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Avian and Bat Fatality Rates at Old-Generation and Repowered Wind Turbines in California

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ABSTRACT Wind turbines in the Altamont Pass Wind Resource Area (APWRA), California, USA, have caused annual fatalities of thousands of raptors and other birds. Alameda County implemented an Avian Protection Program requiring mitigation measures and eventual repowering to modern wind turbines, all intended to reduce raptor fatality rates 50% from levels estimated for 1998–2003. Two years into the 3-year program, we compared estimates of fatality rates between 1998–2003 and 2005–2007 and between a repowered wind project (Diablo Winds) and the APWRA's old-generation wind turbines. The APWRA-wide fatality rates increased significantly for multiple bird species, including 85% for all raptors and 51% for all birds. Fatality rates caused by the Diablo Winds repowering project were not lower than replaced turbines, but they were 54% and 66% lower for raptors and all birds, respectively, than those of concurrently operating old-generation turbines in 2005–2007. Because new-generation turbines can generate nearly 3 times the energy per megawatt of rated capacity compared to the APWRA's old turbines, repowering the APWRA could reduce mean annual fatality rates by 54% for raptors and 65% for all birds, while more than doubling annual wind-energy generation. Alternatively, the nameplate capacity of a repowered APWRA could be restricted to 209 megawatts to meet current energy generation (about 700 gigawatt-hr), thereby reducing mean annual fatalities by 83% for raptors and 87% for all birds. In lieu of repowering, bird fatalities could be reduced by enforcing operating permits and environmental laws and by the County requiring implementation of the Alameda County Scientific Review Committee's recommendations. (JOURNAL OF WILDLIFE MANAGEMENT 73(7):1062–1071; 2009)

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The Altamont Pass Wind Resource Area (APWRA) began operations during the 1980s and was until recently the world's largest wind farm, with a permitted generating capacity of 580 megawatts (MW). It supplies emission-free electric power to thousands of homes, but many of the thousands of dead birds found by the wind turbines are protected by the Migratory Bird Treaty Act (MBTA) and some are protected by other state and federal laws (Appendix). Smallwood and Thelander (2008) estimated bird fatality rates in the APWRA during 1998–2003, but those estimates preceded some repowering and implementation of mitigation measures to reduce wind turbine–caused fatalities.

In 1998 the APWRA included about 5,400 wind turbines of various models, ranging in capacity from 40 kilowatts (kW) to 400 kW but most were 100 kW to 150 kW. In February 2005 the Diablo Winds Energy Project repowered 21 MW of rated capacity by replacing 126 Flowind (FloWind Corp., San Rafael, CA) vertical-axis wind turbines with 31 Vestas (Vestas Wind Systems A/S, Randers, Denmark) horizontal axis wind turbines (Table 1). The new turbines were more widely spaced and operated at lower rotor speed (rotations/min), which were traits thought by some to be safer for birds (Erickson et al. 2001, Tucker 1996). Hunt (2002) concluded repowering with larger turbines would be safer for golden eagles (*Aquila chrysaetos*), but Orloff and Flannery (1992) and Smallwood and Thelander (2004, 2005) found that turbines with larger rotor-swept areas killed more of some raptor species.

In August 2005, Alameda County renewed the conditional use permits held by most APWRA wind companies, requiring new, more stringent mitigation measures to reduce wind turbine–caused fatality rates. This Avian Protection Program was to be assessed through November 2009 by an avian monitoring team and Scientific Review Committee (SRC). The program was modified in January 2007 following a settlement agreement to litigation brought by environmental groups, including a goal to reduce wind-turbine–caused raptor fatalities by 50% since the 1998–2003 study (Smallwood and Thelander 2008), where raptors were represented by 4 target species: golden eagle, red-tailed hawk (*Bueo jamaicensis*), American kestrel (*Falco sparverius*), and burrowing owl (*Athene cunicularia*).

By November 2007, wind companies implemented some mitigation measures required by County use permits and recommended by the SRC (Table 2). Our objectives were to compare estimates of APWRA fatality rates between 1) the periods 1998–2003 and 2005–2007, and 2) a repowered wind project and the concurrently operating old-generation wind turbines.

STUDY AREA

The APWRA encompassed about 165 km^2 of ridges and hills generally extending northwest to southeast and bisected by intermittent streams and ravines in eastern Alameda and southeastern Contra Costa counties, California, USA. Elevations ranged 78 m to 470 m above mean sea level. Slopes were covered mostly by nonnative, annual grasses, which grew during the rainy months of January through March and were dead or dormant by early June. 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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Table 1. Attributes of wind turbines involved in the Diablo Winds Energy Project, which repowered 21 megawatts (MW) of rated capacity in the Altamont Pass Wind Resource Area, California, USA, in February 2005.

Attribute	Repowered Flowind[a] vertical-axis turbines		New Vestas[b] horizontal axis turbines	
Model	F-17	F-19	V47	V47
No. turbines	105	21	24	7
Rated output/turbine (MW)	0.15	0.25	0.66	0.66
No. of blades	2	2	3	3
Rotor diam (m)	17.2	19.1	47	47
Rotor speed (revolutions/min)	66.3	59.7	28.5	28.5
Hub ht above ground (m)			50	55
Highest blade reach above ground (m)	29.5	32.3	73.5	78.5
Lowest blade reach above ground (m)	4	4	26.5	31.5
Inter-turbine spacing within rows (m)	51	51	104	104

[a] FloWind Corp., San Rafael, California, USA.
[b] Vestas Wind Systems A/S, Randers, Denmark.

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 southwest or northwest. Old-generation wind turbine models were listed in Smallwood and Thelander (2008).

METHODS

We performed fatality searches at 2 sets of wind turbines during 1998–2003 (Table 3). We searched all set 1 turbines, because they were the only turbines to which the companies granted access until 2002, when all other turbines became available for fatality monitoring. We systematically selected set 2 turbines from the remaining pool of turbines to ensure homogenous interspersion of searched and unsearched turbines across the north to south and east to west extents of the APWRA (Smallwood and Thelander 2008). Altogether, we searched 4,074 (75%) of the 5,400 turbines in the APWRA during 1998–2003. Within set 1, we also searched all 126 Flowind vertical-axis turbines (21 MW) in 25 rows with an average interval of 45 days. These turbines ceased operations in 2000–2001 and were replaced in 2005 by 31 modern Vestas V47 turbines (20.46 MW) as part of the Diablo Winds Energy Project repowering (Table 3). Also within set 1, we searched 899 turbines (81.63 MW) that we selected randomly for the 2005–2007 fatality monitoring and so were directly comparable between monitoring periods.

We performed fatality searches since 2005 at 2,650 (53%) of the APWRA's old-generation wind turbines (Table 3). Fatality searches were within 84 randomly selected plots stratified by north and south aspects of the APWRA and by turbine size (i.e., very small: 40–65 kW; small: 100–150 kW; and medium: 250 kW). Each plot included 10–60 turbines in 1–7 rows. To estimate APWRA-wide fatality rates during 2005–2007, we extrapolated estimates from turbines in randomly selected plots to the 547.02 MW of rated capacity from which we drew our old-generation

Table 2. Implementation of Alameda County Avian Protection Program to reduce avian fatality rates in the Altamont Pass Wind Resource Area, California, USA, 22 September 2005 through 31 October 2007.

Mitigation measure (required by permit or recommended by Alameda County Scientific Review Committee [SRC])	Action taken
Convene SRC by 31 Oct 2005 (Permit).	SRC convened on 11 Sep 2006.
Remove or relocate turbines classified (K. S. Smallwood and L. Spiegel, California Energy Commission, unpublished data) as Tier 1 (most hazardous) by 31 Oct 2005 and as Tier 2 by 9 Feb 2007 (Permit).	Most operated in Apr 2007 and some operated in Sep 2007. No confirmed determination of removals or relocations through Nov 2007.
Remove vacant towers and towers supporting broken turbines, 50% by 22 Mar 2006 and 100% by 22 Sep 2006 (Permit).	Vacant towers and towers with broken turbines were not removed.
Subject to approval by United States Fish and Wildlife Service, remove all artificially created rock piles away from turbines by 20 Mar 2006 (Permit).	Rock piles were not removed.
Implement other on-site measures recommended by Smallwood and Thelander (2004) and SRC by 20 Mar 2006 (Permit).	None were implemented (see below).
Cease rodent control activities on all sites.	Wind companies stopped funding rodent control, but some land owners likely continued control efforts.
Pending SRC approval of an experimental design, paint turbine blades using Hodos (2003) scheme on a trial or larger basis (Permit). The intent was to lessen motion smear caused by moving wind turbine blades.	One company painted one blade black on 42 turbines, but without using the correct paint or obtaining SRC approval due to experimental design concerns.
Winter-time shut-down of turbines in a cross-over design, so northern turbines were to shut down during 2 months of winter and the southern turbines operated, and vice versa during winter's second half; the shut-down order was to switch between the winters of 2005–2006 and 2006–2007 (Permit).	Shut-downs were completed, but the permit requirement deviated from the original recommendation for a 4-month winter shut-down (K. S. Smallwood and L. Spiegel, unpublished data).
Remove vacant lattice towers used as end-of-row flight diverters (SRC).	Vacant towers were not removed.
Provide turbine power output data so the SRC can test hypotheses of causal mechanisms and more effectively recommend turbine removals (SRC).	No power output data were provided during our study.
Repowering should be pursued to reduce avian fatality rates (SRC).	No repowering was pursued during our study.

Table 3. Attributes of wind turbines and avian and bat fatality searches compared between 1998–2003 and 2005–2007 and within land held by East Bay Regional Park District (EBRPD), Altamont Pass Wind Resource Area, California, USA.

Attributes	Monitoring period 1998–2003		Monitoring period 2005–2007			
	Smallwood and Thelander (2008)		Consultants to Alameda County (Avian Protection Program)			Smallwood et al. (2009)
Sample	Set 1	Set 2	Group 1	Group 2	Diablo Winds	EBRPD
Start and end dates	Mar 1998–Sep 2002	Nov 2002–May 2003	Oct 2005–Oct 2007	Mar 2007–Oct 2007	Apr 2005–Nov 2007	Jun 2006–Sep 2007
Duration (yr)	1.5–4.5	0.5	2	0.6	2.7	1.3
Sample selection	Census	Systematic	Random	Random	Census	Census
Turbine models	All available	All available	Old-generation	Old-generation	Vestas V47	Nordtank, Howden
Turbine sizes (kilowatts)	40–400	65–400	40–400	100–120	660	65 & 330
No. turbines	1,526	2,548	2,114	536	31	62
Rated capacity (megawatts)	153.25	267.09	212.62	54.34	20.46	12.52
Search radius (m)	50	50	50	50	75	60
Mean search interval (days)	53	>90	41	41	33	17

turbine sample. Three complications emerged from this sampled pool. In 2005, the Buena Vista Wind Energy project replaced 179 small wind turbines in Contra Costa County with 38 1-MW Mitsubishi turbines. It began operations in January 2007, but fatality monitoring by other investigators did not begin there until January 2008. We assumed fatality rates were similar between the Buena Vista project and the rest of the sampled pool of turbines, but we cannot validate the accuracy of our assumption. A second complication was an infrastructure problem that resulted in shutting down all 200 Vestas 100-kW turbines owned by the City of Santa Clara from November 2005 through February 2007, except for January 2006. We searched for fatalities at 12.8 MW (128 turbines) of this 20 MW of capacity, despite nonoperation. The third complication was refused access to 186 turbines (12.1 MW capacity) owned by Northwind Inc. in Contra Costa County. However, East Bay Regional Park District (EBRPD) allowed us to use estimates of fatality rates from EBRPD property (Smallwood et al. 2009), which included about 12% of the Northwind Inc. turbines. To the estimates of fatality rates extrapolated to 547.02 MW of capacity, we added estimates from 12.52 MW of capacity on the EBRPD property and 20.46 MW in the Diablo Winds project.

Searches were performed by biologists walking parallel transects about 4–8 m apart, viewing all ground out to 50 m at most old-generation wind turbines, 60 m at the 330 kW Howden turbines, and 75 m at the 660 kW Diablo Winds turbines. We documented as fatalities all carcasses or body parts found, such as groups of flight feathers, head, wings, tarsi, and tail feathers. When possible, we identified carcasses to species, age class, and sex. We assessed carcass condition to estimate number of days since death. Generally we assumed carcasses were 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 judgment because carcass decomposition rates vary according to environmental conditions. Presence of blood generally indicated <4 days since death, but onset of rigor mortis, odor, and maggots or other insect larvae varied greatly with temperature, so we had to use these signs as guides in the context of current environmental conditions to estimate number of days since death. We photographed nearly all carcasses.

We considered each fatality record as unlikely, possibly, probably, or certainly caused by wind turbines. Fatalities unlikely caused by turbines were unfledged birds or those determined to have been caused by electrocution, vehicle collision, or predation. They were possible if within the fatality search radius but nearby an electric distribution pole or lines, implicating electrocution or line strike as causes of death, or if they were burrowing owls next to burrows, implicating predation. They were probable if found near wind turbines and another cause of death was not determined. They were certain if evidence suggested a turbine was involved, such as oil or grease on the bird, paint on the bird, or the bird was split in two or dismembered due to impact. We considered most of the fatalities found probably caused by wind turbines, 71% during 1998–2003 and 91% during 2005–2007. To estimate turbine-caused fatality rates we used fatalities considered possibly, probably, or certainly caused by wind turbines, or 98.6% of fatalities reported in 1998–2003 and 97.3% in 2005–2007.

Within each turbine row we expressed unadjusted fatality rate (F_U) as number of fatalities per MW per year, where we summed MW across all turbines in the row. Although individual turbines killed birds, we used the wind turbine row as our study unit because 1) we believed birds often sensed and reacted to the wind turbine row as a barrier or threat, and 2) we often could not determine which turbine in the row killed the bird. We used the MW of rated capacity of all turbine addresses initially searched within the row, regardless of whether the address later supported a functional or broken turbine or a vacant tower. We took this approach because we were not regularly updated on turbine functionality, which varied, and we were often unable to determine functionality while wind speeds were too low for power generation. To number of years in the fatality-rate calculation, we added average search interval (in days converted to yr) to represent the time period when carcasses could have accumulated before our first search. We derived fatality-rate estimates from fatalities estimated to have occurred ≤ 90 days before discovery. We discovered most excluded fatalities during start-up searches at newly visited turbines. Out to 125 m, we included carcasses found outside the search radius because we assumed 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 fatality-rate estimate, F_A, for carcasses not found due to searcher-detection error and scavenger removals as

$$F_A = \frac{F_U}{p \times R_C} \tag{1}$$

where F_U was unadjusted fatality rate, p was proportion of fatalities found by searchers during searcher-detection trials in grasslands across the United States and reported in Smallwood (2007), and R_C was estimated cumulative proportion of carcasses remaining since the last fatality search, assuming wind turbines will deposit carcasses at a steady rate through the search interval. We estimated R_C by scavenger-removal rates estimated from trials throughout the United States and averaged by Smallwood (2007):

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

where R_i was proportion of carcasses remaining by the ith day following initiation of a scavenger-removal trial (intended to correspond with no. of days since the last fatality search during monitoring), and I was average search interval (days). We looked up R_C values in Smallwood (2007; Appendix) according to species group and search interval. We calculated standard error of the adjusted fatality rate, SE[F_A], using the delta method (Goodman 1960):

$$\mathrm{SE}[F_A] = \sqrt{\left(\frac{1}{p \times R_C} \times \mathrm{SE}[F_U]\right)^2 \times \left(\frac{F_U}{p} \times \frac{-1}{{R_C}^2} \times \mathrm{SE}[R_C]\right)^2 \times \left(\frac{F_U}{R_C} \times \frac{-1}{p^2} \times \mathrm{SE}[p]\right)^2} \tag{3}$$

We did not adjust estimates for background mortality, crippling bias, or search radius bias. Background mortality is the fatality rate caused by factors other than wind turbines and supporting infrastructure. Crippling bias refers to the rate of mortally wounded animals dying undetected outside the search radius or moving from unsearched turbines to searched turbines. Search-radius bias refers to the rate of wind turbine–killed birds thrown beyond the search radius and not found. Birds thrown 50 m laterally from turbines atop steep slopes can land farther down the hill than the 50 m measured from the searcher to the turbine base.

Differing from Smallwood and Thelander (2008), we included carcasses removed by companies as part of the Wildlife Response and Reporting System (WRRS), which was the industry's system of reporting carcasses found incidentally by turbine maintenance personnel. As a result, our 1998–2003 estimates reported herein will sometimes differ from Smallwood and Thelander (2008). Including WRRS data undoubtedly introduced some small error in our fatality-rate estimates because we applied the same scavenger-removal adjustments to these few fatalities as to the carcasses detected during our standard fatality searches.

We estimated bat fatality rates by applying scavenger-removal and searcher-detection rates estimated for small-bodied bird species (Smallwood 2007). However, numerous unpublished reports found that searchers miss more bats than small birds, and scavengers quickly remove many bats. Therefore, our estimates of bat fatality rates were likely biased low, but at least they were consistent between estimates reported herein, enabling preliminary comparisons between time periods and turbine fields.

Due to complexity of the APWRA-wide estimates of fatality rates, including 2 sampling approaches during 1998–2003 and multiple separate estimates added together in 2005–2007, we did not test for APWRA-wide differences in fatality rates. Instead, we simply compared estimated means and standard errors between monitoring periods. We used the t-test to test whether mean fatality rates differed between 1998–2002 and 2005–2007 within the 81.63 MW of turbines that were directly comparable (reference turbines) and within the 21 MW of the repowered Diablo Winds turbines.

RESULTS

APWRA-Wide Fatality Rates

Between 1998–2003 and 2005–2007, estimated mean adjusted fatality rate decreased 40% for American kestrel and increased 121% for red-tailed hawk, 17% for golden eagle, 30% for burrowing owl, 10% for all 4 target species combined, and 23% for all birds combined (Appendix). However, we did not test these mean differences for significance due to differences in sampling designs leading to the APWRA-wide fatality-rate estimates.

Comparing adjusted fatality rates only from old-generation turbines mutually monitored during both 1998–2003 and 2005–2007, fatality rates increased 110% for burrowing owl, 247% for barn owl (*Tyto alba*), 163% for rock pigeon (*Columba livia*), and 94% for western meadowlark (*Sturnella neglecta*), but not significantly for any other species (Table 4). Fatality rates increased 81% for the 4 target species together, 85% for all raptors, and 51% for all birds. Estimated mean fatality rate of red-tailed hawk increased 79%, but this increase was not significant.

Diablo Winds Fatality Rates

The first repowering project in the APWRA did not change fatality rates for any species or group of species, because fatality rates did not differ between the old vertical-axis turbines and the new horizontal axis turbines (Table 5). Though not significant, mean adjusted fatality rate increased for golden eagle from zero at the vertical-axis turbines in 1998–2001 to one eagle in 3 years during 2005–2007. Mean adjusted fatality rate increased 124% for red-tailed hawk, but decreased 13% for American kestrel, 21% for burrowing owl, 12% for all 4 target species together, and 25% for all

Table 4. Comparison of mean fatality-rate estimates at wind turbines mutually searched during both the 1998–2002 and in 2005–2007 monitoring programs, using 2-tailed paired-sample *t*-tests (df = 109). We searched turbines 1.5–4.5 years (most >2 yr) in 1998–2002 and 2 years in 2005–2007. Turbines totaled 81.63 megawatts (MW) of rated capacity in 110 rows, mostly in the central, eastern, and southern aspects of the Altamont Pass Wind Resource Area, California, USA.

	Adjusted fatality-rate (deaths/MW/yr)					
	1998–2003		2005–2007			
Species[a]	$\bar{x}$	SE	$\bar{x}$	SE	Paired-sample *t*-value	*P*-value
Turkey vulture	0.009	0.009	0.003	0.003	0.676	0.500
Golden eagle	0.070	0.024	0.091	0.035	0.499	0.619
Red-tailed hawk	0.437	0.121	0.782	0.148	1.756	0.082
Buteo spp.	0.000	0.000	0.016	0.015	1.083	0.281
Northern harrier	0.006	0.003	0.015	0.011	0.864	0.389
Prairie falcon	0.003	0.003	0.006	0.004	0.608	0.545
American kestrel	0.496	0.147	0.532	0.146	0.172	0.864
Burrowing owl	1.442	0.345	3.025	0.524	2.690	0.008
Great horned owl	0.043	0.023	0.048	0.026	0.149	0.882
Barn owl	0.077	0.027	0.268	0.065	2.663	0.009
Double-crested cormorant	0.017	0.017	0.000	0.000	1.000	0.320
Great blue heron	0.000	0.000	0.004	0.004	1.000	0.320
Great egret	0.000	0.000	0.156	0.156	1.000	0.320
Killdeer	0.000	0.000	0.012	0.012	1.000	0.320
Black-necked stilt	0.000	0.000	0.130	0.130	1.000	0.320
American avocet	0.059	0.049	0.000	0.000	1.186	0.238
Gull spp.	0.030	0.019	0.122	0.049	1.987	0.049
Ring-billed gull	0.029	0.024	0.000	0.000	1.229	0.222
California gull	0.028	0.016	0.035	0.035	0.173	0.863
Duck spp.	0.000	0.000	0.017	0.017	1.000	0.320
Mallard	0.187	0.065	0.137	0.090	0.824	0.412
Northern flicker	0.247	0.157	0.087	0.090	0.888	0.377
Wild turkey	0.013	0.013	0.000	0.000	1.000	0.320
Dove spp.	0.000	0.000	0.101	0.052	1.952	0.054
Rock pigeon	1.339	0.340	3.520	0.642	3.846	0.000
Mourning dove	2.538	0.943	1.054	0.305	1.488	0.140
White-throated swift	0.000	0.000	0.027	0.027	1.000	0.320
American crow	0.068	0.044	0.049	0.031	0.345	0.731
Common raven	0.088	0.068	0.145	0.053	0.668	0.506
Pacific-slope flycatcher	0.058	0.058	0.000	0.000	1.000	0.320
Western kingbird	0.021	0.021	0.000	0.000	1.000	0.320
Horned lark	0.455	0.171	0.456	0.364	0.003	0.998
Tree swallow	0.000	0.000	0.013	0.013	1.000	0.320
Cliff swallow	0.063	0.063	0.046	0.036	0.226	0.821
Mountain bluebird	0.000	0.000	0.081	0.051	1.578	0.117
Northern mockingbird	0.082	0.082	0.000	0.000	1.000	0.320
Loggerhead shrike	0.066	0.052	0.438	0.185	1.918	0.058
European starling	1.704	0.466	3.235	0.770	1.713	0.090
Sparrow spp.	0.000	0.000	0.044	0.044	1.000	0.320
Savanna sparrow	0.073	0.073	0.000	0.000	1.000	0.320
Western meadowlark	1.964	0.526	3.817	0.693	2.070	0.041
Blackbird spp.	0.000	0.000	0.713	0.488	1.460	0.147
Red-winged blackbird	0.505	0.223	0.330	0.148	0.686	0.494
Tricolored blackbird	0.030	0.030	0.000	0.000	1.000	0.320
Brewer's blackbird	0.246	0.142	0.226	0.120	1.000	0.320
Brown-headed cowbird	0.058	0.058	0.000	0.000	1.000	0.320
House finch	0.693	0.331	0.000	0.000	2.090	0.039
Cockatiel	0.000	0.000	0.068	0.068	1.000	0.320
Unidentified bird spp.	0.450	0.170	0.269	0.127	2.109	0.037
Songbird spp.	0.526	0.233	1.184	0.372	1.560	0.122
Medium nonraptor spp.	0.000	0.000	0.199	0.090	2.214	0.029
Large nonraptor spp.	0.000	0.000	0.125	0.073	1.708	0.090
Bats	0.115	0.073	0.263	0.172	0.79	0.433
Target raptor species	2.445	0.381	4.430	0.538	3.13	0.002
Total raptors	2.583	0.380	4.786	0.537	3.48	0.001
Total birds	14.220	1.542	21.627	2.079	3.00	0.003

[a] See Appendix for scientific names.

birds (Table 5). Adjusted fatality rate of bats increased from zero at the old vertical-axis turbines to 16.4/year at the new, repowered turbines, but this difference was not significant, probably due to small sample sizes.

Compared to concurrently operating old-generation turbines during 2005–2007, adjusted fatality rates in the repowered Diablo Winds turbines were lower by 64% for red-tailed hawks, 92% for American kestrel, 92% for rock

Table 5. Fatality rates caused by Diablo Winds Energy Project in the Altamont Pass Wind Resource Area, California, USA, 1) before (1998–2001) and after (2005–2007) repowering from Flowind 150-kilowatt (kW) and 250-kW vertical-axis turbines to Vestas 660-kW turbines, using 2-tailed paired-sample *t*-tests (df = 35), and 2) between repowered wind turbines in the Diablo Winds Energy Project and old-generation wind turbines operating concurrently in 2005–2007, using 2-tailed independent samples *t*-tests (df = 344).

	Adjusted fatality-rates (deaths/megawatt/yr)						*P*-value	
	Before repowering 1998–2002		After repowering 2005–2007		Old generation turbines 2005–2007		Before to after repowering at Diablo Winds	Diablo Winds to old turbines after repowering
Species[a]	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE		
Turkey vulture	0.000	0.000	0.016	0.016	0.018	0.013	0.337[c]	0.970[b]
Golden eagle	0.000	0.000	0.016	0.016	0.118	0.029	0.337[c]	0.489[b]
Red-tailed hawk	0.111	0.066	0.247	0.096	0.692	0.081	0.238[b]	0.001[c]
American kestrel	0.076	0.076	0.066	0.066	0.779	0.131	0.934[b]	0.000[c]
Burrowing owl	1.809	0.730	1.429	0.431	1.873	0.261	0.719	0.737[b]
Barn owl	0.208	0.186	0.012	0.012	0.257	0.048	0.444[b]	0.314[b]
Pied-billed grebe	0.000	0.000	0.268	0.268	0.000	0.000	0.337[c]	0.337[c]
Gull spp.	0.157	0.157	0.100	0.053	0.113	0.035	0.795[b]	0.940[b]
Mallard	0.519	0.426	0.033	0.033	0.122	0.063	0.410[b]	0.781[b]
Cliff swallow	0.487	0.403	0.000	0.000	0.036	0.024	0.383[b]	0.766[b]
Loggerhead shrike	0.000	0.000	0.179	0.121	0.321	0.110	0.165[c]	0.799[b]
European starling	0.628	0.319	0.604	0.361	3.317	0.453	0.963[b]	0.238[b]
Horned lark	0.085	0.085	0.090	0.090	0.515	0.178	0.971[b]	0.637[b]
Rock pigeon	0.089	0.071	0.114	0.072	1.468	0.235	0.820[b]	0.000[c]
Mourning dove	0.000	0.000	0.157	0.107	0.574	0.131	0.147[c]	0.532[b]
Hammond's flycatcher	0.000	0.000	0.090	0.090	0.005	0.005	0.337[c]	0.366[c]
Western meadowlark	2.249	0.945	1.747	0.597	3.135	0.338	0.715[b]	0.409[b]
Blackbird spp.	0.325	0.325	0.000	0.000	0.381	0.174	0.470[b]	0.666[b]
Brewer's blackbird	0.330	0.330	0.000	0.000	0.357	0.119	0.470[b]	0.554[b]
House finch	0.450	0.346	0.090	0.090	0.000	0.000	0.455[b]	0.337[c]
Unidentified bird	0.000	0.000	0.411	0.275	0.299	0.108	0.161[c]	0.839[b]
Bats	0.000	0.000	0.783	0.548	0.087	0.057	0.179[c]	0.231[c]
Target species	1.996	0.763	1.758	0.393	3.462	0.309	0.784[c]	0.002[c]
Total raptors	2.204	0.762	1.786	0.388	3.737	0.316	0.628[c]	0.000[c]
Total birds	7.523	1.564	5.669	1.291	14.380	1.054	0.432[b]	0.000[c]

[a] See Appendix for scientific names.
[b] Assumed equal variances, because $P > 0.05$ in Levene's Test for Equality of Variances.
[c] Assumed unequal variances, because $P \leq 0.05$ in Levene's Test for Equality of Variances.

pigeon, 49% for all target raptors, 54% for all raptors, and 66% for all birds (Table 5). Though not significant, mean adjusted fatality estimates were lower by 87% for golden eagles, 24% for burrowing owls, 95% for barn owl, 83% for horned lark (*Eremophila alpestris actia*), 73% for mourning dove (*Zenaida macroura*), 44% for loggerhead shrike (*Lanius ludovicianus*), and 44% for western meadowlark. Adjusted fatality rate of bats was nearly 800% greater at repowered turbines compared to concurrently operated old-generation turbines, but this large difference was not significant, probably due to sample sizes.

DISCUSSION

The APWRA-wide estimates of adjusted fatality rates did not lessen since 1998–2003, even though 200 100-kW Vestas turbines did not operate over 16 months of the 2005–2007 monitoring period and most APWRA turbines were shut down for 2 months of each winter. Among the mutually surveyed old-generation wind turbines, adjusted fatality rates increased significantly for the target raptors, all raptors, and all birds. We propose 4 alternative hypotheses for why the Avian Protection Program has not yet reduced fatality rates.

First, our data suggest that fatality rates might have increased if wind power generation increased within the APWRA. However, wind-power generation data from 1999 and 2006 did not support this hypothesis, assuming power generation during these years represented the corresponding fatality monitoring periods. We related monthly power-generation data maintained by the California Energy Commission to our estimated annual adjusted fatality rates for the subset of old-generation wind turbines that we searched during both monitoring periods. The capacity factor (annual MW-hr/MW of rated capacity, expressed as %) of the APWRA's old generation turbines actually decreased between 1999 and 2006 from 16.7% to 13.3%. Thus, annual deaths per gigawatt (GW)-hour increased for most species, and it increased from 1.71 raptors/GW-hour to 3.98 raptors/GW-hour (133%) and from 9.42 birds to 17.92 birds/GW-hour (90%). Fatality rates increased although power generation from old-generation turbines decreased.

Second, we suggest that increases in fatality rates may have tracked increases in avian abundance in the APWRA. We were unable to test whether relative abundance increased because utilization data remained unprepared to account for methodological differences between monitoring periods, especially the maximum distance from the observer at which birds were recorded.

Third, we suggest that fatality rates increased due to methodological bias. Our adjustments for scavenger removal were intended to account for the difference in average search interval between the 1998–2002 and 2005–2007 monitoring periods, but we lack an independent check on whether the adjustment was sufficient. It is possible that fatality rates only appeared to increase due to the shorter search interval in 2005–2007.

Fourth, we suggest that fatality rates might have increased due to inadequate or even counterproductive implementation of the Avian Protection Program (Table 2). The wind companies delayed relocating hazardous turbines until late 2007. Wind companies left vacant lattice towers at ends of rows as flight diverters, but this practice may have caused more raptor fatalities because raptors readily perched on vacant towers, which were adjacent to operating turbines. We often observed perched raptors flush as other territorial or predatory birds approached, and perched raptors often altered flight patterns of smaller raptors. Increases in these types of interactions could have led to increased collisions. Vacant towers and broken turbines were also left within turbine rows, which created gaps amongst functional turbines, and these gaps might have encouraged raptors to attempt row crossings where other raptors were perched. Alameda County required a winter shut-down that reactivated half the turbines when red-tailed hawks peaked in number and were likely habituated to shut-down turbines. For a company with 20% of the APWRA's turbines, the County waived the required increase in the duration of its winter shut-down. The blade-painting experiment of Altamont Winds, Inc. (Oakland, CA) was too small in scope to be noticed in APWRA-wide estimates of fatality rates. Finally, the year-long delay in forming the SRC also delayed scientific input on these measures.

The Diablo Winds repowering project did not reduce fatality rates compared to replaced turbines, but probably because the replaced turbines were largely defunct by the time we monitored them for fatalities in 1998–2001. We lack sufficient resolution in the wind-energy generation data at the California Energy Commission to test whether the Flowind vertical-axis turbines were declining in power output before replacement, but we recall that they rarely operated during our fatality searches. We suspect that starting with Diablo Winds, the least productive wind turbines are those selected for repowering, resulting in small if any reductions in fatality rates within the repowering project. Perhaps more relevant than comparing to fatality rates caused by a group of turbines already phased out of existence, we found substantially lower fatality rates caused by the new Diablo Winds turbines compared to concurrently operating old-generation turbines during 2005–2007. Fatality rates seemed lower yet after factoring in the improved capacity factor of the repowered turbines, which was 36.9% at Diablo Winds in 2006 compared with 13.3% at concurrently operating old-generation turbines. Fatalities per GW-hour at the repowered Diablo Winds project were lower than at the concurrently operating old-generation turbines by 94% for golden eagle, 84% for red-tailed hawk, 96% for American kestrel, 67% for burrowing owl, 78% for target raptors, 80% for all raptors, and 85% for all birds. Repowering the entire APWRA would likely reduce fatality rates a great deal, especially if considered on a power generation basis and if carefully done by locating new turbines where they pose the least hazard (Smallwood and Neher 2005, Smallwood et al. 2009). The improved capacity factor of new-generation turbines could also offset much of the nameplate capacity in the APWRA, so assuming the 36.9% capacity factor would apply throughout the APWRA, the same power generation could be achieved by 209 MW of nameplate capacity instead of the permitted 580 MW operating in the APWRA today. This capacity would include 209–317 wind turbines, assuming the turbines would range in size from 660 kW to 1 MW or 4% to 6% of the approximately 5,000 turbines that operated in 2005–2007. Turbine operations could also be restricted to times of day, seasons, or specific wind conditions to further reduce fatality rates.

A possible downside to repowering, however, may be increased bat fatalities caused by wind turbines. Extrapolating the mean adjusted bat fatality rate from Diablo Winds to a completely repowered APWRA, about 454 bat fatalities/year might result, but using more realistic scavenger-removal and searcher-detection rates could increase this number to thousands of bats. Bat fatalities in the APWRA need additional, focused research.

MANAGEMENT IMPLICATIONS

To reduce avian fatality rates caused by wind turbines in the Altamont Pass, the old-generation wind turbines should be carefully repowered as soon as possible because estimated mean annual fatalities could be reduced 54% for all raptors and 65% for all birds, while adding about 1,000 GW-hours of wind energy annually due to the nearly 3-fold increase in the capacity factor of new-generation turbines. Alternatively, the nameplate capacity of the repowered APWRA could be restricted to 209 MW to meet current energy generation levels, thereby reducing estimated mean annual fatalities 83% for all raptors and 87% for all birds. To lessen fatality rates before repowering, Alameda County would need to enforce permit conditions and require implementation of SRC recommendations, including a 4-month winter shut-down of all wind turbines, removal or careful relocation of the most hazardous turbines, and removal of vacant towers and broken turbines. Finally, State and Federal regulatory agencies could help reduce fatality rates by enforcing the MBTA and other environmental laws.

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Appendix. Avian and bat species recorded as fatalities or mortally wounded at wind turbines of the Altamont Pass Wind Resource Area (APWRA), California, USA, from January 1989 through October 2007, including estimates of wind turbine–caused fatality rates from 2 time periods of scientific monitoring. We denote status as FE = Federal Endangered, FT = Federal Threatened, CE = California Endangered, CT = California Threatened, CFP = California Fully Protected, CSC = California Department of Fish and Game listing of California Species of Concern. California Fish and Game Code 3503.5 protected all raptors, and the Migratory Bird Treaty Act protected all species in the table except exotic species and bats. We revised fatality estimates for 1998–2003 from those of Smallwood and Thelander (2008) by including the wind companies' Wildlife Response and Reporting System (WRRS) data and using similar assumptions to those of the 2005–2007 monitoring period. The 2005–2007 annual fatality estimates were sums of estimated annual fatalities from separate monitoring efforts, including from East Bay Regional Park District, Diablo Winds Energy Project, and a stratified random sample of turbines. LCL and UCL denote lower and upper confidence limits, respectively.

Species or taxonomic group	Species name	Status	Recorded deaths 1989–2007	Estimated APWRA-wide annual fatalities (80% CI)					
				1998–2003			2005–2007		
				Total	LCL	UCL	Total	LCL	UCL
Turkey vulture	*Cathartes aura*		32	2.5	0.6	4.5	10.2	0.8	19.6
Golden eagle	*Aquila chrysaetos*	CSC, CFP	495	55.3	24.3	86.3	64.7	42.3	87.0
Cooper's hawk	*Accipiter cooperii*	CSC	1						
Red-tailed hawk	*Buteo jamaicensis*		1250	177.3	114.5	240.2	391.7	302.8	480.6
Ferruginous hawk	*Buteo regalis*	CSC	13	0.0	0.0	0.0	4.0	−1.0	8.9
Swainson's hawk	*Buteo swainsoni*	CT	2	0.0	0.0	0.0	0.5	−0.2	1.2
Rough-legged hawk	*Buteo lagopus*		1						
Red-shouldered hawk	*Buteo lineatus*		1	0.0	0.0	0.0	0.3	−0.1	0.7
Buteo spp.	*Buteo* spp.		45	0.0	0.0	0.0	16.6	6.4	26.9
Northern harrier	*Circus cyaeneus*	CSC	10	0.7	0.1	1.2	3.3	0.7	5.9
White-tailed kite	*Elanus leucurus*	CFP	3	0.0	0.0	0.0	0.4	−0.1	0.8
Hawk spp.			8	0.0	0.0	0.0	1.0	−0.3	2.2
Peregrine falcon	*Falco peregrinus*	CE, CFP	2						
Prairie falcon	*Falco mexicanus*	CSC	8	1.1	0.2	2.0	1.3	0.3	2.4
American kestrel	*Falco sparverius*		217	731.2	286.0	1,176.3	439.9	285.3	594.5
Falcon spp.	*Falco* spp.		2						
Burrowing owl	*Athene cunicularia*	CSC	287	858.3	241.2	1,475.4	1,112.4	736.8	1,487.9
Great horned owl	*Bubo virginianus*		91	7.3	3.3	11.2	31.8	18.6	45.0
Long-eared owl	*Asio otus wilsonianus*	CSC	2						
Barn owl	*Tyto alba*		286	46.0	19.2	72.7	150.2	103.6	196.8
Owl spp.			3	0.0	0.0	0.0	0.1	0.0	0.3
Large raptor spp.			4	0.0	0.0	0.0	1.3	0.1	2.6
Raptor spp.			66	0.2	−0.1	0.5	2.3	0.2	4.4
Common poorwill	*Phalaenoptilus nuttallii*		1						
Brown pelican	*Pelicanus occidentalis*	FE, CE	1						
Double-crested cormorant	*Phalacrocorax auritus*	CSC	2	2.1	−0.7	4.8	0.0	0.0	0.0
Pied-billed grebe	*Podilymbus podiceps*		1	0.0	0.0	0.0	5.4	−2.3	13.2
Black-crowned night heron	*Nycticorax nycticorax*	CSA	3	1.1	0.0	2.2	0.0	0.0	0.0
Great blue heron	*Ardea herodius*		9	0.0	0.0	0.0	0.7	−0.2	1.7
Great egret	*Ardea alba*		2	0.0	0.0	0.0	28.1	−9.1	65.3

Appendix. Continued.

Species or taxonomic group	Species name	Status	Recorded deaths 1989–2007	Estimated APWRA-wide annual fatalities (80% CI)					
				1998–2003			2005–2007		
				Total	LCL	UCL	Total	LCL	UCL
Cattle egret	*Bubulcus ibis*	Exotic	1	3.1	−1.1	7.3	0.0	0.0	0.0
Sandhill crane	*Grus canadensis*	CT	1	0.0	0.0	0.0	1.5	−0.5	3.5
Long-billed curlew[a]	*Numenius americanus*	CSC	3						
Black-necked stilt	*Himantopus mexicanus*		1	0.0	0.0	0.0	23.0	−11.2	57.1
American avocet	*Recurvirostra americana*		4	6.7	−0.9	14.3	0.0	0.0	0.0
Lesser yellowlegs	*Tringa flavipes*		1	1.9	−1.1	4.9	0.0	0.0	0.0
Killdeer	*Charadrius vociverus*		4	0.0	0.0	0.0	6.3	−1.3	13.9
Ring-billed gull	*Larus delawarensis*		6	8.6	1.2	16.0	0.0	0.0	0.0
California gull	*Larus californicus*	CSC	21	8.8	2.8	14.8	6.4	−2.1	14.8
Herring gull	*Larus argentatus*		2						
Thayer's gull	*Larus thayeri*		1						
Mew gull	*Larus canus*		1						
Gull spp.	*Larus* spp.		85	109.2	38.0	180.4	65.0	31.0	98.9
Mallard	*Anas platyrhynchos*		67	55.6	13.0	98.2	67.5	17.3	117.7
Ring-necked duck	*Aythya collaris*		1	4.2	−1.5	9.9	0.0	0.0	0.0
Duck spp.			5	0.0	0.0	0.0	9.8	1.8	17.7
Wild turkey	*Melleagris gallopavo*	exotic	3	1.5	−0.5	3.6	0.9	−0.3	2.1
Mourning dove	*Zenaida macroura*		77	468.0	−112.0	1047.9	313.2	59.3	567.1
Rock pigeon	*Columba livia*	exotic	731	324.9	197.8	452.1	2,292.5	1,266.6	3,318.3
Band-tailed pigeon	*Columba fasciata*		1						
Dove spp.			11	0.0	0.0	0.0	35.6	1.4	69.9
Northern flicker	*Colaptes auratus*		9	147.3	−116.9	411.5	15.3	−7.5	38.1
White-throated swift	*Aeronautes saxatalis*		3	0.0	0.0	0.0	40.9	−10.1	91.9
Vaux's swift	*Chaetura vauxi vauxi*		1						
Tree swallow	*Tachycineta bicolor*		1	0.0	0.0	0.0	2.3	−1.1	5.8
Violet-green swallow	*Tachycineta thalassina*		2	2.4	−1.4	6.2	0.0	0.0	0.0
Cliff swallow	*Hirundo pyrrhonota*		10	29.8	−4.6	64.3	27.0	−4.9	59.0
Loggerhead shrike	*Lanius ludovicianus*	CSC	29	122.8	−97.7	343.4	181.4	21.6	341.2
Northern shrike	*Lanius excubitor*		1						
European starling	*Sturnus vulgaris*	exotic	315	1,319.0	−712.7	3,350.7	1,882.9	421.5	3,344.4
Northern mockingbird	*Mimus polyglottos*		3	9.3	−5.5	24.0	9.3	−4.5	23.2
Swainson's thrush	*Catharus ustulatus*		1	0.0	0.0	0.0	8.4	−4.1	20.9
American robin	*Turdus migratorius*		1						
Horned lark	*Eremophila alpestris actia*	CSC	56	114.0	−24.9	252.9	292.5	34.5	550.5
American crow	*Corvus brachyrhynchos*		24	15.8	2.5	29.0	30.5	12.1	48.9
Common raven	*Corvus corax*		86	40.8	1.0	80.6	88.8	40.1	137.6
Scrub jay	*Aphelocoma californica*		3	0.0	0.0	0.0	0.9	−0.4	2.2
Corvid spp.			14						
Pacific-slope flycatcher	*Empidonax difficilis*		1	6.4	−3.8	16.6	0.0	0.0	0.0
Western kingbird	*Tyrannus verticalis*		1	2.5	−1.5	6.5	0.0	0.0	0.0
Hammond's flycatcher	*Empidonax hammondii*		2	0.0	0.0	0.0	4.7	−2.2	11.7
Say's phoebe	*Sayornis saya*		4	0.0	0.0	0.0	11.3	−5.5	28.0
Western tanager	*Piranga ludoviciana*		1	0.0	0.0	0.0	2.2	−1.1	5.5
American pipit	*Anthus rubescens*		2	0.0	0.0	0.0	3.3	−1.6	8.1
Bluebird spp.			3	0.0	0.0	0.0	51.0	−6.1	108.1
Mountain bluebird	*Sialia currucoides*		22	146.5	−117.7	410.8	33.8	2.6	65.1
Western bluebird	*Sialia mexicana*		5						
House wren	*Troglodytes aedon*		1	0.0	0.0	0.0	4.7	−2.3	11.7
Rock wren	*Salpinctes obsoletus*		2	0.0	0.0	0.0	8.9	−4.3	22.2
Yellow warbler	*Dendroica petechia*	CSC	1	3.6	−2.1	9.3	0.0	0.0	0.0
Sparrow spp.			3	0.0	0.0	0.0	7.8	−3.8	19.4
Townsend's warbler	*Dendroica townsendi*		1						
Orange-crowned warbler	*Vermivora celata*		1						
Fox sparrow	*Passerella iliaca*		1						
Savanna sparrow	*Passerculus sandwichensis*		2	33.0	−31.1	97.1	0.0	0.0	0.0
Lincoln sparrow	*Melospiza lincolnii*		1	0.0	0.0	0.0	2.9	−1.4	7.3
Western meadowlark	*Sturnella neglecta*		344	1,594.2	−796.5	3,984.9	1,761.7	411.2	3,112.3
Brewer's blackbird	*Euphagus cyanocephalus*		39	340.5	−249.7	930.7	193.8	26.1	361.4
Brown-headed cowbird	*Molothrus ater*		3	145.9	−151.8	443.6	28.8	−14.0	71.6
Red-winged blackbird	*Agelaius phoeniceus*		35	77.3	−3.1	157.7	139.6	20.2	259.1
Tricolored blackbird	*Agelaius tricolor*	CSC	1	3.9	−2.3	10.1	0.0	0.0	0.0

Appendix. Continued.

Species or taxonomic group	Species name	Status	Recorded deaths 1989–2007	Estimated APWRA-wide annual fatalities (80% CI)					
				1998–2003			2005–2007		
				Total	LCL	UCL	Total	LCL	UCL
Blackbird spp.			16	9.5	−5.7	24.8	210.5	10.4	410.6
House finch	*Carpodacus mexicanus*		23	99.9	−6.5	206.3	1.8	−0.8	4.4
House sparrow	*Passer domesticus*	exotic	1	46.5	−49.3	142.3	0.0	0.0	0.0
Cockatiel	*Leptolophus hollandicus*	exotic	2	3.0	−1.8	7.7	12.2	−5.9	30.4
Small nonraptors			120	74.7	−4.4	153.7	339.9	65.8	614.0
Medium, large nonraptors			91	0.0	0.0	0.0	122.6	47.0	198.3
Bird spp.			120	285.9	−168.8	740.6	169.5	18.0	321.0
Target raptor species			2,249	1,822.1	666.0	2,978.2	2,008.6	1,367.1	2,650.0
Total raptors			2,289	1,879.8	689.3	3,070.3	2,232.0	1,496.1	2,967.9
Total birds			5,283	7,549.9	−1,731.9	16,831.8	9,297.1	3,217.8	1,5376.4
Mexican free-tail bat	*Tadarida brasiliensis*		3						
Western red bat	*Lasiurus borealis teleotis*		2						
Hoary bat	*Lasiurus cinereus*		11						
Bat spp.			3						
Total bats			19	14.4	−3.5	32.3	68.4	−5.4	142.1

[a] Reportedly found by Orloff and Flannery (1992) but did not appear in WRRS data base.