmade objects and from euthanized birds from wildlife rehabilitation centers or public institutions. We used the latter only if euthanasia was by nonpharmacological means under veterinarian directive. We stored all carcasses frozen prior to use.

From a pool of 10-m digital elevation model centroid points in a Geographic Information System (GIS) layer, we randomly selected 20 carcass placement sites within the 60-m fatality search radius around 52 wind turbines separated by 50 m within rows and farther between rows. Of the 20 placement sites, we only used 1–5 at once and we rotationally placed carcasses to avoid swamping any one turbine area with carcasses and possibly entraining scavengers to repeated food sources. We ran scavenger trials from 12 December 2006 through 28 September 2007. Each placed carcass represented one trial, and was monitored by an event-triggered camera trap (see below) for 21 days or until scavenger(s) removed the carcass, whichever came first. We monitored remaining carcasses weekly for carcass condition through 28 September 2007. We determined carcasses as removed when we could not locate body parts containing flesh or bone or ≥10 disarticulated feathers, or for any reason we felt a fatality searcher would no longer regard the remains as evidence of a fatality. Even if a carcass was removed, we monitored any trace evidence left behind until the study's end.

We marked carcasses to distinguish them from carcasses found during fatality searches by clipping 1 cm of the feather vane from the distal end of each rectrix and remige. We attached a shoat ring or cage clip to each leg at the tibiotarsus or tarsometatarsus and to each wing at the humerus. Shoat rings were steel wire about 3 mm in diameter and 15 mm, 22 mm, and 25 mm long. Cage clips were 8 × 22-mm strips of malleable metal. Usually, we used cage clips on small birds and shoat rings on larger birds, but we discontinued using shoat rings after several weeks because rings rusted quickly, and we discontinued attaching any metal markers to wings of carcasses by halfway through the study. We washed our hands before and after carcass handling, wore fresh latex gloves while handling and marking carcasses, and rinsed all marking tools with alcohol before use to avoid imparting human scent.

After placing a carcass, we mounted an infrared digital game camera (Silent Image [RECONYX, Inc., Holmen, WI], Model RM30, developed for Primos, Inc.) on an angle-iron post and faced the camera north to minimize direct sunlight on the camera's lens and infrared sensors (Fig. S1, <www.wildlife.journals.org>). Usually, we placed cameras 1–2 m from the carcass and <1 m above ground and tilted it slightly downward to center the carcass in the camera's field of view. We recorded the distance and bearing from the carcass to the closest wind turbine and took a position using a Trimble Geo XT or Magellan Meridian Gold Global Positioning System (GPS). We recorded carcass orientation relative to north, photographed the carcass using an object for scale, and then estimated effective vegetation height around the carcass using a 25.4 × 40.6-cm board marked off in 2.54 × 2.54-cm alternating black and white squares.

We trained one camera on each placed carcass, deploying ≤ 5 cameras at once. Animal intrusion into an infrared field triggered a camera, which took 5 photos at 1-second intervals upon each trigger event, with a camera recovery period of 1 second between trigger events. We checked cameras weekly, but we checked them biweekly during July and August when the cameras' compact flash (CF) cards often filled in 3–4 days due to wind-induced grass movement. The CF memory cards of 256 megabytes (MB) and 512 MB stored up to 5,000 and 10,000 photos, respectively. Images were stamped with time, date, temperature, and moon phase.

During weekly to twice weekly carcass checks, we recorded time and date and whether the carcass was intact (noting feather loss or soft-tissue loss), dismembered, feathers only, or removed. We photographed and described the condition and location of each body part affected by vertebrate scavenging throughout the removal trial or until no evidence remained. When carcass remains were not evident at placement sites, we thoroughly searched the area within a 20-m radius and visually scanned within 60 m of the nearest turbine. If we found no feathers or other carcass remains, we designated the carcass as removed. In cases where exact times of scavenging events were not captured by cameras due to equipment failure or other reasons, we estimated time to scavenging event as the midpoint between field checks of the carcass site, never >7 days.

We employed 2 carcass-free controls, one using a camera trained on a placed black rubber object about the size of a European starling (*Sturnus vulgaris*) and the other with no object. We interspersed these control trials in time and space with the regular trials. Also, during control trials we followed the same field procedures and camera set-up protocols as if we were placing carcasses to control for potential scavenger cues caused by time spent at the site, patterns of human behavior, and presence of vehicles.

Fatality Searches

We searched for bird carcasses from 16 June 2006 through 26 September 2007, every 2 weeks during the first 13 months of the study, then monthly during the last 3 months. Searchers walked parallel paths 6–8 m apart, 0–60 m from the axis of the wind turbine row. Search areas included all wind turbines regardless of their operational status, except for 7 derelict turbines on the west side of the study area and 2 vacant Howden towers that had not operated in many years.

We took ≥ 2 photos of each carcass, including an engineers' survey card for scale. We recorded species, sex, age class, discovery date, searcher's name, and whether the carcass was discovered during a standard search or incidental to travel or other study activities. We determined cause of death as blade strike, entrapment in the turbine (typically indicated by oiled feathers), collision with electric distribution lines, electrocution on electric distribution pole, auto collision, predation, unknown, or specified other cause. We described the injury(s) and noted carcass condition and surroundings.

Searchers estimated number of days since death and rated carcass articulation 1–5, where 1 indicated complete disassembly of the skeleton and 5 indicated a completely intact, articulated skeleton. The articulation rating represented decay, not dismemberment caused directly by collision, electrocution, or predation. We numbered each body part, described it, reported distance and bearing to the nearest wind turbine, and reported photo numbers. We subsequently monitored each body part. Monitoring data included revisit dates, photo numbers, carcass condition, and color. Upon each visit we described the carcass as stiff or loose, flesh as fresh (i.e., no decay), gooey, or dried; enamel as present or absent on culmen, talons, and feathers; bones as exposed or not; feather color as original, intermediate, bleached, or not applicable; and flies or beetles present as larvae, pupae, or adults. For skeletal remains, we monitored presence, condition, width, and length of the skull, sternum, pelvis, and of each coracoid, scapula, humerus, ulna, radius, carpometacarpus, femur, tibiotarsus, and tarsometatarsus. We classified bone condition as broken, complete, smooth, or weathered.

We estimated fatality rates only from carcasses ≤ 90 days since death. We determined carcasses were older than 90 days if flesh was gone, culmen and talon enamel had separated from bone, and bones and feathers were bleached, but we also used judgment because carcass decomposition varies with environmental conditions. Presence of blood generally indicated <4 days since death, but rigor mortis, odor, and presence of insect larvae varied with temperature, so we interpreted all these indicators in the environmental context to estimate time since death. We assumed the wind turbine caused the fatality when we found the carcass within the search radius, unless evidence indicated another cause of death.

To assess potential levels of background mortality and crippling bias possibly ongoing in the APWRA, we also recorded bird and bat fatalities found while mapping mammal burrow systems (Smallwood et al. 2009). In late summer to early winter 2006, we mapped mammal burrow systems on foot along transects 12–15 m apart across 381 ha, overlapping all fatality search areas around wind turbines and large areas without wind turbines. In autumn 2007, we mapped burrows in 12 randomly selected plots covering 87.6 ha. We photographed, described, and logged positions with a GPS of carcasses found during burrow mapping.

Analytical Methods

For each wind turbine row, we expressed unadjusted fatality rate (F_U) as the number of fatalities/MW/year, where MW was the sum of the rated power output of the wind turbines composing a row of turbines. For those turbines for which the owners (Babcock & Brown Group) provided power output data, we also expressed F_U as the number of fatalities/GWh, where GWh was the electric energy generated by each Howden wind turbine during the study and averaged across the turbines in the row. We defined the wind turbine row as our study unit because we sometimes could not determine which turbine in the row killed the bird. We added 15 days to the number of years used in the fatality rate estimate, to represent the time period when carcasses could have accumulated before the first search (Smallwood and Thelander 2008).

We adjusted fatality rates (F_A) for carcasses not found due to searcher detection error and scavenger removals as

$$F_A = F_U / (p \times R_C), \tag{1}$$

where p was the proportion of fatalities found by searchers and R_C was the estimated cumulative proportion of carcasses remaining since the last fatality search, assuming wind turbines deposit carcasses at a steady rate through the search interval. We averaged both p and R_C from trials throughout the United States (Smallwood 2007). We also estimated new R_C values based on our novel scavenger removal trials. To estimate R_C, we first used least-squares regression to develop predictive models of the proportions of bird carcasses remaining each day into a fatality search rotation. We developed models for groups of species that were typically small-bodied (i.e., <38 cm body length) or medium- or large-bodied (>38 cm length) and whether raptors or nonraptors. We also developed models from our new scavenger removal trials for groups defined by season of carcass placement (i.e., winter and early spring vs. summer), and we estimated adjusted fatality rates separately for these seasons. We used model predictions to calculate R_C (Smallwood 2007):

$$R_C = \frac{\sum_{i=1}^{I} R_i}{I}, \tag{2}$$

where R_i was the model-predicted proportion of carcasses remaining by the ith day following the initiation of a scavenger removal trial, and I was duration of the scavenger removal trial.

For fatality rate estimates based on conventional scavenger removal trials, we used R_C values from Smallwood (2007; Appendix) for the corresponding search interval (d) and appropriate species group (i.e., small nonraptors, medium and large nonraptors, and rock pigeons [*Columba livia*]). We calculated standard error of the adjusted fatality rate (SE[F_A]) using the delta method (Goodman 1960).

RESULTS

Scavenger Removals

We determined the fates of 63 of 64 avian carcasses placed before remote cameras (Table S1, <www.wildlifejournals.org>) and recorded scavenger visits to 65% of carcasses (Figs. S2 and S3, <www.wildlifejournals.org>). Scavengers removed 50 carcasses (79%) from search areas, including all remains of 37 carcasses (59%) and enough of the remains of 8 carcasses (13%) to probably not have been determined as fatalities by fatality searchers. By 21 days after placement, which was the trial duration we used for predictive model development, scavengers removed 73% of all carcasses. However, of 14 carcasses placed during winter and early spring, scavengers removed only 4 (29%) within 21 days.

Among all carcasses, the first scavenging event averaged 4.45 days (SD = 5.69) since placement (Table S1, <www.wildlifejournals.org>). Only an American crow (*Corvus brachyrhynchos*) carcass remained unvisited until after 30 days (Table S1, <www.wildlifejournals.org>). Days until first scavenging event did not relate with species' body mass, suggesting that carcass size did not affect how fast scavengers detected carcasses. Nevertheless, carcass removal rates were slower for large-bodied species than for small-bodied species (Fig. 1; Fig. S4, <www.wildlifejournals.org>).

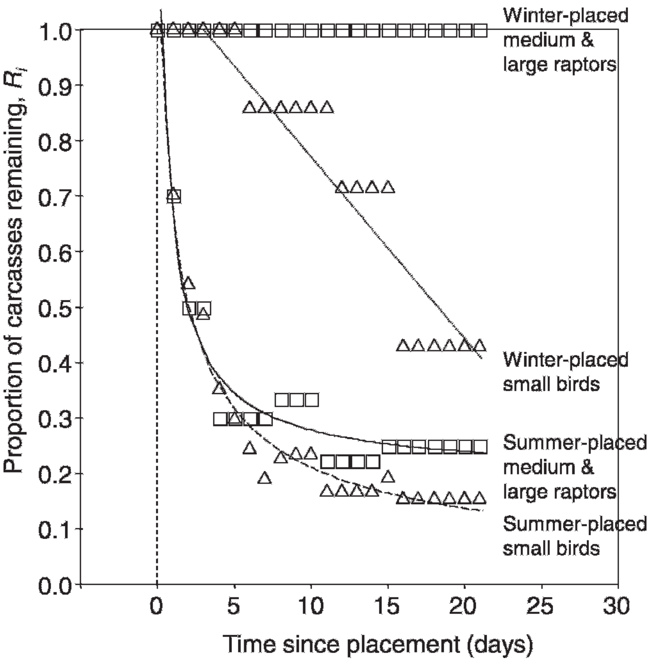

Figure 1. Proportions of carcasses remaining as functions of days since placement for small nonraptor birds (triangles) placed in summer (dashed line) and winter (dotted line) and for medium and large raptors (squares) placed in summer (solid line) and winter (aligned along top of graph) during 12 December 2006 to 28 September 2007 in Vasco Caves Regional Preserve, California, USA.

Power and inverse functions were the least-squares regression models that best fit relationships between proportions of carcasses remaining and days into the scavenger removal trial (Table 1). No model was fit to data representing medium and large raptor removals during winter-time placement because none were removed until after the 21-day trial duration. Average proportions of carcasses remaining, assuming steady rates of carcass deposition, were lower than those based on conventional scavenger removal trials (Fig. 2; Appendix).

Cameras set as controls produced no photos of scavengers during 3 weeks of trials without a carcass. Cameras produced no photos during 4 weeks of trials with an inorganic object placed in front of the camera.

Fatality Rates at Wind Turbines

We found carcasses of 59 birds and 1 bat (Table 2), but only 18 birds (31%) and the bat during standard fatality searches. We found the other 41 birds incidentally while performing other related research activities, and we included 7 of these in fatality rate estimation because we found them within the standard fatality search areas. One fatality had been found by wind company personnel as documented in the wind companies' Wildlife Reporting and Response System.

Table 1. Least-squares regression models fit to the proportion of placed carcasses remaining each day into scavenger removal trials during 2006–2007 in Vasco Caves Regional Preserve, California, USA, where *a* and *b* represented the model's intercept and slope parameters, respectively.

Proportion of carcasses remaining	Season placed	Model	*a*	*b*	r^2	SE	*P*
Small birds	Summer	Power	1.010	−0.654	0.95	0.12	<0.001
	Winter	Linear	1.132	−0.033	0.90	0.07	<0.001
	All	Power	1.058	−0.523	0.96	0.09	<0.001
Medium-large raptors	Summer	Inverse	0.201	0.843	0.95	0.04	<0.001
	All	Inverse	0.492	0.520	0.93	0.03	<0.001
All carcasses	Summer	Inverse	0.151	0.930	0.95	0.05	<0.001
	Winter	Power	1.161	−0.143	0.85	0.06	<0.001
	All	Power	0.928	−0.353	0.94	0.04	<0.001

Adjusted by conventional scavenger removal rates, estimated mean annual fatality rates at wind turbines in Vasco Caves Regional Preserve were 4.6 red-tailed hawks (*Buteo jamaicensis*), 4.2 barn owls (*Tyto alba*), 18.1 burrowing owls (*Athene cunicularia*), 28.3 total raptors, and 59.3 total birds (Table 3). Adjusted by new scavenger removal rates, estimated mean annual fatality rates at these wind turbines were 13.4 red-tailed hawks, 12.3 barn owls, 17.7 burrowing owls, 47.5 total raptors, and 98.7 total birds (Table 3).

Adjusted by new scavenger removal rates, we estimated Howden model wind turbines caused about the same annual number of fatalities regardless of whether we calculated fatality rates from MW of rated capacity or GWh of energy actually produced (Table 4). However, fatalities/GWh generated in Howden turbine rows declined quickly with increasing capacity factor (Fig. 3).

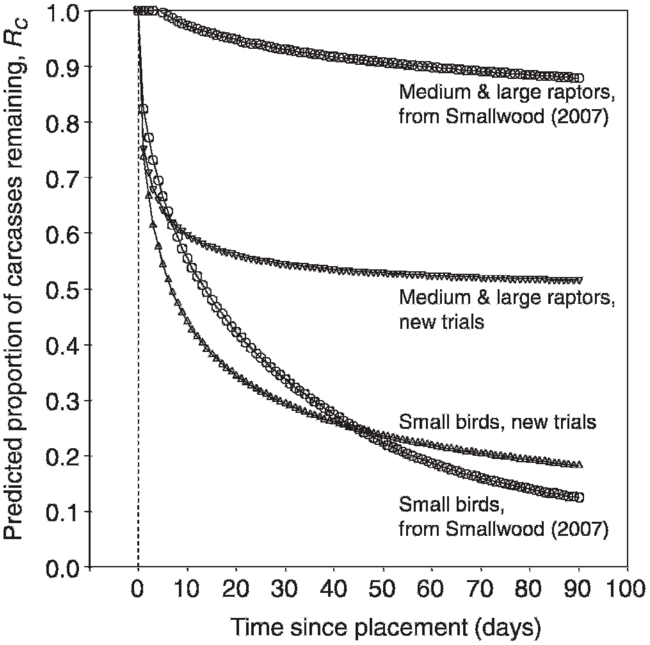

Figure 2. Predicted proportions of bird carcasses remaining each day into a fatality search rotation, R_C, assuming a steady rate of bird collisions at wind turbines (Smallwood 2007). Predicted proportions of carcasses remaining each day into a fatality search rotation declined at similar rates between small birds placed in our new scavenger removal trials (upward triangles) in 2006–2007 in Vasco Caves Regional Preserve, California, USA, and in conventional trials across the United States (lower set of circles), but declined more quickly for medium- and large-sized raptors in our trials (downward triangles) as compared to conventional trials (upper set of circles).

Outside of standard searches, we found a loggerhead shrike (*Lanius ludovicianus*) carcass under an electric distribution line servicing wind turbines, and we assumed the bird died after striking the line. We found carcasses of 2 barn owls and 1 burrowing owl that were dragged from the direction of wind turbines, but we did not include them in fatality rate estimates because 2 of the feather trails were to turbines outside our study and the other did not extend into the fatality search area. We found a severely injured golden eagle (*Aquila chrysaetos*) atop the study area's largest hill, 558 m and 588 m from the nearest Nordtank and Howden wind turbines, respectively. The eagle's injury was typical of wind turbine blade strikes, consisting of a compound fracture to the right radius and ulna. Three weeks after our study we captured an emaciated red-tailed hawk about 500 m from the nearest wind turbine. This hawk also had a compound fracture to the right radius and ulna. We found carcasses of 5 other birds that we thought likely transported themselves away from wind turbines before perishing from injuries, including a red-tailed hawk, a ferruginous hawk (*Buteo regalis*), a Cooper's hawk (*Accipter cooperii*), and an American kestrel (*Falco sparverius*). However, we were uncertain about what killed these birds or how they ended up where we found them. We assumed another 22 bird carcasses we found incidentally or during mammal burrow surveys to have represented background mortality, but we had no way of determining how many had died of natural causes, traveled from wind turbines on their own after being struck, or were transported from wind turbines by vertebrate scavengers.

DISCUSSION

We remain uncertain whether our efforts to avoid scavenger swamping succeeded entirely because we do not know how many volitionally placed carcasses was too many for the scavengers to process and remove. Experimentally varying numbers of placed carcasses might reveal how many carcasses are too many in a particular project area, but such an experiment would require much more space and time than we had available to prevent confounding. As it was, our placement of carcasses automatically exceeded normal deposition rates by wind turbines because our study did not modify ongoing fatality rates. How many additional carcasses is enough to swamp scavengers remains an open question, but at a minimum our trial lessened the effects of scavenger swamping and probably improved accuracy of our fatality rate estimates.

Table 2. Species found dead or mortally wounded in the study area and number used to estimate wind turbine-caused fatality rates in 2006–2007, Vasco Caves Regional Preserve, California, USA.

Common name	No. dead birds found during:				No. used in fatality rate estimation
	Total	Standard search	Incidental	Burrow surveys	
Bat sp.	1	1	0	0	
Golden eagle	1	0	1	0	0
American kestrel	1	0	1	0	0
Red-tailed hawk	8	2	5	1	4
Ferruginous hawk	1	0	1	0	1
Cooper's hawk	1	0	0	1	0
White-tailed kite	1	0	0	1	0
Great horned owl	2	0	0	2	0
Barn owl	12	1	1	10	3
Burrowing owl	13	8	1	4	10
Rock pigeon (*Columba livia*)	5	3	0	2	2
Say's phoebe (*Sayornis saya*)	1	0	0	1	0
White-throated swift (*Hirundapus caudacutus*)	1	1	0	0	1
Cliff swallow (*Hirundo pyrrhonota*)	1	1	0	0	1
Loggerhead shrike	2	0	0	2	0
European starling	2	0	2	0	2
Common raven	2	0	1	1	0
Western meadowlark (*Sturnella neglecta*)	3	1	0	2	1
Passerine spp.	2	1	0	1	0
All raptors	40	11	10	19	18
All birds	59	18	13	28	25

Our new scavenger removal rates led to higher estimates of fatality rates for most species and groups (Table 5). Using the old removal rates in Table 5, however, we compared our estimated fatality rates in Vasco Caves Regional Preserve to those derived from Alameda County's concurrent fatality monitoring at 2,650 (53%) of the APWRA's old-generation wind turbines (Smallwood and Karas 2009). Our mean fatality rates were lower than the APWRA-wide rates by 53% for red-tailed hawk, 75% for burrowing owl, 58% for all raptors, and 28% for all birds. A possible explanation for differences might be that most wind turbines in our study area, though old-generation, were >3 times larger in rated capacity than most of the rest of the APWRA's wind turbines.

Consistent with other fatality estimates in the APWRA, ours herein were undoubtedly biased low by crippling bias as evidenced by wounded birds we recovered outside of the turbine search areas. One golden eagle walked ≥500 m across a ravine and up a very steep hill from the closest turbines it could have collided with, and a red-tailed hawk had covered at least this distance. One of us (D. A. Bell) participated in the recovery of 2 other wounded golden eagles in the APWRA, showing this species' resilience once grounded by wing injuries. We found one male golden eagle with a broken but not severed right manus 414 m from the closest turbine; the eagle flew and ran another 450 m before capture. Another golden eagle with a severed right manus evaded capture for ≥8 days. Medical examination of the latter eagle, along with photographs of a severed right manus found 28 days prior to its capture, suggested that it survived on the ground for ≥28 days. Whereas some unknown portion of carcasses we found incidentally was undoubtedly caused by predation or other natural causes, wind turbines likely caused some if not many of the

Table 3. Estimates of annual fatalities adjusted by conventional scavenger removal trials conducted across the United States (Smallwood 2007) and new trials intended to prevent scavenger swamping during 2006–2007 in Vasco Caves Regional Preserve, California, USA. Estimates apply to 54 operating wind turbines in 11 rows, totaling 12.52 MW of rated capacity, and include lower and upper confidence limits (LCL and UCL, respectively) of 80% confidence intervals.

	Adjusted annual fatalities and 80% CI					
	Old scavenging rates			New scavenging rates		
Species	$\bar{x}$	LCL	UCL	$\bar{x}$	LCL	UCL
Red-tailed hawk	4.6	−0.7	9.9	13.4	−2.2	29.1
Ferruginous hawk	1.4	−0.4	3.2	4.1	−1.2	9.3
Barn owl	4.2	0.7	7.7	12.3	−0.1	25.2
Burrowing owl	18.1	6.7	29.5	17.7	−0.8	36.1
Rock pigeon	2.8	0.2	5.4	4.9	−1.5	11.2
Cliff swallow	5.7	−2.1	13.6	9.5	−3.8	22.8
European starling	10.9	−1.3	23.1	18.0	−3.0	39.0
Western meadowlark	2.9	−1.0	6.8	4.7	−1.9	11.4
White-throated swift	8.6	−3.1	20.3	14.2	−5.7	34.1
All raptors	28.3	6.3	50.3	47.5	−4.7	99.7
All birds	59.3	−1.0	119.5	98.7	−20.6	218.1

Table 4. Estimates of annual fatalities caused by 34 operating Howden wind turbines (James Howden and Company, Renfrew, Scotland) in 7 rows, totaling 11.22 megawatts (MW) of rated capacity during 2006–2007 in Vasco Caves Regional Preserve, California, USA, calculated from fatalities/MW of rated capacity/year and from fatalities/gigawatt-hour (GWh) generated during the study. We adjusted all estimates by novel scavenger removal trials intended to prevent scavenger swamping, and include lower and upper confidence limits (LCL and UCL, respectively) of 80% confidence intervals.

	Adjusted annual fatalities and 80% CI					
	Based on per-MW rates			Based on per-GWh rates		
Species	$\bar{x}$	LCL	UCL	$\bar{x}$	LCL	UCL
Red-tailed hawk	1.7	−0.5	4.0	0.8	−0.2	1.8
Ferruginous hawk	5.6	−1.6	12.9	5.5	−1.6	12.5
Barn owl	6.4	−1.9	14.7	4.3	−1.2	9.8
Burrowing owl	24.3	−0.5	49.1	29.5	−1.4	60.4
Rock pigeon	6.7	−2.0	15.5	8.2	−2.4	18.9
Cliff swallow	13.0	−5.2	31.2	6.8	−2.7	16.4
European starling	5.2	−2.1	12.4	3.7	−1.5	8.9
Western meadowlark	6.5	−2.6	15.6	5.9	−2.3	14.0
All raptors	38.1	−4.5	80.7	40.1	−4.4	84.6
All birds	69.5	−16.3	155.4	64.7	−13.4	142.9

fatalities. Scavengers likely carried some of these birds from the wind turbines to locations where we found dropped carcasses, consistent with the high scavenger removal rates we recorded. As additional evidence of scavenger carries, we found a white-tailed kite (*Elanus leucurus*) carcass on an animal trail and multiple other carcasses under trees, a fence post, and under rock overhangs, all places where vertebrate scavengers would likely bring food. However, we still do not know what proportion of incidental carcasses represented background mortality, crippling bias, or scavenger removal from wind turbines.

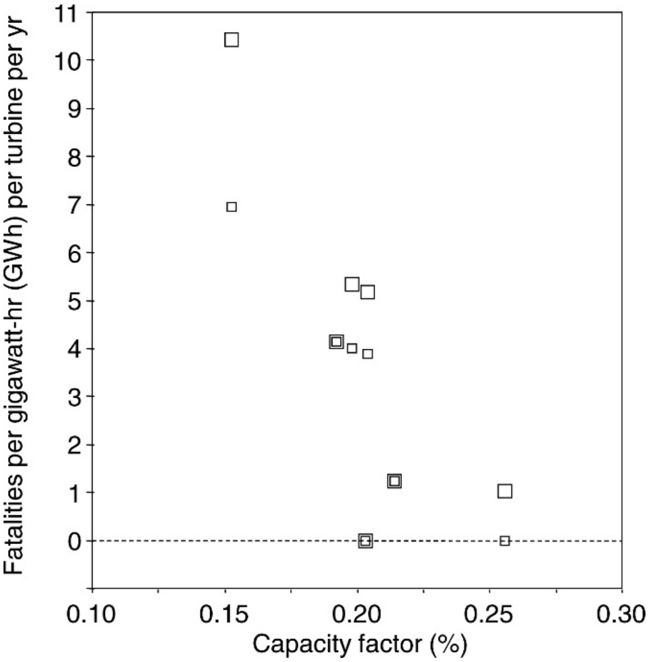

Figure 3. Fatality rates of raptors (small squares) and all birds (large squares) decreased with increasing capacity factor of all operable wind turbines in the turbine row during 2006–2007 in Vasco Caves Regional Preserve, California, USA. Note that these capacity factors were larger than annual capacity factors, because they were based on 2 summers, a season of peak power generation. The Howden turbines (James Howden and Company, Renfrew, Scotland) in our study achieved a capacity factor of 11.8% in 2006.

Camera traps revealed the vertebrate scavenger guild in our study area, including coyote (*Canis latrans*), raccoon (*Procyon lotor*), striped skunk (*Mephitis mephitis*), common raven (*Corvus corax*), red-tailed hawk, and great horned owl (*Bubo virginianus*). Other species visiting carcasses included American badger (*Taxidea taxus*), turkey vulture (*Cathartes aura*), and California ground squirrel (*Spermophilus beecheyi*). Cameras revealed a coyote urinating on a red-tailed hawk carcass 2 days after placement and scent-rolling on it 3 other times; this carcass was not removed until 31 days, suggesting that mammalian carnivores might sometimes use large raptor carcasses as territory markers. Cameras also photographed a coyote swallowing a California quail (*Callipepla californica*) whole, coyotes and common ravens removing carcasses without leaving a trace, and on-site feeding on carcasses resulting in carcass parts remaining to the end of the trial. We also saw photos of potential scavengers (i.e., coyotes, American badgers, and a California ground squirrel) staring at the camera, including at 3 carcasses not removed by trial's end, suggesting that camera traps might sometimes discourage mammalian scavengers from removing carcasses. (Other scavenger trials have used flags or other carcass markers, which might have the same effect.)

The Reconyx cameras sometimes failed to record scavenger visits and carcass removals due to battery failures, incorrect time stamps on CF memory cards, and unsuitable sensitivity levels ($n = 5$). Missed recordings might have resulted from scavengers removing carcasses between photos or during the camera-recovery phase, from cameras firing until memory cards filled or batteries depleted due to vegetation movement in high winds or due to reflected sunlight or ambient heat flooding trigger sensors. Nevertheless, set up to avoid these problems, event-triggered camera traps offer researchers more informative means to perform scavenger removal trials for generating more accurate fatality rate estimates at wind resource areas worldwide.

MANAGEMENT IMPLICATIONS

Many estimates of scavenger removal rates prior to our study were likely biased low due to scavenger swamping, so

Table 5. Estimates of wind-turbine–caused fatality rates adjusted by conventional scavenger removal trials conducted across the United States (Smallwood 2007) and new trials intended to prevent scavenger swamping during 2006–2007 in Vasco Caves Regional Preserve, California, USA. Estimates were from 54 operating wind turbines in 11 rows, totaling 12.52 megawatts of rated capacity.

Species	Adjusted fatality rate (deaths/megawatt/yr)				Fatality rate change (%) from old to new scavenging rates
	Old scavenging rates		New scavenging rates		
	$\bar{x}$	SE	$\bar{x}$	SE	
Red-tailed hawk	0.367	0.333	1.072	0.976	+192
Ferruginous hawk	0.111	0.111	0.324	0.326	+192
Barn owl	0.337	0.217	0.984	0.802	+192
Burrowing owl	1.445	0.710	1.411	1.147	−2
Rock pigeon	0.225	0.163	0.388	0.393	+73
Cliff swallow	0.459	0.487	0.757	0.828	+65
European starling	0.872	0.760	1.437	1.309	+65
Western meadowlark	0.230	0.244	0.379	0.414	+65
White-throated swift	0.688	0.730	1.135	1.240	+65
All raptors	2.259	2.097	3.791	3.252	+68
All birds	4.733	5.742	7.886	7.436	+67

managers should reconsider earlier estimates at wind farms throughout the United States and should pursue additional trials that limit carcass placement to more realistically simulate deposition rates from wind turbines and that place carcasses of small birds instead of larger surrogate species. Previously reported estimates of avian fatality rates in the APWRA and elsewhere should be adjusted upwards. Given that >50% of all summer-placed bird carcasses were removed in <10 days, fatality search intervals should be ≤14 days. Also, we found that fatalities/GWh increased at wind turbines with lower capacity factors, indicating that fatalities might be lessened by relocating less efficient turbines to sites where they will operate more often or by repowering them with modern, more efficient turbines. Power output data should be routinely provided to fatality monitors at wind resource areas.

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Appendix. Predicted percentages of cumulative carcasses remaining within search areas of wind turbines, based on volitionally placed carcasses at random locations and at intervals intended to prevent scavenger swamping during 2006–2007 in Vasco Caves Regional Preserve, California, USA. We converted all predicted values <0 to 0 and all values >1 to 1, and we presented predictions daily through 30 days and every third day thereafter to 90 days. All predictions were from Table 1.

	Predicted carcasses remaining (%)								
	Placed in winter			**Placed in summer**			**Placed all seasons**		
Days since trial start	**Small birds**	**Medium and large raptors**	**All bird species**	**Small birds**	**Medium and large raptors**	**All bird species**	**Small birds**	**Medium and large raptors**	**All bird species**
1	1.000	1.000	1.000	0.642	0.623	0.616	0.736	0.753	0.727
2	1.000	1.000	0.996	0.567	0.553	0.538	0.666	0.709	0.678
3	1.000	1.000	0.981	0.514	0.506	0.487	0.615	0.680	0.642
4	1.000	1.000	0.967	0.474	0.472	0.449	0.575	0.659	0.613
5	0.993	1.000	0.953	0.442	0.446	0.421	0.543	0.643	0.589
6	0.984	1.000	0.941	0.415	0.425	0.398	0.516	0.631	0.568
7	0.972	1.000	0.929	0.393	0.408	0.379	0.493	0.620	0.551
8	0.959	1.000	0.919	0.374	0.394	0.364	0.474	0.611	0.535
9	0.945	1.000	0.910	0.357	0.382	0.350	0.456	0.604	0.522
10	0.931	1.000	0.901	0.342	0.372	0.339	0.441	0.597	0.509
11	0.916	1.000	0.893	0.329	0.362	0.329	0.427	0.592	0.498
12	0.901	1.000	0.886	0.318	0.354	0.320	0.414	0.587	0.488
13	0.886	1.000	0.879	0.307	0.347	0.312	0.403	0.582	0.478
14	0.871	1.000	0.872	0.297	0.341	0.305	0.392	0.578	0.470
15	0.855	1.000	0.866	0.289	0.335	0.299	0.383	0.575	0.462
16	0.840	1.000	0.860	0.280	0.330	0.293	0.374	0.572	0.454
17	0.824	1.000	0.855	0.273	0.325	0.287	0.366	0.569	0.447
18	0.808	1.000	0.850	0.266	0.321	0.283	0.358	0.566	0.440
19	0.792	1.000	0.845	0.259	0.317	0.278	0.351	0.563	0.434
20	0.776	1.000	0.840	0.253	0.313	0.274	0.344	0.561	0.428
21	0.760	1.000	0.836	0.248	0.309	0.270	0.338	0.559	0.423
22	0.744	1.000	0.831	0.242	0.306	0.267	0.332	0.557	0.417
23	0.728	1.000	0.827	0.237	0.303	0.263	0.326	0.555	0.412
24	0.712	1.000	0.823	0.233	0.300	0.260	0.320	0.553	0.408
25	0.696	1.000	0.820	0.228	0.297	0.257	0.315	0.552	0.403
26	0.680	1.000	0.816	0.224	0.295	0.254	0.310	0.550	0.399
27	0.664	1.000	0.812	0.220	0.293	0.252	0.306	0.549	0.395
28	0.647	1.000	0.809	0.216	0.290	0.249	0.301	0.547	0.391
29	0.631	1.000	0.806	0.212	0.288	0.247	0.297	0.546	0.387
30	0.615	1.000	0.802	0.209	0.286	0.245	0.293	0.545	0.383
33	0.566	0.800	0.793	0.199	0.281	0.239	0.282	0.541	0.373
36	0.519	0.800	0.785	0.191	0.276	0.234	0.272	0.539	0.363
39	0.479	0.800	0.778	0.183	0.272	0.229	0.263	0.536	0.355
42	0.445	0.800	0.771	0.176	0.268	0.225	0.255	0.534	0.347
45	0.416	0.800	0.764	0.170	0.265	0.222	0.247	0.532	0.340
48	0.390	0.800	0.758	0.164	0.262	0.218	0.241	0.530	0.334
51	0.367	0.800	0.752	0.159	0.260	0.215	0.235	0.528	0.328
54	0.346	0.800	0.747	0.155	0.257	0.213	0.229	0.527	0.322
57	0.328	0.800	0.742	0.150	0.255	0.210	0.223	0.526	0.317
60	0.312	0.800	0.737	0.146	0.253	0.208	0.219	0.524	0.312
63	0.297	0.800	0.733	0.142	0.251	0.206	0.214	0.523	0.307
66	0.283	0.800	0.728	0.139	0.250	0.204	0.210	0.522	0.303
69	0.271	0.800	0.724	0.136	0.248	0.203	0.205	0.521	0.299
72	0.260	0.800	0.720	0.133	0.247	0.201	0.202	0.520	0.295
75	0.249	0.800	0.716	0.130	0.245	0.200	0.198	0.519	0.291
78	0.240	0.800	0.713	0.127	0.244	0.198	0.194	0.519	0.288
81	0.231	0.800	0.709	0.124	0.243	0.197	0.191	0.518	0.284
84	0.223	0.800	0.706	0.122	0.242	0.196	0.188	0.517	0.281
87	0.215	0.800	0.703	0.120	0.241	0.194	0.185	0.517	0.278
90	0.208	0.800	0.700	0.117	0.240	0.193	0.182	0.516	0.275