Bird Mortality in the Altamont Pass Wind Resource Area, California

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ABSTRACT The 165-km^2 Altamont Pass Wind Resource Area (APWRA) in west-central California includes 5,400 wind turbines, each rated to generate between 40 kW and 400 kW of electric power, or 580 MW total. Many birds residing or passing through the area are killed by collisions with these wind turbines. We searched for bird carcasses within 50 m of 4,074 wind turbines for periods ranging from 6 months to 4.5 years. Using mortality estimates adjusted for searcher detection and scavenger removal rates, we estimated the annual wind turbine–caused bird fatalities to number 67 (80% CI = 25–109) golden eagles (*Aquila chrysaetos*), 188 (80% CI = 116–259) red-tailed hawks (*Buteo jamaicensis*), 348 (80% CI = −49 to 749) American kestrels (*Falco sparverius*), 440 (80% CI = −133 to 1,013) burrowing owls (*Athene cunicularia hypugaea*), 1,127 (80% CI = −23 to 2,277) raptors, and 2,710 (80% CI = −6,100 to 11,520) birds. Adjusted mortality estimates were most sensitive to scavenger removal rate, which relates to the amount of time between fatality searches. New on-site studies of scavenger removal rates might warrant revising mortality estimates for some small-bodied bird species, although we cannot predict how the mortality estimates would change. Given the magnitude of our mortality estimates, regulatory agencies and the public should decide whether to enforce laws intended to protect species killed by APWRA wind turbines, and given the imprecision of our estimates, directed research is needed of sources of error and bias for use in studies of bird collisions wherever wind farms are developed. Precision of mortality estimates could be improved by deploying technology to remotely detect collisions and by making wind turbine power output data available to researchers so that the number of fatalities can be related directly to the actual power output of the wind turbine since the last fatality search. (JOURNAL OF WILDLIFE MANAGEMENT 72(1):215–223; 2008)

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The Altamont Pass Wind Resource Area (APWRA) began operations during the 1980s and by 1998 included about 5,400 wind turbines of various models (Fig. 1). The rated capacities of these wind turbines ranged from 40 kW to 400 kW but most ranged from 100 kW to 150 kW. If the APWRA were to generate the 580 MW of capacity for which the wind farm was rated, it would have supplied emission-free electric power sufficient for the needs of about 230,000 homes. However, beginning with the first installations, these wind turbines also killed birds that flew into the rotating blades, most species of which are protected by the Migratory Bird Treaty Act (MBTA) and some of which are protected by other state and federal laws (Table 1). Accurate estimates of the APWRA's impacts on birds are needed to decide how much effort to direct towards mitigating the impacts and to alert decision-makers of the potential impacts on birds that could be caused by other wind farms.

Annual deaths previously attributed to the APWRA's wind turbines included 28–43 golden eagles (*Aquila chrysaetos*) reported by the wind power companies (Hunt et al. 1999). Scientific estimates during 1989 and 1990, respectively, were 81 ± 112 (95% CI) and 0 ± 112 golden eagles, 121 ± 136 and 104 ± 234 medium-sized raptors such as Buteo hawks, 227 ± 416 and 82 ± 451 American kestrels (*Falco sparverius*), and 429 and 186 raptors of all species (Orloff and Flannery 1992). Estimates of annual mortality during 1998–2003 were 76–116 golden eagles, 881–1,300 raptors, and 1,767–4,721 birds (Smallwood and Thelander 2004, 2005), though these estimates were admittedly crude.

Our first objective was to estimate mortality, which could serve as a comparative baseline to assess the effectiveness of future mitigation measures and to assess potential impacts of other proposed wind farm projects. Mortality estimates also may help with formulation of compensatory mitigation and might contribute to cumulative impacts analysis of other proposed activities in the region. Our second objective was to critically assess the precision of estimates to identify needed improvements in methodology applied to mortality monitoring. This assessment is needed because mortality estimates are being compared among wind farms for hypothesis testing (Madders and Whitfield 2006, Barclay et al. 2007) and for assessing the relative magnitude of impacts caused by wind turbines (Erickson et al. 2001), even though most estimates compared have not been peer reviewed or examined closely for consistency in methods and assumptions.

STUDY AREA

The APWRA encompassed about 165 km^2 of hilly terrain covered mostly by nonnative, annual grasses in eastern Alameda and southeastern Contra Costa Counties, California, USA (Fig. 1). Grasses and forbs grew during the rainy months of January through March, and were dead or dormant by early June. Elevations ranged from 78 m to 470 m above mean sea level. Ridges and hills generally extended northwest to southeast, bisected by intermittent streams and ravines. Cattle grazers held most of the land, leasing out wind energy rights to wind power companies.

Wind turbines were arranged in rows of up to 62 turbines, typically along ridge crests (i.e., peaks of the ridge features)

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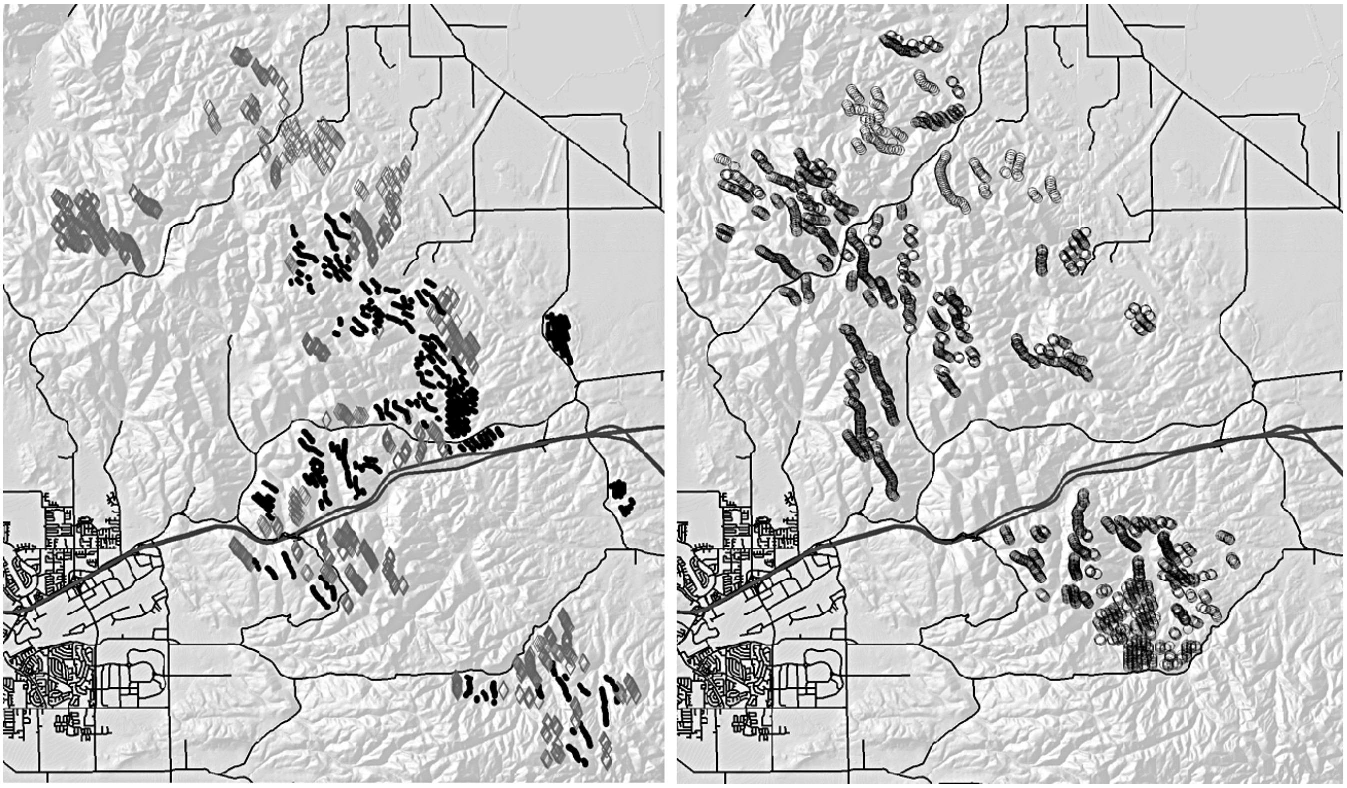

Figure 1. Relative search effort devoted to each wind turbine in the study in the Altamont Pass Wind Resource Area (APWRA), California, USA. In the left map solid circles denote turbines searched between March 1998 and September 2002 (set 1) and open diamonds denote wind turbines not searched (set 3), and in the right map open circles denote turbines searched November 2002 until May 2003 (set 2). Livermore appears at the lower left corners, and the thick line cutting through the APWRA from Livermore is Highway 580. Other lines represent paved roads in the area. The east–west extent of each map is about 17.7 km.

and ridgelines extending down toward ephemeral streams. Wind turbine rows also occupied slopes, valleys, and hill peaks and all operated in winds from any direction, although most winds originated from the northwest or southwest. Wind turbines in the APWRA included KCS-56 100-kW turbines on lattice towers (Kenetech Windpower Inc., Livermore, CA), 120-kW and 150-kW turbines on tubular towers (Bonus Wind Turbines, Inc., Brande, Denmark), 150-kW and 250-kW vertical axis turbines (FloWind Corp., San Rafael, CA), 40-kW turbines on lattice towers (Enertech Corporation, Norwich, VT), and Micon 65-kW turbines on tubular towers (Moerup Manfacturing Co., Randers, Denmark). Others on tubular towers included 330-kW (James Howden and Company, Renfrew, Scotland), 110-kW (Danwin A/S, Helsingor, Denmark), 65-kW (Nordtank Energy Group, Balle, Denmark), 250-kW (Wind Energy Group, Ltd., Southall, Middlesex, England), Polenko 100-kW (Holec Power Systems, Inc., Livermore, CA), and 75-kW to 300-kW turbines (Windmaster, Byron, CA). Others on lattice towers included 65-kW (Windmatic, Herring, Denmark) and 100-kW turbines (Vestas Wind Systems A/S, Randers, Denmark). KVS-33 400-kW turbines (Kenetech Windpower Inc.) occurred on both lattice and tubular towers. Tower heights ranged from 14 m to 43.1 m above ground, with blades extending from 4 m to 52 m above ground at their lowest and highest reaches, respectively.

METHODS

We searched for bird carcasses at 1,526 wind turbines in 182 rows from March 1998 through September 2002 (hereafter set 1). We added groups of wind turbines into set 1 as we gained access, and we searched all of them 6–34 ($\bar{x} = 18$) times. From November 2002 until May 2003 we searched another 2,548 turbines arranged in 380 rows (hereafter set 2). We accessed set 2 turbines 6 months before our study ended, and searched them only twice. We selected set 2 turbines systematically from the unsearched turbines to achieve maximal north–south, east–west representation of the APWRA and to intersperse the unsearched turbines (hereafter set 3). In total, we searched for bird fatalities at 75% of the APWRA's wind turbines (Fig. 1), and we performed 32,439 fatality searches, where a fatality search was one search covering 50 m around one turbine.

Because wind turbines in our study area were arranged in rows, we searched them efficiently by walking strip transects along both sides and around the ends. Two field biologists explored the ground, maintaining about 4–6 m between parallel transect segments, which extended to 50 m away from the centerline of the wind turbine row. An earlier study in the APWRA found 96% of the carcasses deposited by wind turbines were $\leq$50 m from the turbine (Orloff and Flannery 1992), and we found 85–88% of the carcasses $\leq$50 m from the turbine (Smallwood and Thelander 2004). Our

Table 1. Status and summary of birds found killed by wind turbines in the Altamont Pass Wind Resources Area, California, USA, May 1998–May 2003.[a]

Species or taxonomic group	Species name	Status	All wind turbine–caused fatalities	Carcasses used in mortality estimates
Golden eagle	*Aquila chrysaetos*	BGEPA, CSC, CFP, PBP	54	29
Red-tailed hawk	*Buteo jamaicensis*	PBP	213	156
Ferruginous hawk	*Buteo regalis*	CSC, PBP	2	2
Buteo spp.	*Buteo* spp.	PBP	23	0
Northern harrier	*Circus cyaneus*	CSC, PBP	3	3
White-tailed kite	*Elanus leucurus*	CFP, PBP	1	0
Prairie falcon	*Falco mexicanus*	CSC, PBP	3	3
American kestrel	*Falco sparverius*	PBP	59	55
Turkey vulture	*Cathartes aura*	PBP	6	3
Barn owl	*Tyto alba*	PBP	50	40
Great horned owl	*Bubo virginianus*	PBP	18	11
Burrowing owl	*Athene cunicularia hypugaea*	PBP	70	67
Raptors		PBP	17	4
Double-crested cormorant	*Phalacrocorax auritus*	CSC	1	1
Black-crowned night heron	*Nycticorax nycticorax*		2	2
Cattle egret	*Bubulcus ibis*	exotic	1	1
Mallard	*Anas platyrhynchos*		35	26
Ring-necked duck	*Aythya collaris*		1	1
American avocet	*Recurvirostra americana*		3	3
Lesser yellowlegs	*Tringa flavipes*		1	1
Ring-billed gull	*Larus delawarensis*		4	4
California gull	*Larus californicus*	CSC	7	7
Gulls	*Larus* spp.		18	8
Northern flicker	*Colaptes auratus*		6	6
Mourning dove	*Zenaida macroura*		34	34
Rock dove	*Columba livia*	exotic	196	183
Wild turkey	*Meleagris gallopavo*	exotic	1	1
Common raven	*Corvus corax*		12	9
American crow	*Corvus brachyrhynchos*		5	4
Brown-headed cowbird	*Molothrus ater*		2	2
Brewer's blackbird	*Euphagus cyanocephalus*		13	13
Red-winged blackbird	*Agelaius phoeniceus*		12	12
Tricolored blackbird	*Agelaius tricolor*	CSC	1	1
Blackbirds			1	1
European starling	*Sturnus vulgaris*	exotic	67	57
California horned lark	*Eremophila alpestris actia*	CSC	23	22
Western meadowlark	*Sturnella neglecta*		96	96
Western kingbird	*Tyrannus verticalis*		1	1
Pacific-slope flycatcher	*Empidonax difficilis*		1	1
Loggerhead shrike	*Lanius ludovicianus*	CSC	5	4
Cliff swallow	*Hirundo pyrrhonota*		5	5
Violet-green swallow	*Tachycineta thalassina*		1	1
Northern mockingbird	*Mimus polyglottos*		1	1
Mountain bluebird	*Sialia currucoides*		5	4
Yellow warbler	*Dendroica petechia brewsteri*	CSC	1	1
Savannah sparrow	*Passerculus sandwichensis*		2	2
House finch	*Carpodacus mexicanus*		14	12
House sparrow	*Passer domesticus*	exotic	1	1
Cockatiel	*Nymphicus hollandicus*	exotic	1	1
Passerine			16	12
Unknown small birds			42	27
Raptors as a group		PBP	519	373
All birds as a group			1,157	941

[a] The following abbreviations represent special status of the species: BGEPA = Bald and Golden Eagle Protection Act, CFP = California Fully Protected, CSC = California Department of Fish and Game listing of California Species of Concern, and PBP = Protection of Birds of Prey under California Fish and Game Code 3503.5. The Migratory Bird Treaty Act protects all species in the table except wild turkey, rock dove, European starling, house sparrow, and cockatiel.

carcass searches averaged 8–10 minutes per wind turbine, which we performed 5 hours per day using 2-person crews, so each crew searched 30–40 wind turbines per day. Most set 1 turbines were given roughly similar search effort over the time spans searched ($\bar{x} = 7.2$ searches/yr).

We documented as fatalities all carcasses or body parts we found, such as groups of flight feathers, head, wings, tarsi, and tail feathers. When possible, we identified carcasses to species, age class, and sex, and we classified each species as either small-bodied ($\leq$38 cm in body length) or large-bodied (>38 cm). We assigned each carcass a probable cause of death based on injuries and proximity to hazards such as wind turbines, roads, or electric distribution poles. We attributed predation to carcasses with feathers plucked and scattered. Wind turbine injuries included severed or twisted torso, decapitation, severed wing(s), tail, or leg(s), and other forms of blunt force trauma. We estimated the number of days since death by assessing carcass condition. Generally we assumed carcasses older than 90 days if the enamel on culmen and talons had separated from the bone, flesh was gone, and bones and feathers were bleached, but we used considerable judgment because carcass decomposition rates vary according to environmental conditions. The presence of blood generally indicates <4 days since death, but the onset of rigor mortis, odor, and maggots or other insect larvae vary greatly with temperature, so we had to use these signs as guides in the context of current environmental conditions to estimate the number of days since death. We photographed most carcasses upon discovery, and we placed some in cages in the field to monitor decomposition. We reported all fatalities to the wind turbine owners, who collected the carcasses and deposited them with the United States Fish and Wildlife Service.

Within each turbine row we expressed unadjusted mortality (M_U) as number of fatalities/MW/year, where MW was the sum of the megawatts of rated power outputs for all of the wind turbines in the row surveyed. Although individual turbines killed birds, we used the wind turbine row as our study unit because we believed birds often sensed and reacted to the wind turbine row as a barrier or threat. We added 3 months to the number of years used in the mortality estimate, to represent the time period when carcasses could have accumulated before our first search. We excluded from mortality estimates all fatalities estimated to have occurred >90 days before discovery, and we excluded 9 carcasses found incidentally after all search rotations had ceased at a particular row. We included carcasses found outside the search radius during searches because we assumed the likelihood of seeing carcasses outside the search radius would not vary significantly among turbine rows in the APWRA's short-stature grassland.

We adjusted our mortality estimate, M_A, for carcasses not found due to searcher detection error and scavenger removals as

$$M_A = \frac{M_U}{pR} \tag{1}$$

where M_U was unadjusted mortality expressed as number of fatalities/MW of rated capacity per year, p was the proportion of turbine-caused bird fatalities found by searchers during searcher detection trials, R was the estimated proportion of carcasses remaining since the last fatality search and estimated by scavenger removal trials (Smallwood 1997). We calculated its standard error, SE[M_A], using the delta method (Goodman 1960):

$$\mathrm{SE}[M_A] = \left[\left(\frac{1}{pR} \times \mathrm{SE}[M_U]\right)^2 \times \left(\frac{M_U}{p} \times \frac{-1}{R^2} \times \mathrm{SE}[R]\right)^2 \times \left(\frac{M_U}{R} \times \frac{-1}{p^2} \times \mathrm{SE}[p]\right)^2\right]^{1/2}. \tag{2}$$

We did not perform searcher efficiency and scavenger removal trials in the APWRA but instead used estimators of searcher detection and scavenger removal rates developed by Smallwood (1997), who synthesized results from reported searcher detection and scavenger removal trials performed in wind farms throughout the United States.

Search detection rates were 51% (SE = 2.133%) for small nonraptor birds, 78% (SE = 5.384%) for medium and large nonraptor birds (including rock doves [*Columba livia*]), 75% (SE = 9.129%) for small raptors, and 100% (SE = 0%) for large raptors, based on averages among reports of searcher detection trials in grasslands across the United States (Smallwood 1997). To predict the proportion of carcasses remaining after each successive day into scavenger removal trials or into the periods intervening fatality searches, we used logarithmic models developed using least squares regression for small-bodied nonraptor birds (SE = 0.158), medium and large-bodied nonraptor birds (SE = 0.129), small-bodied raptors (SE = 0.040), and large-bodied raptors (SE = 0.089), and we used a linear model developed for rock dove (SE = 0.080; Smallwood 1997, table 4).

Assuming wind turbines will deposit carcasses at a steady state, for each species group we averaged the above model predictions across the number of days equaling the average number of days between fatality searches for all set 1 and set 2 turbines:

$$R_C = \frac{\sum_{I}^{i=1} R_i}{I \times 100} \tag{3}$$

where R_C was the cumulative carcasses remaining, R_i was the percent of carcasses remaining by the ith day following the initiation of a scavenger removal trial and corresponding with the number of days since the last fatality search, and I was the average number of days between fatality searches among set 1 and set 2 turbines.

We made no adjustment for background mortality, which is usually small, nor did we adjust estimates for crippling bias, search radius bias, and carcasses removed by wind turbine maintenance personnel or by administrators of the Wildlife Response and Reporting System (WRRS), which was the industry's system of reporting of carcasses found incidentally by turbine maintenance personnel. Background mortality is mortality caused by factors independent of the wind turbines and their supporting infrastructure. Crippling bias refers to number of birds mortally injured by the wind turbines but which die undetected somewhere else. Search radius bias refers to number of birds killed by wind turbines but thrown beyond the search radius and not found. Most of these potential adjustments would increase mortality estimates by unknown degrees by adding undiscovered fatalities to the total. Another potential source of error is the proportion of turbine rows where we recorded zero fatalities but where scavengers might have removed carcasses prior to our searches, or where our searches missed carcasses. We did not adjust these zero-values for searcher detection and scavenger removal errors because zero divided by p or R equals zero.

For each species, we estimated mortality separately for set 1 and set 2 turbines, even though mortality did not differ between the sets for 75% of the species. We calculated the APWRA-wide mean mortality as the weighted mean from sets 1 and 2:

$$M_{A,3} = \frac{(M_{A,1} \times 153.25 \text{ MW}) + (M_{A,2} \times 267.09 \text{ MW})}{418.255 \text{ MW}} \quad (4)$$

where $M_{A,1}$, $M_{A,2}$, and $M_{A,3}$ were adjusted mortality estimates for turbine sets 1, 2, and 3, respectively, and set 3 represented the 25% of the turbines not searched and which equaled the weighted mean adjusted mortality across the APWRA. Set 1 wind turbines composed 153.25 MW of rated capacity and set 2 composed 267.09 MW. The set 3 wind turbines were interspersed with the turbines we searched (Fig. 1), and they were of the same models. We treated the set 2 mortality estimates as if they were annual estimates, but we did not search the set 2 turbines during summer. All mortality estimates represented mortality caused directly by wind turbines and did not include fatalities caused by electrocution on the power collection system, collisions with overhead power lines, or collisions with automobiles traveling the wind turbine service roads.

RESULTS

We found 1,157 bird fatalities attributed to wind turbine collisions (Table 1). Of these, we excluded 216 from mortality estimations because they were either estimated to have been killed >90 days before discovery or they were found after the last of the searches at a particular wind turbine row (Table 1). To the unadjusted mortality estimates (Table 2), we used equations 1–3 to factor in search detection and scavenger removal rates quantified from other studies to arrive at adjusted mortality estimates (Table 3).

Adjusted mortality differed significantly between sets 1 and 2 for American crow (*Corvus brachyrhynchos*), California gull (*Larus californicus*), cliff swallow (*Hirundo pyrrhonota*), great horned owl (*Bubo virginianus*), house finch (*Carpodacus mexicanus*), California horned lark (*Eremophila alpestris actia*), mallard (*Anas platyrhynchos*), mourning dove (*Zenaida macroura*), ring-billed gull (*Larus delawarensis*), rock dove, red-winged blackbird (*Agelaius phoeniceus*), and turkey vulture (*Cathartes aura*; $P < 0.05$ in each case), so we used equation 4 to calculate APWRA-wide adjusted mortality as the weighted mean between turbine sets 1 and 2. Before adjusting mortality estimates for searcher detection and scavenger removal rates, we estimated the APWRA's wind turbines annually killed ≥56 golden eagles, 168 red-tailed hawks (*Buteo jamaicensis*), 55 American kestrels (*Falco sparverius*), 80 burrowing owls (*Athene cunicularia hypugaea*), 434 raptors, and 1,058 birds (Table 3). After adjusting estimates for searcher detection and scavenger removal rates, we estimated wind turbine collisions in the APWRA annually killed 67 (80% CI = 25–109) golden eagles, 188 (80% CI = 116–259) red-tailed hawks, 348 (80% CI = −49 to 749) American kestrels, 440 (80% CI = −133 to 1,013) burrowing owls, 1,127 (80% CI = −23 to 2,277) raptors, and 2,710 (80% CI = −6,100 to 11,520) birds (Table 3).

DISCUSSION

We estimated collisions with wind turbines in the APWRA killed 434 raptors and 1,058 birds before factoring in carcasses not found due to searcher detection error and scavenger removal. Factoring in search detection and scavenger removal, we estimated the APWRA's wind turbines killed 1,127 raptors and 2,710 birds, and possibly as many as 2,277 raptors and 11,520 birds. Follow-up fatality monitoring in the APWRA in 2005–2006, using similar methods and assumptions, preliminarily supported equal if not greater estimates of wind turbine–caused mortality of raptors and other birds (W. P. Erickson, WEST, Inc., unpublished data), so levels of mortality we detected have continued into 2006. However, because the follow-up monitoring used similar methods, uncertainty ranges will be similarly large.

Even though we performed many more fatality searches over twice as long a time period compared to past research efforts in the APWRA, our mortality estimates were imprecise. The lower bound annual mortality estimate of most species was <0. A principal source of our imprecision was long intervals between fatality searches, averaging 53 days between searches in set 1 and 90 days in set 2. Scavenger removal trials indicated that our average search interval among set 1 turbines would on average present our fatality searchers with only 21% of small-bodied bird carcasses and 18% of small-bodied raptor carcasses deposited by the wind turbines since the previous fatality search (Smallwood 1997). Scavenger removal trials indicated our search interval among set 2 turbines would on average present fatality searchers with only 12% of small-bodied bird carcasses and 11% of small-bodied raptor carcasses. Thus, mortality estimates for these groups of birds were increased 5- to 10-fold due to scavenger removal, but only at wind turbine rows where we found ≥1 carcass. We made no adjustments at the many wind turbine rows where we found zero birds.

Our mortality estimates are not alone in their imprecision. Most of the lower limit estimates of the 90% confidence interval were <0 at the Tehachapi and San Gorgonio Wind Resource Areas, California, even though these mortality estimates were made for multispecies groups such as raptors, waterbirds, and passerines (Anderson et al. 2004, 2005). Most of the lower limits of the 95% confidence interval were <0 at Foote Creek Rim Wind Plant, Wyoming, USA (Young et al. 2003). All of the mortality estimates of multispecies groups in the APWRA during 1989–1991 were associated with 95% confidence interval lower limits <0 (Orloff and Flannery 1992). It appears mortality monitoring at wind farms has repeatedly produced imprecise mortality

Table 2. Summary of unadjusted mortality estimates for 2 sets of wind turbines in the Altamont Pass Wind Resources Area, California, USA, searched at different time periods and for different durations and intersearch intervals.[a]

Species or taxonomic group	Mortality (deaths/MW/yr)					
	Set 1 turbine rows		Set 2 turbine rows		All turbine rows	
	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE
Golden eagle	0.0359	0.0118	0.1384	0.0679	0.0967	0.0477
Red-tailed hawk	0.3245	0.0656	0.2652	0.0885	0.2893	0.0805
Ferruginous hawk	0.0000	0.0000	0.0382	0.0273	0.0227	0.0175
Northern harrier	0.0029	0.0018	0.0000	0.0000	0.0012	0.0007
Prairie falcon	0.0047	0.0030	0.0000	0.0000	0.0019	0.0011
American kestrel	0.0703	0.0166	0.1115	0.0390	0.0947	0.0310
Turkey vulture	0.0108	0.0064	0.0000	0.0000	0.0044	0.0023
Barn owl	0.0720	0.0256	0.0315	0.0161	0.0480	0.0197
Great horned owl	0.0309	0.0128	0.0043	0.0043	0.0151	0.0074
Burrowing owl	0.1789	0.0325	0.1110	0.0692	0.1386	0.0561
Raptor spp.	0.0000	0.0000	0.0605	0.0346	0.0359	0.0221
Double-crested cormorant	0.0037	0.0037	0.0000	0.0000	0.0015	0.0014
Black-crowned night heron	0.0020	0.0014	0.0000	0.0000	0.0008	0.0005
Cattle egret	0.0000	0.0000	0.0027	0.0027	0.0016	0.0017
Mallard	0.0697	0.0258	0.0121	0.0121	0.0356	0.0172
Ring-necked duck	0.0000	0.0000	0.0036	0.0036	0.0021	0.0023
American avocet	0.0121	0.0102	0.0000	0.0000	0.0049	0.0037
Lesser yellowlegs	0.0010	0.0010	0.0000	0.0000	0.0004	0.0004
Ring-billed gull	0.0155	0.0095	0.0000	0.0000	0.0063	0.0035
California gull	0.0158	0.0073	0.0000	0.0000	0.0064	0.0027
Gull spp.	0.0076	0.0042	0.0137	0.0087	0.0112	0.0071
Northern flicker	0.0152	0.0096	0.0204	0.0169	0.0183	0.0143
Mourning dove	0.1705	0.0571	0.0231	0.0122	0.0830	0.0287
Rock dove	0.5244	0.1120	0.1248	0.0468	0.2873	0.0709
Wild turkey	0.0028	0.0028	0.0000	0.0000	0.0011	0.0010
Common raven	0.0230	0.0148	0.0097	0.0097	0.0151	0.0116
American crow	0.0284	0.0169	0.0000	0.0000	0.0115	0.0062
Brown-headed cowbird	0.0033	0.0033	0.0241	0.0241	0.0157	0.0166
Brewer's blackbird	0.0230	0.0106	0.0512	0.0342	0.0397	0.0257
Red-winged blackbird	0.0399	0.0135	0.0000	0.0000	0.0162	0.0050
Tricolored blackbird	0.0020	0.0020	0.0000	0.0000	0.0008	0.0007
Blackbird spp.	0.0049	0.0049	0.0000	0.0000	0.0020	0.0018
European starling	0.1329	0.0302	0.1362	0.0657	0.1349	0.0530
Horned lark	0.0468	0.0122	0.0000	0.0000	0.0190	0.0045
Western meadowlark	0.2197	0.0440	0.2024	0.0783	0.2095	0.0661
Western kingbird	0.0013	0.0013	0.0000	0.0000	0.0005	0.0005
Pacific-slope flycatcher	0.0033	0.0033	0.0000	0.0000	0.0013	0.0012
Loggerhead shrike	0.0218	0.0150	0.0000	0.0000	0.0089	0.0055
Cliff swallow	0.0154	0.0079	0.0000	0.0000	0.0063	0.0029
Violet-green swallow	0.0012	0.0012	0.0000	0.0000	0.0005	0.0005
Northern mockingbird	0.0048	0.0048	0.0000	0.0000	0.0019	0.0018
Mountain bluebird	0.0056	0.0049	0.0183	0.0150	0.0131	0.0114
Yellow warbler	0.0018	0.0018	0.0000	0.0000	0.0008	0.0007
Savannah sparrow	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043
House finch	0.0515	0.0198	0.0000	0.0000	0.0209	0.0072
House sparrow	0.0000	0.0000	0.0080	0.0080	0.0048	0.0051
Cockatiel	0.0015	0.0015	0.0000	0.0000	0.0006	0.0006
Passerine spp.	0.0370	0.0142	0.0256	0.0231	0.0302	0.0199
Unknown small bird	0.0420	0.0130	0.0654	0.0243	0.0559	0.0203
All raptors as a group	0.7309	0.1761	0.7604	0.3469	0.7484	0.2860
All birds as a group	2.2869	0.6661	1.5060	0.7365	1.8236	0.7144

[a] Set 1 included 153.25 MW of rated capacity from 1,526 wind turbines in the search rotation through May 1998 September 2002. Set 2 included 267.09 MW from 2,538 wind turbines in the November 2002 through May 2003 rotation. We calculated the values in the all turbine rows columns as the weighted means from sets 1 and 2.

estimates. The methodology needs to be changed (see Management Implications).

Our mortality estimates did not include birds killed by autos, guyed meteorological towers, and the power collection system (i.e., overhead power lines and energized pole-mounted equipment), though we did record these fatalities when we found them. Our estimates also did not include injured birds dying undetected elsewhere or birds removed by the wind turbine owners without our knowledge. (A postproject review of WRRS indicated some birds were

Table 3. Summary of adjusted mortality estimates for two sets of wind turbines in the Altamont Pass Wind Resources Area, California, USA, searched at different time periods and for different durations and intersearch intervals.[a]

Species or taxonomic group	Unadjusted annual deaths	Adjusted mortality (deaths/MW/yr)		Adjusted annual deaths		
		$\bar{x}$	SE	$\bar{x}$	Lower bound of 80% CI	Upper bound of 80% CI
Golden eagle	56.1	0.115	0.056	66.7	24.7	108.7
Red-tailed hawk	167.8	0.324	0.096	187.8	116.4	259.3
Ferruginous hawk	13.2	0.028	0.021	16.1	0.5	31.7
Northern harrier	0.7	0.001	0.001	0.7	0.1	1.2
Prairie falcon	1.1	0.002	0.001	1.1	0.2	2.0
American kestrel	54.9	0.599	0.540	347.6	−53.7	748.8
Turkey vulture	2.6	0.004	0.003	2.5	0.6	4.5
Barn owl	27.8	0.052	0.022	30.2	13.5	46.9
Great horned owl	8.8	0.016	0.008	9.1	2.9	15.3
Burrowing owl	80.4	0.759	0.771	440.0	−133.4	1013.4
Raptor spp.	20.8	0.044	0.027	25.5	5.4	45.5
Double-crested cormorant	0.9	0.002	0.004	1.3	−1.4	4.0
Black-crowned night heron	0.5	0.001	0.001	0.7	−0.3	1.7
Cattle egret	0.9	0.003	0.006	2.0	−2.5	6.5
Mallard	20.6	0.058	0.052	33.8	−4.8	72.3
Ring-necked duck	1.2	0.005	0.008	2.7	−3.4	8.7
American avocet	2.8	0.007	0.010	4.2	−3.3	11.7
Lesser yellowlegs	0.2	0.001	0.001	0.3	−0.4	1.1
Ring-billed gull	3.7	0.010	0.009	5.5	−1.3	12.4
California gull	3.7	0.010	0.007	5.6	0.3	10.9
Gull spp.	6.5	0.022	0.025	12.9	−5.4	31.1
Northern flicker	10.6	0.066	0.361	38.3	−230.5	307.1
Mourning dove	48.1	0.208	0.594	120.7	−320.9	562.3
Rock dove	166.6	0.325	0.157	188.6	72.2	305.0
Wild turkey	0.6	0.002	0.003	1.0	−1.0	3.0
Common raven	8.8	0.027	0.035	15.4	−10.7	41.4
American crow	6.7	0.017	0.017	9.8	−2.7	22.4
Brown-headed cowbird	9.1	0.065	0.427	37.9	−279.3	355.1
Brewer's blackbird	23.0	0.153	0.831	88.6	−529.4	706.5
Red-winged blackbird	9.4	0.035	0.060	20.1	−24.7	65.0
Tricolored blackbird	0.5	0.002	0.007	1.0	−4.2	6.2
Blackbird spp.	1.2	0.004	0.017	2.5	−10.3	15.2
European starling	78.2	0.469	2.177	271.8	−1346.9	1890.5
Horned lark	11.0	0.041	0.062	23.6	−22.5	69.8
Western meadowlark	121.5	0.716	3.193	415.1	−1959.1	2789.3
Western kingbird	0.3	0.001	0.005	0.7	−2.7	4.0
Pacific-slope flycatcher	0.8	0.003	0.011	1.7	−6.9	10.2
Loggerhead shrike	5.2	0.019	0.055	11.0	−29.7	51.7
Cliff swallow	3.7	0.013	0.031	7.8	−15.1	30.6
Violet-green swallow	0.3	0.001	0.004	0.6	−2.6	3.8
Northern mockingbird	1.1	0.004	0.017	2.4	−10.0	14.8
Mountain bluebird	7.6	0.052	0.310	30.3	−200.1	260.8
Yellow warbler	0.5	0.002	0.006	0.9	−3.9	5.7
Savannah sparrow	2.5	0.015	0.087	8.6	−55.7	73.0
House finch	12.1	0.045	0.084	26.0	−36.3	88.3
House sparrow	2.8	0.021	0.140	12.0	−92.3	116.3
Cockatiel	0.3	0.001	0.005	0.8	−3.2	4.7
Passerine spp.	17.5	0.099	0.483	57.1	−302.2	416.5
Unknown small bird	32.4	0.206	1.000	119.5	−623.9	862.9
All raptors as a group	434.1	1.943		1,127.2	−22.8	2,277.2
All birds as a group	1,057.7	4.672		2,710.0	−6,099.8	11,519.8

[a] Set 1 included 153.25 MW of rated capacity from 1,526 wind turbines in the search rotation through May 1998 September 2002. Set 2 included 267.09 MW from 2,538 wind turbines in the November 2002 through May 2003 rotation.

removed without our knowledge.) Therefore, our estimates were incomplete in their representation of the APWRA's overall impacts on birds. Furthermore, we were unable to assess how the fatalities affected local or regional bird populations or whether the birds killed were residents or migrants.

Hunt (2002) concluded the local golden eagle population appeared stable during his 1994–2000 study, which overlapped ours, despite the wind turbine–caused mortality. W. G. Hunt (Santa Cruz Predatory Bird Research Group, personal communication) also concluded the golden eagles killed in the APWRA were local birds. However, we have not seen evidence refuting the possibility that many of the golden eagles killed by APWRA wind turbines may have been floaters from populations elsewhere in the western United States, Mexico, and Canada. If recruitment from other populations can continue to replace members of the local nesting population, despite the number killed by wind turbines, then the local number of nesting pairs may not change noticeably. If local bird populations produce fewer birds than the numbers killed by the wind turbines, then we would regard the APWRA as an ecological sink because more birds would be coming into the APWRA than leaving it.

Smallwood et al. (2007) concluded the APWRA might serve as an ecological sink to burrowing owls because turbine-caused mortality might equal or exceed local production. However, Smallwood et al. (2007) estimated annual mortality of 99–380 burrowing owls in the APWRA, which was lower than our estimate of 345–1,219. Our estimate is greater because Smallwood et al. (2007) relied on results of a scavenger removal trial using surrogate, nonraptor species in eastern Oregon, USA (W. P. Erickson and J. Jeffrey, WEST, Inc., unpublished data), whereas we relied on a recently developed predictive model (Smallwood 1997) based on a removal trial using small-bodied raptor species in the APRWA (Orloff and Flannery 1992).

Our incorporation of the set 2 turbines likely introduced a seasonal bias to our mortality estimates because we conducted no fatality searches during summer. Also, the longer search interval used among set 2 turbines usually produced larger standard errors for species and species groups found at both set 1 and set 2 turbines. However, we felt the bias and statistical error introduced by incorporating set 2 turbines were offset by the spatial distribution of these turbines across the full north–south and east–west extent of the APWRA. Including the set 2 turbines offset the bias of extrapolating the mortality estimates from the set 1 turbines, which were clustered in the east-central portion of the study area.

MANAGEMENT IMPLICATIONS

Despite low precision in estimated numbers of birds killed annually by APWRA wind turbines, our fatality counts and resulting mortality estimates demonstrated that ongoing operations kill relatively large numbers of raptors and other birds protected by the MBTA and other environmental laws. Regulatory agencies and the public need to decide whether to enforce laws intended to protect species killed by APWRA wind turbines, and whether to enforce the wind power companies' compliance with their conditional use permits. Alternative, safer wind turbine designs could be explored, as well as preproject site screening for likely wildlife impacts. Replacing the existing wind turbines with new-generation models on taller towers might reduce the APWRA's bird mortality $\geq$70% (K. S. Smallwood, unpublished data; W. P. Erickson, unpublished data). Unavoidable impacts could be compensated through habitat protections.

Assessments of proposed new wind power projects should regard existing reports of mortality as imprecise and likely lower than actual mortality levels. Until the uncertainties and biases of mortality estimates can be reduced through directed research, mitigation plans should account for the imprecision in mortality estimates by using adaptive management principles. Funds are needed to support monitoring and research and could be provided as part of the cost of wind farm development and operation. To improve precision of mortality estimates, fatality monitoring should include shorter search intervals (e.g., every other day at a sufficient sample of turbines), and needs to last $\geq$3 years. Fatality monitoring needs species-specific scavenger removal rates based on methods improved through directed research, and the extent of crippling bias needs to be learned. Mortality estimates should be expressed in terms of kilowatt-hours, so fatality monitors should be provided power output data from each wind turbine on a schedule corresponding with the fatality searches. Developing technologies to remotely detect collisions could vastly improve mortality estimation, while also cutting costs. Also, resident birds need to be tagged and monitored to learn the extent to which wind turbine collisions affect local populations.

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In both papers, equation 3 yields proportions of cumulative carcasses remaining, rather than percentages. To yield percentage values, either multiply equation 3 by 100% or eliminate the multiplier '100' from the denominator.