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Management and Conservation Article

Influence of Behavior on Bird Mortality in Wind Energy Developments

K. SHAWN SMALLWOOD,[1] *3108 Finch Street, Davis, CA 95616, USA*
LOURDES RUGGE,[2] *California State University, Sacramento, Department of Biological Sciences, 6000 J Street, Sacramento, CA 95819, USA*
MICHAEL L. MORRISON, *Department of Wildlife and Fisheries Sciences, Texas A&M University, College Station, TX 77843, USA*

ABSTRACT As wind power generation is rapidly expanding worldwide, there is a need to understand whether and how preconstruction surveys can be used to predict impacts and to place turbines to minimize impacts to birds. Wind turbines in the 165-km^2 Altamont Pass Wind Resource Area (APWRA), California, USA, cause thousands of bird fatalities annually, including hundreds of raptors. To test whether avian fatality rates related to rates of utilization and specific behaviors within the APWRA, from March 1998 to April 2000 we performed 1,959 30-minute behavior observation sessions (360° visual scans using binoculars) among 28 nonoverlapping plots varying from 23 ha to 165 ha in area and including 10–67 turbines per plot, totaling 1,165 turbines. Activity levels were highly seasonal and species specific. Only 1% of perch time was on towers of operating turbines, but 22% was on towers of turbines broken, missing, or not operating. Of those species that most often flew through the rotor zone, fatality rates were high for some (e.g., 0.357 deaths/megawatt of rated capacity [MW]/yr for red-tailed hawk [*Buteo jamaicensis*] and 0.522 deaths/MW/yr for American kestrel [*Falco sparverius*]) and low for others (e.g., 0.060 deaths/MW/yr for common raven [*Corvus corax*] and 0.012 deaths/MW/yr for turkey vulture [*Cathartes aura*]), indicating specific behaviors or visual acuity differentiated these species by susceptibility to collision. Fatality rates did not correlate with utilization rates measured among wind turbine rows or plots for any species except burrowing owl (*Athene cunicularia*) and mallard (*Anas platyrhynchos*). However, mean monthly fatality rates of red-tailed hawks increased with mean monthly utilization rates ($r^2 = 0.67$) and especially with mean monthly flights through turbine rows ($r^2 = 0.92$). Fatality rates increased linearly with rates of utilization ($r^2 = 0.99$) and flights near rotor zones ($r^2 = 1.00$) for large raptor species and with rates of perching ($r^2 = 0.13$) and close flights ($r^2 = 0.77$) for small non-raptor species. Fatalities could be minimized or reduced by shutting down turbines during ≥ 1 season or in very strong winds or by leaving sufficiently large areas within a wind farm free of wind turbines to enable safer foraging and travel by birds. (JOURNAL OF WILDLIFE MANAGEMENT 73(7):1082–1098; 2009)

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KEY WORDS Altamont Pass, behavior, birds, fatality rate, utilization, wind turbine.

The Altamont Pass Wind Resource Area (APWRA) has caused numerous bird fatalities due to collisions with wind turbines, electrocutions on electric distribution poles, and other causes related to the wind farm (Howell et al. 1991; Orloff and Flannery 1992, 1996; Smallwood and Thelander 2008). Wind turbine–caused fatality rates were recently estimated at 2,710 (SE = 11.848) birds per year in the APWRA, including 1,127 (SE = 1.547) raptors per year (Smallwood and Thelander 2008). As a result of these high fatality rates, bird mortality has been investigated at other wind farms throughout North America, and bird behaviors and activity levels have been investigated at some of these (Janss and Clave 2000; Kerlinger 2000; Anderson et al. 2004, 2005; Hoover and Morrison 2005). These investigations attest to the importance attributed to bird behaviors and activity levels in relation to bird collisions with wind turbines.

Investigators have often monitored live birds at wind farms pre- and postconstruction, usually due to operating permit requirements but sometimes for research purposes. Bird monitoring has been directed toward measuring site utilization and identifying behaviors that are more hazardous and which might be exploited to mitigate wind turbine collisions. At wind farms these objectives are usually pursued simultaneously using visual scans over timed sessions to not only count birds using the area, but also to identify flight paths and frequencies of behaviors that might help guide wind turbine placement and tower height, inter-turbine arrangement, timing of operations, and land management practices.

During the last 2 decades, it has been hypothesized that specific behaviors predispose certain species to more likely collide with operating wind turbines (e.g., Orloff and Flannery 1992; Erickson et al. 1999; Strickland et al. 2001*b*; Smallwood and Thelander 2004, 2005). It has been hypothesized that the amount of time a species uses a wind farm, referred to as utilization rate, also contributes to wind turbine collision rates (Morrison 1998, Anderson et al. 2001, Strickland et al. 2001*a*, Hunt 2002). We related wind turbine–caused fatality rates to rates of utilization and specific behaviors. We also related bird behaviors and activity levels that were associated with wind turbines to environmental conditions in the APWRA. We hypothesized that birds lose track of wind turbines while focused on diving for prey items, fly-catching, and hovering.

STUDY AREA

The APWRA occupied about 16,450 ha of mostly annual grassland in eastern Alameda County and southeastern Contra Costa County, California, USA. It ranged from 78 m to 470 m above mean sea level, composed of hills, ridges, and valleys, and including stock ponds, small seasonal ponds, and marshes. Most ridges were oriented northwest to southeast, bisected by seasonal streams. Other

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[1] *E-mail: puma@yolo.com*

[2] *Present address: ECORP Consulting, Inc., 2525 Warren Drive, Rocklin, CA 95677, USA*

physiographic elements included alkali meadow, emergent marsh, riparian woodland and scrub, and rock outcrops. Landowners principally grazed livestock but also leased land to wind turbine owners.

When our study began, the APWRA included about 5,400 wind turbines of various models with a total rated capacity of about 580 megawatts (MW). These wind turbines were owned by multiple companies and were mounted on 3 tower types with rotor hubs of vertical-axis turbines ranging from 14 m to 43 m above ground. Many were on ridge crests or ridgelines descending into ravines from the ridge crests. Smallwood et al. (2007) and Smallwood and Thelander (2008) provided additional details on APWRA land uses, wind turbines, and other aspects of the study area.

METHODS

Field Methods

Two biologists collected bird behavior data in 28 study plots from 26 March 1998 through 18 April 2000. Study plots were nonoverlapping and ranged from 23 ha to 165 ha ($\bar{x}$ = 94 ha) in area due to complex terrain and the irregular arrangement of wind turbines. Plots contained 10–67 turbines each, totaling 1,165 turbines, or all of the turbines accessible to us in 1998–2000. All the turbines in each plot were visible from a fixed observation point. Twelve plots included wind turbines on lattice towers only, 8 included turbines on tubular towers only, 7 included both tubular towers and vertical-axis turbines, and one included tubular and lattice towers. Observers carried plot maps to identify each turbine and to link it to recorded bird activities. Each observer performed circular visual scans (360°), also called variable distance circular point observations (Reynolds et al. 1980), using 8 × 40 binoculars out to 300 m from the wind turbines in the plot or shorter if the plot boundary was defined by topography (i.e., visibility) or where distances were equal between turbines in the plot under observation and those in the adjacent plot. Observation sessions lasted 30 minutes, and we often performed 2 sessions simultaneously on nonadjacent plots to improve our degree of independence between sessions. We typically completed 6–8 sessions per day.

We sampled all 28 plots once per 10–20 days on average, stratified by morning (0700 hr to 1200 hr) and afternoon (1201 hr to dusk), but most sessions started between 0900 hours and 1700 hours. We visited 20 plots 60–120 times each, and we added another 8 in October 1999 and visited them >20 times each. To represent behaviors in all weather conditions, we observed behaviors throughout the year, unless rain or fog reduced observer visibility to <50% of the turbines in the plot. Sessions were infrequent during January and May but were otherwise distributed evenly among seasons. Most occurred during moderate temperatures, from 10° C to 27° C.

We identified each bird entering the study plot and continuously followed it until it left the plot. We recorded species, number of birds in a flock, times of first and last detection, predominant flight behavior, and number of passes by a turbine. While the bird made its closest pass to the rotor zone, we recorded flight direction, distance to nearest wind turbine, type of wind turbine, and flight height relative to the rotor plane, which was the height above ground from the lowest to highest reaches of the turbine blades. We classified flight behaviors as fly-through, gliding, soaring, high soaring, contouring, circling, kiting–hovering, diving, mobbing, being mobbed, column soaring, surfing, ground hopping, hawking insects, fleeing, interacting with conspecifics, flocking, and flushed. We classified 21 perch structures, including ground, rock–vegetation, tree, fence post, the top, cross-arm, or wire of electric distribution poles, anemometer tower, electric transmission tower, top inner framework or guy wire of vertical-axis wind turbines, top or inside of wind turbine motors, turbine blade, turbine propeller cone, catwalk of wind tower, side ladder of wind tower, and top, lower, or middle framework of diagonal lattice wind turbine towers.

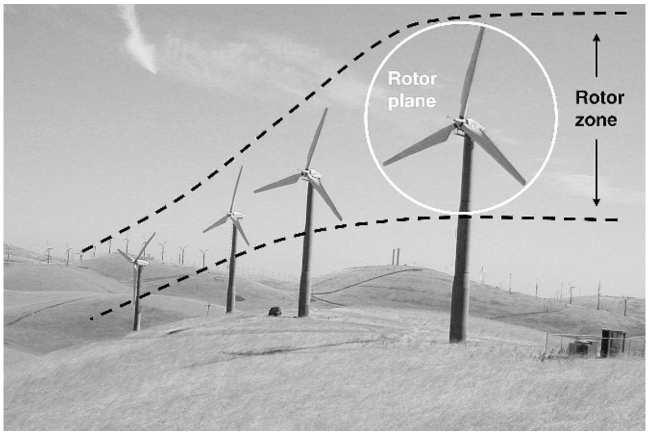

Figure 1. Rotor plane of a Bonus 150-kilowatt wind turbine (Bonus Wind Turbines, Inc., Brande, Denmark) in the Altamont Pass Wind Resource Area, California, USA, 1998–2003, and the upper and lower reaches of the rotor zone of the turbine row, where the rotor zone also extends 50 m laterally in all directions.

Of particular interest were behaviors and distances of flights from the rotor zone, which was where we assumed birds were most vulnerable to collisions. The rotor zone was the reach of the rotating turbine blades or rotor-swept area within 50 m of the blades, which was a 50-m extension of the rotor plane (Fig. 1). To improve accuracy and consistency in recording the closest pass to the rotor zone, both field assistants calibrated height and depth measurements of known objects every 6 months. To minimize observer bias in distance estimates and behavior reporting, we made paired observations over 18 sessions in the study's first month. Observers recorded behavioral information simultaneously but independently on separate data sheets. At the end of each calibration session, we compared information to help ensure consistency of behavior interpretations. Once observers achieved similar distance estimates and behavior records, they began conducting separate 30-minute observation sessions. Four calibration sessions were repeated over 1–2 days every 6 months.

We recorded specific behaviors with alphanumeric codes onto a standardized data sheet, along with session start time, temperature, wind speed, wind direction (its origin), number of turbines operating, and cloud cover at the beginning of each session. For analysis, we lumped actual start times into representative times of the day, so 0800 hours represented 0700–0859 hours, 1000 hours was for 0900–1059 hours, 1200 hours for 1100–1259 hours, 1400 hours for 1300–1459 hours, 1600 hours for 1500–1659 hours, and 1800 hours for 1700–2059 hours. We measured temperature with a handheld thermometer, and we aggregated temperatures across spans of 2.8° C (5° F) for analysis. We measured wind force on the Beaufort scale, where 0 was <0.3 m/second, 1 was 0.3–1.5 m/second, 2 was 1.6–3.3 m/second, 3 was 3.4–5.4 m/second, 4 was 5.5–7.9 m/second, 5 was 8–10.7 m/second, 6 was 10.8–13.8 m/second, and 7 was >13.8 m/second. When wind speed exceeded 15 m/second (near gale winds), we left the field for safety reasons (i.e., parts of wind turbines can become dislodged).

On fatality searches, biologists searched out to 50 m from all rows of wind turbines that were made available to us by the wind companies in the APWRA (Smallwood and Thelander 2008). Search intervals varied from weekly to greater than monthly and spanned 1.5–4.5 years or longer than the behavior observation study at most turbine rows. Fatalities considered herein, along with resulting fatality rate estimates, corresponded with turbine rows and plots included in this behavior study.

Analytical Methods

We expressed utilization rates as number of birds seen per session or per hour when we compared them by month of the year. We expressed utilization rates as mean number of observations per session per hectare when we compared them among plots or turbine rows. Turbine rows were bounded by the line equidistant between adjacent turbine rows and extended to the 300-m plot boundary nearest the turbine row. We used a Geographic Information System to delineate plot and turbine row boundaries and to calculate areas.

We also compared number occurrences of specific behaviors per session, per hour, and per hectare in the same manner we compared utilization rates. We related behavior rates to session start time, temperature during the session, month and season of the year, wind speed, wind direction, and distance from wind turbines.

To estimate fatality rates, we used only fatalities estimated to have been caused ≤ 90 days before discovery, found within 125 m of wind turbines, and not determined to have died by causes other than wind turbines. Even though 50 m was the search radius, searchers recorded all carcasses, no matter how far from turbines. We included carcasses seen out to 125 m because the hills under turbine rows were steep, permitting carcasses thrown from turbines 50 m laterally to fall down the slope farther than 50 m away as measured by rangefinder. Also, many of these carcasses were visible from within the search radius due to short-stature vegetation, though we undoubtedly missed carcasses beyond 50 m more often than within 50 m of turbines. We established our inclusion threshold of 125 m after the study, using our experience in the study area to judge how far searchers could reasonably scan the ground for carcasses from the 50-m search radius.

Within each turbine row, we expressed the fatality rate as number of fatalities per MW per year, where MW was the sum of the MW of rated power outputs for all of the wind turbines in the row searched. Although individual turbines killed birds, we used wind turbine row as our study unit because we sometimes could not determine which turbine within the row killed a bird. To the number of years used in the fatality rate estimate, we added the number of days equal to the average search interval used at each turbine row to represent the time period when carcasses could have accumulated before our first search. We adjusted fatality rates for searcher detection error and scavenger removal rates using the approach of Smallwood (2007), and we used fatality rate estimates in Smallwood and Thelander (2008), but in this case we used estimates specific to each wind turbine row and to behavior plots instead of the entire wind farm.

We compared fatality rates to utilization rates and behavior rates among the 28 observation plots and to turbine rows within the plots using Pearson's correlation tests and least squares regression analysis. We also tested for correlations between fatality and utilization rates by month of the year. We estimated fatality rate by month of the year by multiplying the mean annual fatality rate estimate by the proportion of fatalities backdated to each month, where we based backdating on the field biologists' estimate of number of days since death.

RESULTS

Characteristics of Observation Sessions

During observation sessions, we recorded wind direction most often from the southwest (41%), followed by northeast (17%), west (13%), and northwest (13%). Winds measured on the Beaufort scale were 0 for 1.8% of sessions, 1 for 17.4%, 2–4 for 58.9%, 5 for 11.3%, 6 for 7.4%, and 7 for 3.2% of sessions. Wind speeds measured on the Beaufort scale averaged fastest from the southwest ($\bar{x} = 3.94$, SD = 1.52), followed by the west ($\bar{x} = 3.45$, SD = 1.68), northwest ($\bar{x} = 3.13$, SD = 1.63), south ($\bar{x} = 2.76$, SD = 1.58), north ($\bar{x} = 2.24$, SD = 1.51), northeast ($\bar{x} = 2.14$, SD = 1.08), southeast ($\bar{x} = 2.08$, SD = 1.04), and east ($\bar{x} = 1.97$, SD = 1.09). Average monthly proportion of turbines operating during the session correlated strongly with average monthly wind speed measured on the Beaufort scale ($r_P = 0.98$, $n = 12$, $P < 0.001$), and both variables peaked during summer.

We observed 36 bird species during 1,959 behavior observation sessions spanning 979.5 hours. We recorded 48,396 individuals, or 24.7 individuals per session and 49.4 per hour. Factoring in the number of minutes of observations of tracked individuals, recorded bird activity totaled 460,520 minutes, 67% of which were of gulls (*Larus* spp.) making daily flights to a landfill located west of the

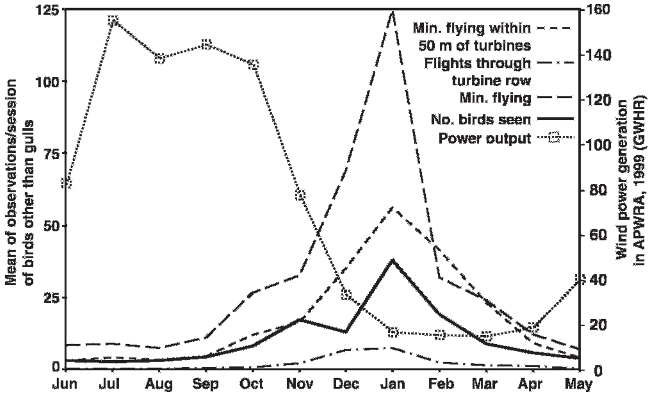

Figure 2. Middle of winter was when we observed avian species to peak in mean flying time, flight time within 50 m of wind turbines, number of passes through the turbine row, and number of birds seen in the plot, but winter was also the nadir of wind power generation in the Altamont Pass Wind Resource Area, California, USA, in 1999–2000.

central aspect of the APWRA. We observed no birds in 184 (9.4%) of the sessions.

Utilization rates (birds/session) were highly seasonal (Figs. 2, 3). Whereas power output peaked over summer, bird activity peaked over winter (Fig. 2). Flights through turbine rows and flights within 50 m of turbines peaked during winter, when wind turbine operations were lowest (Fig. 2). By species, red-tailed hawk and American kestrel (*Falco sparverius*) utilization of the APWRA peaked in late fall, whereas golden eagle (*Aquila chrysaetos*) utilization peaked in summer (Fig. 3). Turkey vulture (*Cathartes aura*) activity peaked in late summer and late winter, and common raven (*Corvus corax*) and gull activity peaked over winter and early spring. Western meadowlark (*Sturnella neglecta*), horned lark (*Eremophila alpestris*), and house finch (*Carpodacus mexicanus*) activity peaked in winter, but mourning dove (*Zenaida macroura*) activity peaked in early spring. Loggerhead shrike (*Lanius ludovicianus*) utilization was even throughout the year. Burrowing owl (*Athene cunicularia*)

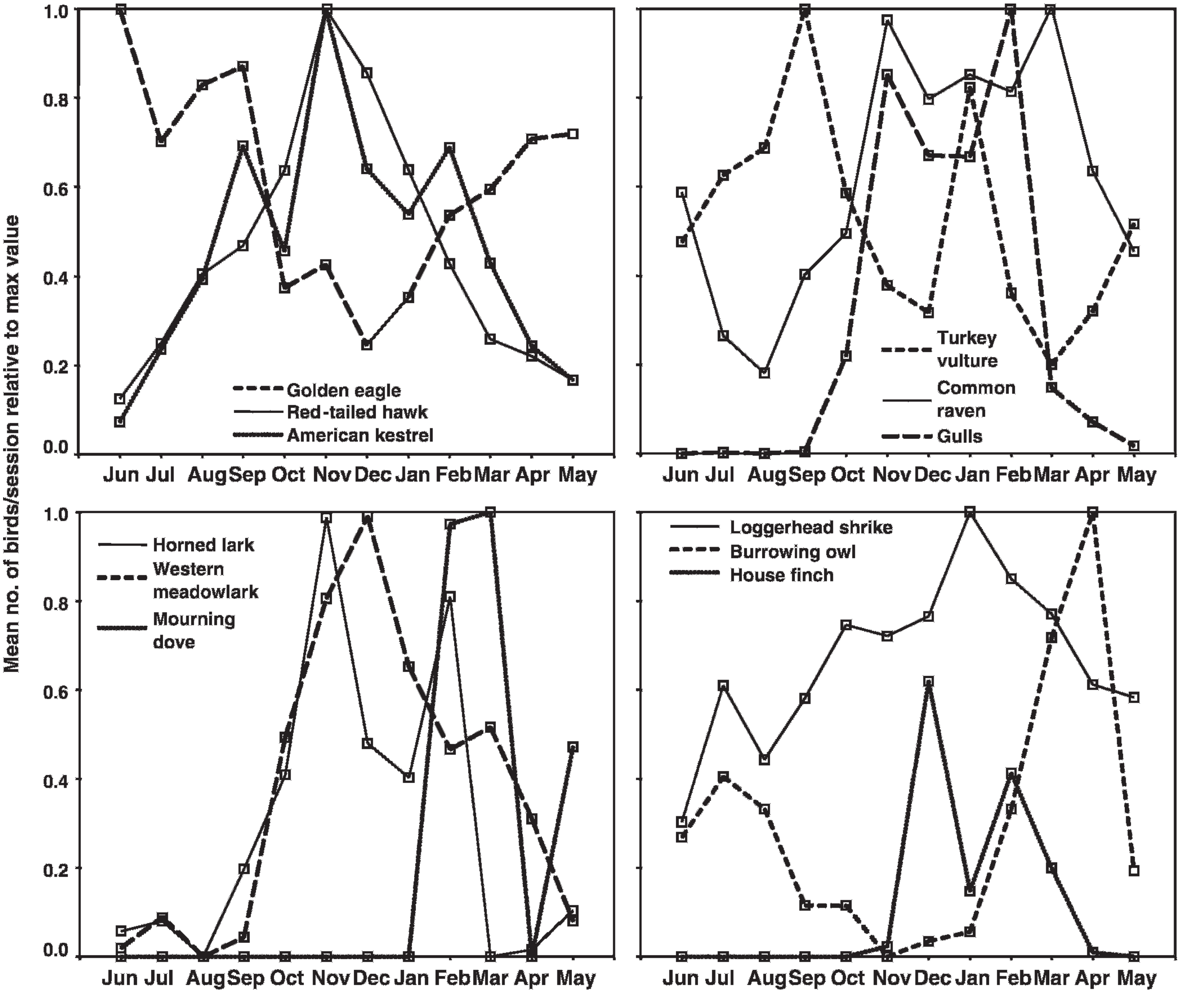

Figure 3. Relative seasonal abundance of various select avian species observed in the Altamont Pass Wind Resource Area, California, USA, during 1998–2000.

Table 1. Behavioral activities by species in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

				Min (%)		Distance (m) to closest turbine		No. of flights	
Species	**Scientific name**	**No. of birds seen**	**Total min**	**Flying**	**Perching**	$\bar{x}$	**SD**	**Through rotor zone**	**<50 m to turbine**
Mallard	*Anas platyrhynchos*	79	83	100	0	85	52	0	16
Common goldeneye	*Bucephala clangula*	1	1	100	0	10		0	2
Great blue heron	*Ardea herodias*	3	3	100	0	60	46	2	5
Turkey vulture	*Cathartes aura*	980	2,542	96	4	72	69	51	1,047
White-tailed kite	*Elanus leucurus*	1	2	100	0	100		0	0
Northern harrier	*Circus cyaneus*	126	389	76	24	76	82	21	162
Cooper's hawk	*Accipiter cooperii*	2	3	100	0	35	7	0	6
Red-tailed hawk	*Buteo jamaicensis*	2,005	15,680	43	57	65	81	270	2,682
Ferruginous hawk	*Buteo regalis*	12	74	59	41	53	41	0	38
Rough-legged hawk	*Buteo lagopus*	6	27	100	0	125	95	0	5
Golden eagle	*Aquila chrysaetos*	465	2,374	58	42	82	73	32	450
American kestrel	*Falco sparverius*	462	3,033	25	75	48	71	102	583
Prairie falcon	*Falco mexicanus*	66	199	58	42	62	60	4	84
Killdeer	*Charadrius vociferus*	2	2	100	0	20		0	1
Long-billed curlew	*Numenius americanus*	7	19	53	47	58	37	0	1
Ring-billed gull	*Larus delawerensis*	503	9,823	100	0	39	27	0	12
California gull	*Larus califfornicus*	36	36	100	0	50	42	0	5
Gull spp.		28,750	299,517	100	0	67	60	14	552
Rock pigeon	*Columba livia*	526	834	85	15	57	71	10	160
Band-tailed pigeon	*Columba fasciata*	30	30	100	0	5		1	1
Mourning dove	*Zenaida macroura*	7	88	8	92	45	38	0	5
Burrowing owl	*Athene cunicularia*	100	1,631	12	88	117	69	0	31
Say's phoebe	*Sayornis saya*	2	6	50	50	50	28	0	1
Loggerhead shrike	*Lanius ludovicianus*	139	846	16	84	49	56	11	98
American crow	*Corvus brachyrhynchos*	25	145	23	77	6	6	8	31
Common raven	*Corvus corax*	1,313	4,280	55	45	42	59	176	1,787
Horned lark	*Eremophila alpestris*	213	676	39	61	36	37	3	45
Cliff swallow	*Petrochelidon pyrrhonota*	23	52	100	0	22	10	0	14
Mountain bluebird	*Sialia currucoides*	118	291	79	21	52	37	0	6
European starling	*Sturnus vulgaris*	259	2,373	10	90	16	58	10	106
Red-winged blackbird	*Agelaius phoeniceus*	470	6,569	12	88	25	29	8	34
Tricolored blackbird	*Agelaius tricolor*	78	298	100	0	88	62	0	0
Western meadowlark	*Sturnella neglecta*	207	721	37	63	31	46	16	72
Brewer's blackbird	*Euphagus cyanocephalus*	337	1,744	40	60	35	66	7	41
Brown-headed cowbird	*Molothrus ater*	2	2	100	0	70		0	2
Blackbird spp.		7,924	67,425	39	61	38	56	45	329
House finch	*Carpodacus mexicanus*	1,024	15,620	13	87	25	48	6	61
Passerine spp.		1,974	23,076	33	67	38	68	25	141

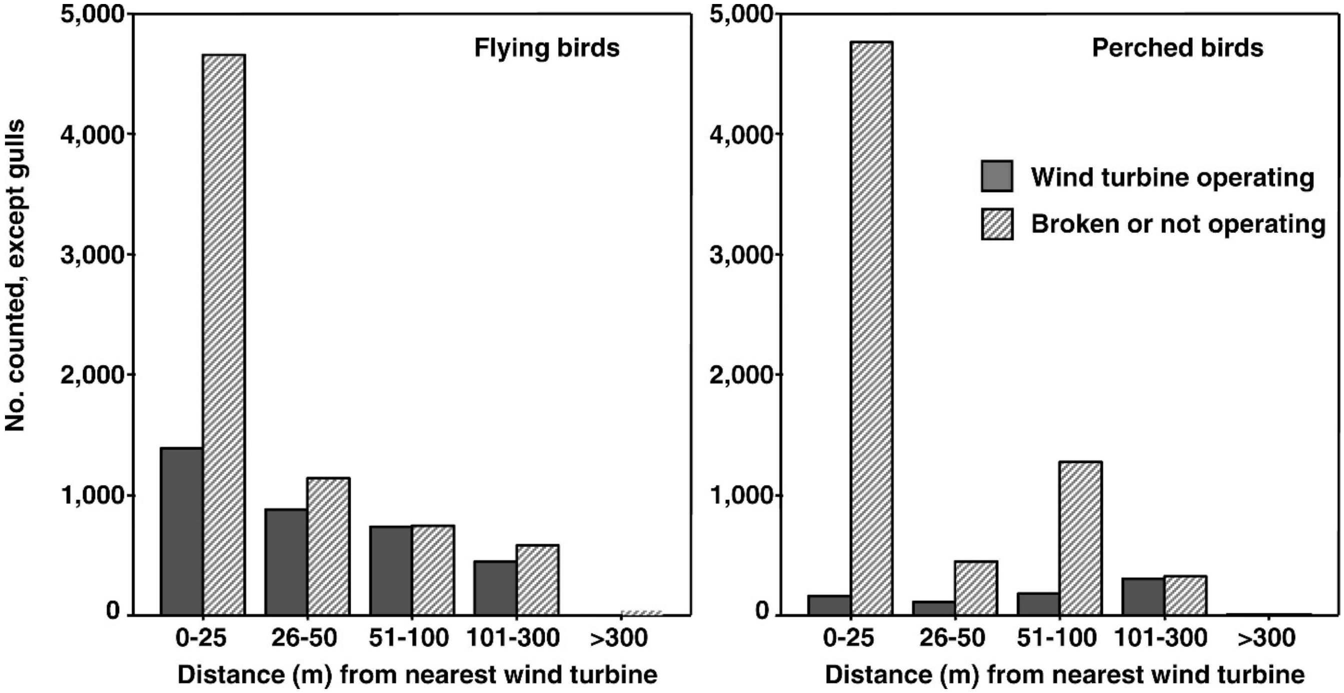

Figure 4. Counts of birds flying (left) and perched (right) by ranges of the distance to nearest turbine and whether the turbine operated at the time of the observation in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

activity peaked in spring, with a secondary peak in July and August (Fig. 3).

Behavior Patterns Around Wind Turbines

Of species observed ≥ 25 times, those observed usually flying included gulls, tricolored blackbird (*Agelaius tricolor*), turkey vulture, northern harrier (*Circus cyaneus*), rock pigeon (*Columba livia*), band-tailed pigeon (*Columba fasciata*), and mountain bluebird (*Sialia currucoides*; Table 1). Species observed usually perching included American kestrel, American crow (*Corvus brachyrhynchos*), European starling (*Sturnus vulgaris*), red-winged blackbird (*Agelaius phoeniceus*), and house finch. The species that averaged the closest distance to wind turbines included American crow, band-tailed pigeon, European starling, house finch, cliff swallow (*Petrochelidon pyrrhonota*), red-winged blackbird, and western meadowlark. We observed most (90%) birds other than gulls ≤ 100 m from wind turbines, and we observed 60% ≤ 25 m from turbines, but 82% of these close distances corresponded with times when the nearest turbine was either not operating or broken (Fig. 4). We recorded 8,618 flights that passed ≤ 50 m from turbines at blade height and 824 flights through the rotor zone; these 2 behaviors were highly correlated with each other while wind turbines were operating ($r_P = 0.96$, $n = 39$, $P < 0.001$).

Number of passes ≤ 50 m from turbines ($F_{<50}$) decreased with increasing proportion of turbines that operated during the observation session, T_{op} ($r^2 = 0.74$, SE $= 0.89$, $P < 0.001$):

$$F_{<50} = 7.98 - 6.41 \times T_{\mathrm{op}}.$$

This same pattern was reflected in number of flights per bird within 50 m of turbines by month of the year (Fig. 5). As the proportion of turbines operating peaked during summer, number of flights per bird within 50 m of turbines was fewest, and when the proportion of turbines operating was smallest during winter, number of flights/bird within 50 m of turbines was greatest.

As the percentage of turbines that were operating increased with wind speed, mean number of birds observed during the session decreased, but mean number of flights per bird within 50 m of turbines increased (Fig. 6). In other words, birds were increasingly out of sight as wind increased

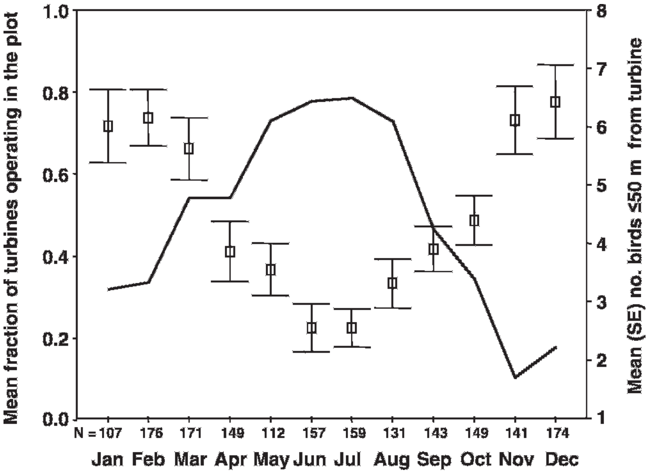

Figure 5. Mean fraction of turbines operating during behavior observation sessions (solid line) peaked over summer and was least during winter, whereas mean number of flights/bird within 50 m of turbines peaked in winter and was least during summer in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

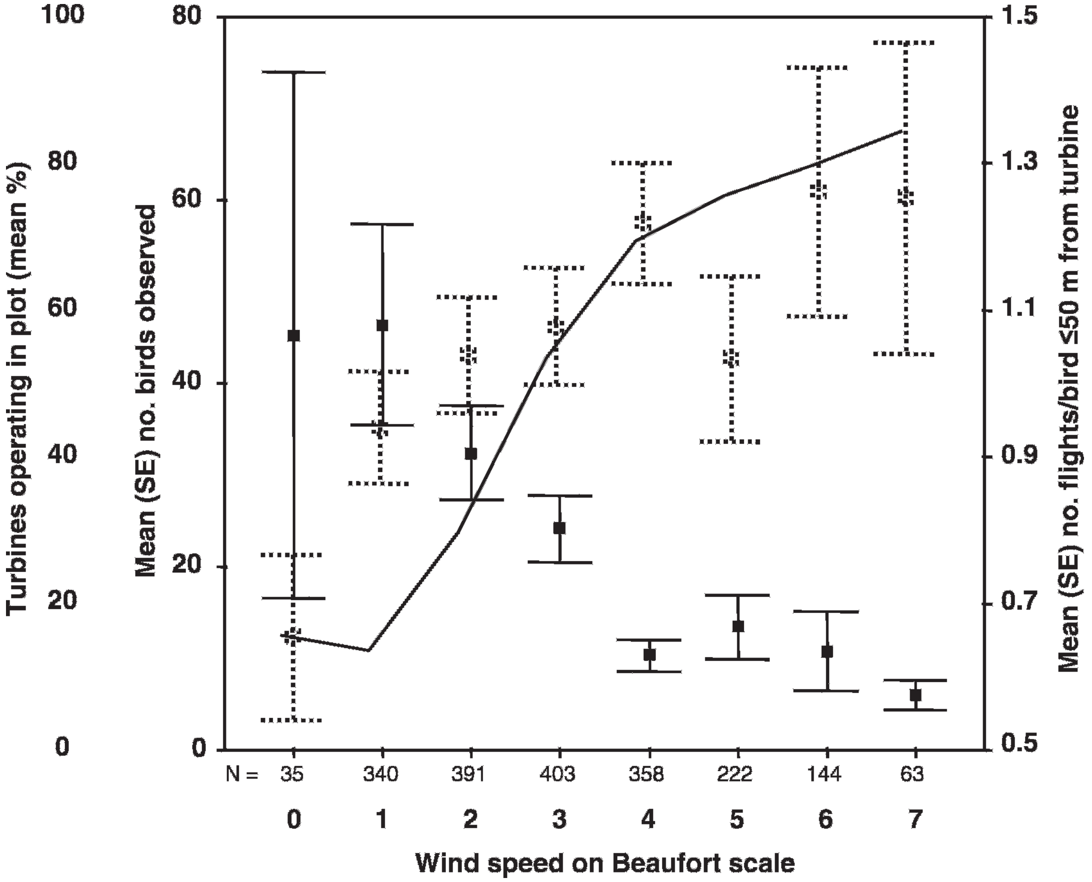

Figure 6. As wind increased in speed, the percentage of wind turbines operating within the behavior observation plot increased (solid line), mean number of birds observed decreased (solid squares and solid error bars), and mean number of flights per bird within 50 m of turbines increased (open squares and dashed error bars) in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

in strength, but flights by birds that remained observable were more frequently close to turbines. Each species responded to wind speeds in their own way, peaking in number and flights per session through the turbine row at particular wind speeds (Fig. 7).

Red-tailed hawk (*Buteo jamaicensis*) was among the most often observed species in the APWRA and the most often performing what we assumed to be more dangerous behaviors (Table 1). Gulls were by far the most commonly observed birds in the APWRA during our study, accounting for nearly 300,000 minutes of observations (we multiplied min/flock by no. of birds/flock). We did not identify most (98%) gulls to species, and of those we identified 93% were ring-billed gull (*Larus delawerensis*) and 7% were California gull (*Larus califfornicus*). Blackbirds were also common, accounting for >70,000 minutes of observation. We did not identify most (90%) blackbirds to species, but red-winged blackbird was 53% of blackbirds we identified. House finch was common and so were unidentified passerine species.

We assumed that dangerous behaviors included flights through turbine rows within the height domain of the blades, and we referred to these flights as through the rotor zone (rather than the rotor plane, which is specifically through the area swept by the blades). We also considered closer distances to turbines or number of flights ≤50 m from turbines to be more dangerous. Flights within 50 m were performed most often by red-tailed hawk (31.1%), common raven (20.7%), turkey vulture (12.2%), American kestrel (6.8%), gulls (6.6%), golden eagle (5.2%), and blackbirds (4.7%), followed by northern harrier (1.9%), rock pigeon (1.9%), and loggerhead shrike (1.1%) and most infrequently by burrowing owl (0.4%), swallows (0.2%), and rough-legged hawk (*Buteo lagopus*; 0.1%), among others (Table 1).

Among species we observed ≥10 times, the ratio of flights ≤50 m from turbines to number of birds observed per session was greatest for ferruginous hawk (*Buteo regalis*; 3.17), followed by common raven (1.36), red-tailed hawk (1.33), northern harrier (1.29), prairie falcon (*Falco mexicanus*; 1.27), American kestrel (1.26), turkey vulture (1.07), and golden eagle (0.97). Bird species with the smallest ratios included tricolored blackbird (0.00), gulls (0.02), band-tailed pigeon (0.03), blackbirds (0.04), mountain bluebird (0.05), and house finch (0.06).

The most commonly recorded flight behaviors included flying through the plot (61%), soaring (16%), and gliding (2%), followed by ground-hopping, flocking, and circling–searching (Table 2). Contouring, diving, fleeing while being mobbed, and being flushed were the rarest behaviors (<1% each). Considering total flight time per observation, the

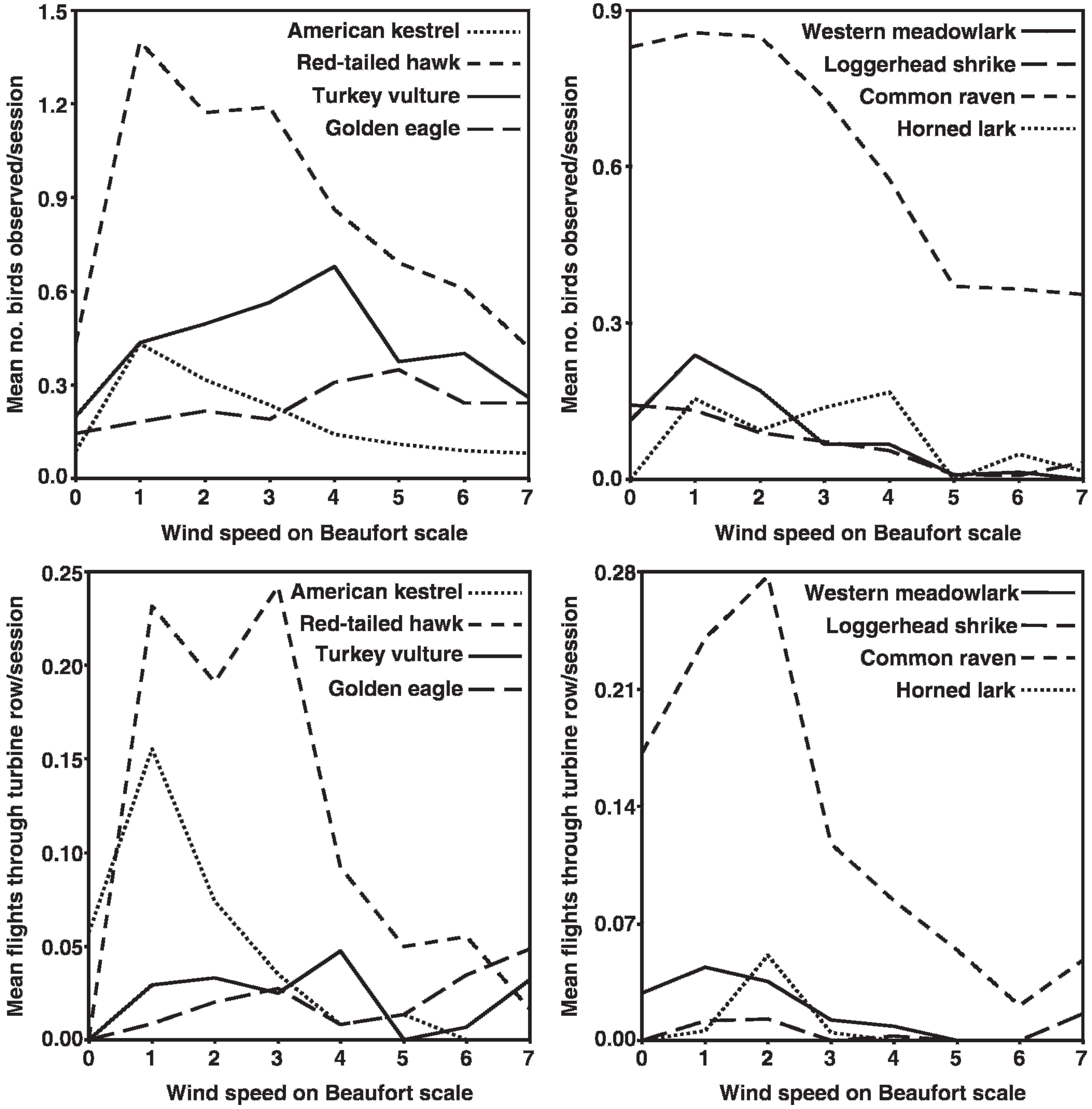

Figure 7. Mean number of birds observed and mean number of passes through the turbine row in relation to wind speed for various select species of birds in the Altamont Pass Wind Resource Area, California, USA, from 1998–2000.

most common behaviors were flying through (77%), column soaring (9%), flocking, and ground-hopping, and the rarest behaviors were diving, fleeing while being mobbed, and being flushed (Table 3).

For some species, operational status of the nearest turbine roughly corresponded with time spent flying to travel, forage, or interact with other birds while within the turbine rotor zone (Table 4). For example, golden eagles were traveling during almost 75% of total recorded time, but 9% of their time was shifted to foraging behaviors (i.e., hovering and contouring) while within the rotor zone, and we saw them interacting with other birds when the nearest turbine was operating. We observed substantial increases in time spent foraging (i.e., hovering, kiting, and diving) of red-tailed hawk (40%), prairie falcon (28%), and American kestrel (25%) while within the rotor zone of operating turbines (Table 4), likely because winds were stronger while turbines operated. Northern harriers spent 29% more of their flight time traveling (i.e., from low contour flights to straight fly-through) while moving through the rotor zone, no matter whether turbines were on.

Table 2. Flight behaviors recorded per bird observation during 1,958 sessions in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

	% of observations[a]													
Flight behaviors	**All birds**	**GOEA**	**RTHA**	**NOHA**	**PRFA**	**AMKE**	**BUOW**	**TUVU**	**CORA**	**MALL**	**LOSH**	**WEME**	**HOLA**	**ROPI**
Soar	4	38	28	24	9	3	3	27	7	0	0	0	0	<1
Column soar	12	<1	<1	0	2	0	0	0	0	0	0	0	0	0
Fly through	61	12	18	35	42	40	41	23	60	97	54	74	71	96
Glide	2	24	15	12	16	4	3	35	10	0	1	3	0	0
Surf	2	2	1	1	2	1	0	<1	3	0	3	0	11	0
Contour	<1	7	<1	17	0	0	0	<1	<1	0	0	0	0	0
Circle–search	3	10	13	8	13	6	0	14	10	0	0	0	0	2
Kite–hover	1	1	19	3	5	18	0	0	1	0	5	0	0	0
Fly-catch	<1	0	0	0	0	2	0	0	<1	0	1	0	0	0
Dive	<1	1	1	0	6	6	3	<1	<1	0	10	0	0	0
Ground hop	7	<1	1	0	2	1	19	<1	2	0	9	17	8	<1
Short flights	2	0	1	0	0	9	32	<1	5	1	11	6	5	2
Display	1	<1	1	0	2	2	0	0	1	0	4	0	5	0
Flocking	6	0	0	0	0	0	0	0	0	0	0	0	0	0
Mob	<1	<1	1	0	2	6	0	0	1	0	0	0	0	0
Mobbed–flee	<1	1	1	0	2	1	0	0	<1	0	1	0	0	0
Flushed	<1	3	1	0	0	1	0	0	<1	1	1	0	0	0
Total no.	46,568	426	1,642	124	64	358	37	971	1,240	79	80	178	205	514

[a] AMKE = American kestrel, BUOW = burrowing owl, CORA = common raven, GOEA = golden eagle, HOLA = horned lark, LOSH = loggerhead shrike, MALL = mallard, NOHA = northern harrier, PRFA = prairie falcon, ROPI = rock pigeon, RTHA = red-tailed hawk, TUVU = turkey vulture, and WEME = western meadowlark.

Table 3. Total minutes of flight behaviors recorded during 1,958 observation sessions in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

	% of flight activity[a]													
Flight behaviors	**All birds**	**GOEA**	**RTHA**	**NOHA**	**PRFA**	**AMKE**	**BUOW**	**TUVU**	**CORA**	**MALL**	**LOSH**	**WEME**	**HOLA**	**ROPI**
Soar	2	45	23	32	11	2	2	31	8	0	0	0	0	<1
Column soar	9	<1	0	0	2	0	0	0	0	0	0	0	0	0
Fly through	77	6	8	20	39	27	9	13	51	98	47	57	56	74
Glide	1	23	11	7	17	8	1	29	14	0	1	2	0	0
Surf	<1	2	<1	<1	3	1	0	<1	2	0	4	0	18	0
Contour	<1	9	<1	28	0	0	0	0	0	0	0	0	0	0
Circle–search	1	9	13	9	12	11	0	26	13	0	0	0	0	3
Kite–hover	1	1	37	3	4	28	0	0	1	0	4	0	0	0
Fly-catch	<1	0	0	0	0	5	0	0	0	0	1	0	0	0
Dive	0	1	1	0	6	5	1	0	<1	0	7	0	0	0
Ground hop	3	<1	4	0	2	1	4	<1	1	0	23	37	19	<1
Short flights	<1	0	1	0	0	5	83	<1	5	1	8	4	4	23
Display	1	1	1	0	1	1	0	0	1	0	3	0	4	0
Flocking	4	0	0	0	0	0	0	0	0	0	0	0	0	0
Mob	0	<1	1	0	2	5	0	0	2	0	0	0	0	0
Mobbed–flee	0	1	1	0	2	1	0	0	<1	0	1	0	0	0
Flushed	0	1	<1	0	0	1	0	0	0	1	1	0	0	0
Total no.	363,186	1,366	6,724	293	116	746	183	2,420	2,318	83	137	258	262	694

[a] AMKE = American kestrel, BUOW = burrowing owl, CORA = common raven, GOEA = golden eagle, HOLA = horned lark, LOSH = loggerhead shrike, MALL = mallard, NOHA = northern harrier, PRFA = prairie falcon, ROPI = rock pigeon, RTHA = red-tailed hawk, TUVU = turkey vulture, and WEME = western meadowlark.

Table 4. Distribution of percentage of time we observed species performing flights typical of traveling or foraging (i.e., soaring, column soaring, flying through, gliding), foraging (i.e., surfing, contouring, circling–searching, kiting, hovering, fly-catching, diving, ground hopping), and interacting with other birds in a non-predatory manner (i.e., short flights, display, flocking, mobbing, being mobbed, fleeing, flushed) in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

	Total flight min (%)			Flight time in rotor zone of nonmoving turbine (%)			Flight time in rotor zone of operating turbine (%)		
Species	**Travel**	**Forage**	**Interact**	**Travel**	**Forage**	**Interact**	**Travel**	**Forage**	**Interact**
Golden eagle	74.7	22.7	2.6	68.3	31.7	0.0	60.0	32.7	7.3
Red-tailed hawk	44.2	52.3	3.5	59.4	38.7	1.9	18.1	79.6	2.3
Northern harrier	59.7	40.3	0.0	88.2	11.8	0.0	88.9	10.1	0.0
Prairie falcon	69.0	26.7	4.3	70.6	17.6	11.8	54.5	45.5	0.0
American kestrel	38.2	49.9	11.9	36.1	51.0	13.0	15.2	75.8	9.1
Burrowing owl	12.0	4.9	83.1	0.0	0.0	100.0	0.0	0.0	0.0
Turkey vulture	72.9	27.0	0.1	79.3	20.7	0.0	71.7	28.3	0.0
Common raven	73.3	17.8	8.9	66.6	23.2	10.2	82.8	4.6	12.6
Mallard	97.6	0.0	2.4	100.0	0.0	0.0	0.0	0.0	0.0
Loggerhead shrike	47.4	40.1	12.4	16.7	41.7	41.7	0.0	0.0	0.0
Western meadowlark	58.9	37.2	3.9	100.0	0.0	0.0	100.0	0.0	0.0
Horned lark	55.7	36.6	7.6	100.0	0.0	0.0	0.0	0.0	0.0
Rock pigeon	74.2	2.9	22.9	72.2	5.6	22.2	86.4	6.8	6.8

We recorded most (83%) burrowing owl flights as interacting with other birds (Table 4), but probably included short foraging flights in addition to interactions with conspecifics. However, we recorded no burrowing owl flights within the rotor zone while the nearest turbine was operating. Both turkey vulture and common raven demonstrated no substantial shifts in flight behaviors within rotor zones (Table 4), but it was also difficult to discern when either of these species was foraging rather than traveling. Mallards (*Anas platyrhynchos*) traveled through study plots 98% of the time, but we did not see them flying through the rotor zone of operating turbines. Loggerhead shrike and horned lark also avoided the rotor zone of operating turbines, but loggerhead shrikes were much more interactive with other birds while within the rotor zone of nonoperating turbines. Western meadowlarks flew through rotor zones, but their flights typified traveling behavior. Rock pigeons were 15% less interactive with other birds while in the rotor zone of operating turbines (Table 4).

Eight species spent ≥25% of their perching time on wind turbines and their towers when turbines were broken or not operating (Table 5). Some birds, including golden eagle, prairie falcon, burrowing owl, and house finch, never perched on operating wind turbines, whereas they did perch on nonoperating turbines (Table 5). Red-tailed hawk, American kestrel, common raven, loggerhead shrike, and western meadowlark perched on operating turbines 1–3% of the time but perched on nonoperating turbines 26–52% of the time. Overall, observations of birds perched on turbines were 22 times more common while the turbines were not operating than when operating (Table 5), though this difference did not factor in the

Table 5. Distribution of perch time among select species observed in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

		Time perching (%)						
Species	**Total min**	**Operating wind turbine**[a]	**Nonoperating wind turbine**[b]	**Power pole**	**Landscape element**	**Transmission tower**	**Electric distribution line**	**Ancillary structure**
Golden eagle	1,003	0	3	26	41	23	4	4
Turkey vulture	96	0	0	0	89	0	11	0
Red-tailed hawk	8,799	1	47	15	18	4	12	3
Northern harrier	86	0	1	0	99	0	0	0
Prairie falcon	83	0	17	12	28	13	30	0
American kestrel	2,239	2	42	5	6	1	39	4
Burrowing owl	1,438	0	4	2	86	8	0	0
Common raven	1,904	3	52	9	20	1	12	2
European starling	2,140	11	76	0	0	0	9	3
House finch	13,525	0	54	0	0	0	45	1
Loggerhead shrike	698	1	26	8	9	0	50	6
Rock pigeon	128	20	65	1	0	0	1	13
Western meadowlark	450	2	50	1	15	0	28	4
Horned lark	409	0	0	0	100	0	0	0
Total	93,366	1	22	2	45	1	13	17

[a] Includes tower structure and all other components of turbine.
[b] Includes towers supporting turbines that are broken, missing, or functional but not operating.

Table 6. We fit models to average number of birds per session per 100 ha within 100-m intervals of distances between the observation point and turbine rows in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

Species or group	Regression model	P	r^2	SE	a	b	Distance from observer before detections at 100 m can be predicted to be fewer by	
							25%	75%
Turkey vulture	Inverse	<0.001	0.97	6.96	−3.373	13,200.123	132	372
Golden eagle	Inverse	<0.001	0.95	3.34	0.485	4,981.640	134	412
Red-tailed hawk	Linear	<0.001	0.93	10.63	122.970	−0.118	332	807
Northern harrier	Linear	<0.050	0.83	1.26	8.541	−0.009	316	738
Prairie falcon	Inverse	<0.001	0.95	1.08	−1.508	1,580.734	109	271
American kestrel	Logarithmic	<0.001	0.98	2.17	127.902	−18.509	178	563
Burrowing owl[a]	Power	<0.050	0.52	0.70	776.740	−0.927	136	446
Common raven	Linear	<0.001	0.85	14.19	103.251	−0.103	325	777
Gull spp.	Inverse	<0.001	0.98	377.92	−954.093	811,838.861	105	252
Mallard	Logarithmic	<0.050	0.70	2.28	29.740	−4.454	168	473
Medium-sized birds	Logarithmic	<0.001	0.96	4.51	194.431	−28.399	175	537
Non-gull spp.	Linear	<0.050	0.66	327.20	1,405.766	−1.421	322	767
Rock pigeon	Logarithmic	<0.001	0.90	5.85	153.008	−22.600	172	507
Mourning dove	Logarithmic	<0.050	0.58	0.60	6.048	−0.916	165	447
Loggerhead shrike	Inverse	<0.001	0.96	1.50	−2.266	2,549.385	130	316
Horned lark	Inverse	<0.001	0.90	2.82	−2.998	2,858.643	129	304
Western meadowlark	Inverse	<0.001	0.84	9.88	−10.973	7,648.279	127	280
Small-bodied birds[b]	logarithmic	<0.050	0.88	127.89	2,957.651	−427.548	178	567

[a] We added the value 1 to number of burrowing owls to prevent taking the log of 0.

[b] We held out record at 600 m as an outlier.

percentage of time during sessions when turbines were not operating.

Rates of Utilization and Fatalities Compared Spatially

Among all species, the largest correlation coefficient was 0.35 between fatality rates at turbine rows and utilization rates (i.e., no. of individuals observed/session/100 ha), so we did not report statistical test results. However, utilization rates among turbine rows declined with increasing distance between the observer and turbine row, indicating a substantial bias (Table 6; Fig. 8). Using models that best fit the data (i.e., homoscedastic pattern in the residuals, smallest root mean square error, and largest r^2 value), distances were much shorter at which predicted utilization rates declined to 25% and 75% of the observed rates at 0–100 m among small-bodied species, for the most part. Utilization rates declined rapidly with distance from observer for gulls, and steeply for golden eagles, turkey vultures, and prairie falcons, whereas rates for northern harriers and common ravens were less responsive to distance from the observer (Table 6).

We saved the unstandardized residuals from utilization rates regressed on distance of turbine row from observer (models in Table 6), and we related these residuals to fatality rates. However, the residuals did not explain variation in fatality rates among turbine rows for any bird species (all $r^2 < 0.1$, $P > 0.25$).

At the plot scale, utilization rate declined with increasing plot size (ha) for turkey vulture ($r = -0.70$, $P < 0.001$), red-tailed hawk ($r = -0.65$, $P < 0.001$), common raven ($r = -0.55$, $P < 0.001$), and American kestrel ($r = -0.44$, $P < 0.05$), but not for any other species. For these 4 species with significant correlations with plot size, we fit regression models and tested unstandardized residuals for a correlation with fatality rate among plots (Table 7). Fatality rate correlated with utilization rate only for all birds as a group ($r = 0.46$, $P < 0.05$), burrowing owl ($r = 0.54$, $P < 0.001$), and mallard ($r = 0.60$, $P < 0.001$). Fatality rate did not change with residuals from models fit for turkey vulture, red-tailed hawk, common raven, and American kestrel.

Behaviors and Fatality Rates

Mean monthly fatality rate of birds as a group increased with increasing flights/session through turbine rows (Fig. 9):

$$F_1 = 0.527 + 0.0876 \times U_T$$

and

$$F_2 = 0.911 + 0.631 \times U_T,$$

where F_1 represented October through April ($r^2 = 0.88$, root mean square error [RMSE] = 0.102, df = 1, 6, $P < 0.05$), F_2 represented May through September ($r^2 = 0.77$, RMSE = 0.041, df = 1, 4, $P < 0.05$), and U_T was utilization of turbine rows, or number of flights/session through the turbine row.

Mean monthly fatality rate of red-tailed hawks increased with increasing utilization rate, or the flights/session (Fig. 10):

$$F_3 = 0.033 + 0.029 \times \ln U,$$

where F_3 was mean monthly fatality rate of red-tailed hawks and U was utilization rate of the APWRA ($r^2 = 0.67$,

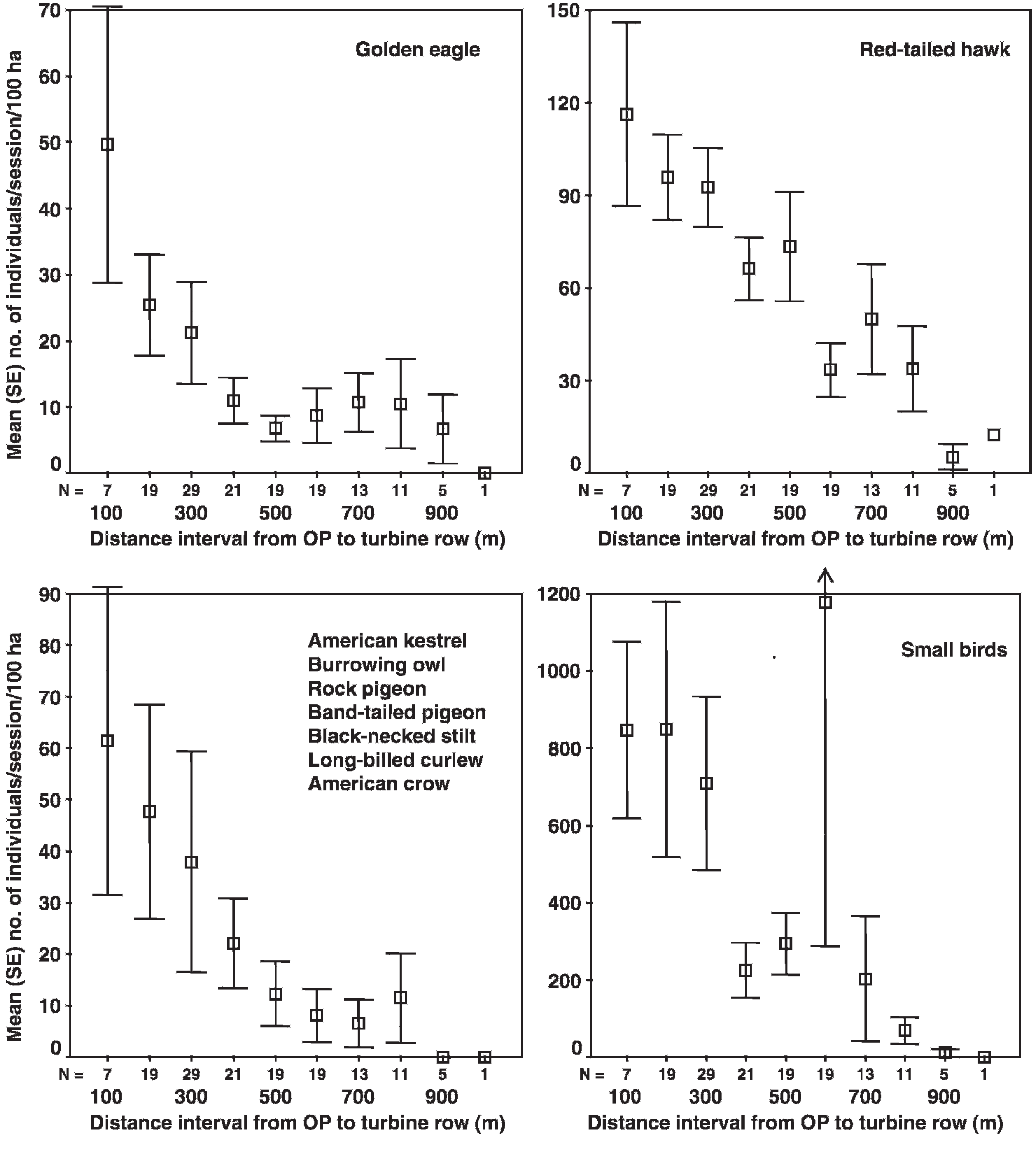

Figure 8. Utilization rates declined with increasing distance between wind turbine row and observer for golden eagles (top left), red-tailed hawks (top right), medium-sized birds (lower left), and small birds (bottom right), where distances were average distances to wind turbines in the row and aggregated to 100-m intervals in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

RMSE = 0.011, df = 1, 10, $P < 0.01$). Mean monthly fatality rate increased with number of flights per session through turbine rows (Fig. 10):

$$F_4 = 0.0512 - \frac{0.0017}{U_T}$$

and

$$F_5 = -0.0474 + 1.3010 \times U_T,$$

where F_4 represented October through April ($r^2 = 0.92$, RMSE = 0.006, df = 1, 6, $P < 0.001$), F_5 represented May through September ($r^2 = 0.92$, RMSE = 0.007, df = 1, 4, $P < 0.01$), and U_T was utilization of turbine rows, or number of flights/session through the turbine row.

Table 7. We fit models fit to average number of birds per session per 100 ha compared to plot size (ha) in the Altamont Pass Wind Resource Area, California, 1998–2000.

							Plot size (ha) before detections in 23 ha can be predicted to be fewer by	
Species	**Regression model**	***P***	r^2	**SE**	***a***	***b***	**25%**	**75%**
Turkey vulture	Logarithmic	<0.001	0.52	20.24	219.567	−40.970	40	122
Red-tailed hawk	Logarithmic	<0.001	0.45	32.34	323.057	−56.939	43	154
American kestrel	Logarithmic	<0.001	0.21	12.13	70.513	−12.018	46	178
Common raven	Linear	<0.001	0.23	29.09	93.943	−0.455	69	161

Mean monthly fatality rate of American kestrels correlated positively with rate of flights within 50 m of wind turbines ($r = 0.68$, $n = 12$, $P < 0.05$) and with number of flights/session through the turbine row ($r = 0.61$, $n = 12$, $P < 0.05$). Mean monthly fatality rates of golden eagles and burrowing owls did not correlate with rates of particular behaviors. Mean monthly fatality rate of western meadowlarks correlated with number of flights/session within 50 m of turbines while at rotor height ($r = 0.60$, $n = 12$, $P < 0.05$).

Fatality rate among plots correlated weakly with frequency of close flights per session per hectare for all birds as a group ($r = 0.38$, $P < 0.05$) but not for any individual species. Fatality rate did not correlate with frequency of hazardous flights made by any species or species group.

Fatality rate increased linearly with rates of utilization (i.e., birds/hr) and specific flight behaviors (i.e., flights/hr) of large raptors and small birds other than raptors within plots where we monitored behaviors (Fig. 11; Table 8). These increases in fatality rate were much faster among small birds than among large raptors, including 3.6 times faster for utilization, 5 times faster for flight time, 37 times faster for flights within 50 m of turbines, and 29 times faster for flights that cross the turbine row (Table 8). Relating fatality rate to rates of utilization and behaviors while birds were at blade height resulted in nonsignificant linear regression models for small birds but increased fatality rates among large raptors. Regressing fatality rate of large raptors on rates of behaviors performed at the heights of the turbine blades resulted in slope coefficients that were 3.5 times larger for utilization, 2.6 times larger for flight time, 7 times larger for flights within 50 m of turbines, and 0.7 times larger for flights through the turbine rows (Table 8).

Large-raptor fatality rate increased fastest with increasing number of flights/hour made by the species at blade height through turbine rows, followed by flights/hour at blade height within 50 m of turbines, and by number of birds/hour counted at blade height (Table 8). Small-bird fatality rate increased with increasing flights/hour made by species through turbine rows, followed by flights/hour within 50 m of turbines. Fatality rates of both large raptors and small birds were least responsive to amount of time species were observed perching/hour.

Whereas utilization (i.e., birds/hr) and recorded behaviors/hour explained nearly all variation in large-raptor fatality rate ($r^2 = 0.99$–1.00), they explained much less of the variation in small-bird fatality rate (Table 8). Number of flights close to turbines was the best predictor of small-bird fatality rate. Three species of small birds were consistent outliers in regressions of fatality rate on behaviors, and we therefore held them out of regression models. These consistent outliers were western meadowlark, mourning dove, and European starling and, compared with the other species of small birds, they died at wind turbines at rates much higher than we observed them during behavior monitoring. American kestrel and burrowing owl also fit none of the patterns observed for small birds and large raptors, and neither did medium- and large-sized species other than raptors, including mallard, gulls, and common raven.

Among species recorded diving toward the ground (i.e., foraging), fatality rate correlated with diving behavior in terms of number of minutes ($r = 0.85$, $n = 7$, $P < 0.05$) and number of individuals ($r = 0.98$, $n = 7$, $P < 0.001$) per hour. Among species observed fly-catching (i.e., foraging), fatality rate correlated with fly-catching in terms of number of minutes ($r = 0.93$, $n = 5$, $P < 0.05$) and number of individuals ($r = 0.88$, $n = 5$, $P < 0.05$) per hour. Among

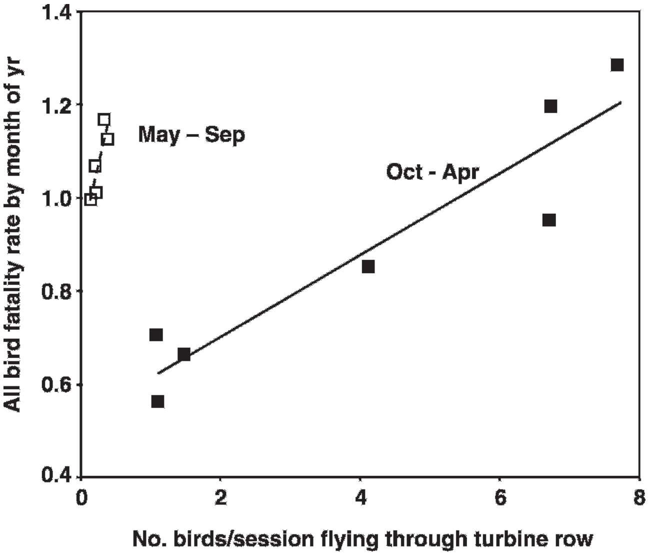

Figure 9. Adjusted fatality rate estimates of all birds increased with number of birds observed flying through turbine rows during observation sessions in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

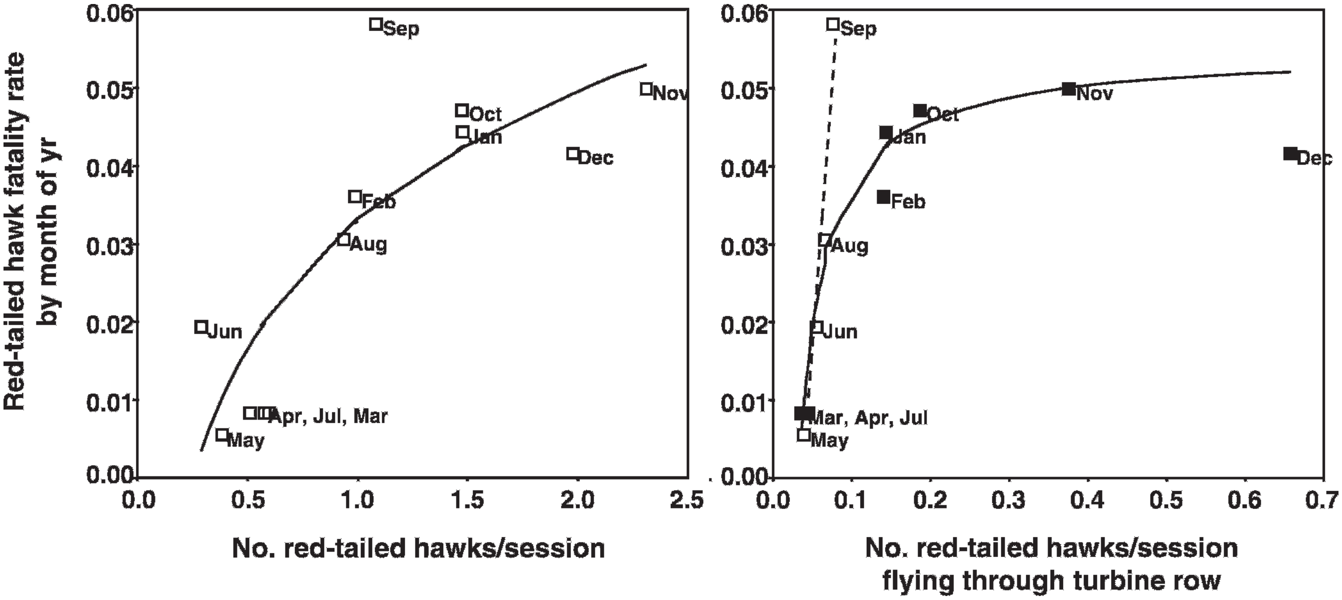

Figure 10. Mean monthly fatality rate estimates of red-tailed hawks increased with utilization rate (left) and rate of flights through turbine rows (right) during observation sessions in the Altamont Pass Wind Resource Area, California, USA, 1998–2000.

species observed hovering, fatality rate correlated with number of birds per hour that were hovering ($r = 0.71$, $n = 9$, $P < 0.05$).

DISCUSSION

Our results did not refute our hypothesis that birds lose track of wind turbines while focused on diving for prey items, fly-catching, and hovering. Those species more often expressing these directed foraging behaviors appeared to be more susceptible to wind turbine collisions. Periods of focused foraging comprised lapses in what otherwise appeared to be nearly constant caution of operating wind turbines by birds in the APWRA. Caution was demonstrated by birds rarely perching on towers of operating turbines and spending less time flying within 50 m of turbines as turbine operations increased through the observation session or seasonally. Northern harrier showed particular caution around wind turbines, switching to traveling flights only while flying within 50 m of turbines or crossing turbine rows, regardless of whether turbines were operating. However, the greater time golden eagle, red-tailed hawk, American kestrel, and prairie falcon spent foraging within the rotor zone of operating turbines probably countered the caution they exercised most of the time.

Another suite of behaviors that corresponded with higher fatality rates was interactions with other birds while in the rotor zone. Golden eagles often displayed territorial behaviors towards younger conspecifics and other raptors while in the rotor zone of operating turbines. Burrowing owls, loggerhead shrikes, rock pigeons, and American kestrels experienced high fatality rates, and we observed these species interacting with other birds while in the rotor zone nearest nonoperating turbines or vacant towers. Interaction behaviors are also distracting, and could lead to collisions with turbines operating adjacent to the nonoperating turbines or with the blades of nonoperating turbines that are allowed to move in the wind (termed feathering).

At wind speeds >1.5 m/sec, birds generally spent increasingly less time in the air with increasing wind speeds. However, of the birds that were flying in these winds, more flew within 50 m of turbines as wind speed increased. In strong winds, the proportion of birds flying within 50 m of wind turbines peaked, and this is when most wind turbines can be seen operating and when birds typically experience the most trouble controlling their flights. We hypothesize that collision risk increases for birds flying in high winds within the APWRA.

As previously hypothesized, collision rates corresponded with utilization rates, especially among small-bodied, non-raptor species and among large raptors flying at blade height. Outliers among interspecific comparisons between fatality rates and rates of utilization and specific flight behaviors included burrowing owl, American kestrel, western meadowlark, European starling, mourning dove, and medium- and large-sized birds other than raptors. For these species, we may have missed the rates of utilization and flight behaviors that matter most, such as nocturnal utilization and behaviors, which would matter if these species were killed mostly at night. This was certainly true of strictly nocturnal species, such as barn owl (*Tyto alba*) and great horned owl (*Bubo virginianus*), which we found dead, but that were unobserved during surveys.

We found that fatality rate precisely related to seasonal utilization of the APWRA by red-tailed hawk and that it related to frequency of flights through turbine rows by red-tailed hawks and all birds as a group. Flights through turbine rows during late spring and summer appeared especially deadly, resulting in steep slopes between fatality rate and flights through turbine rows. Also, mean monthly

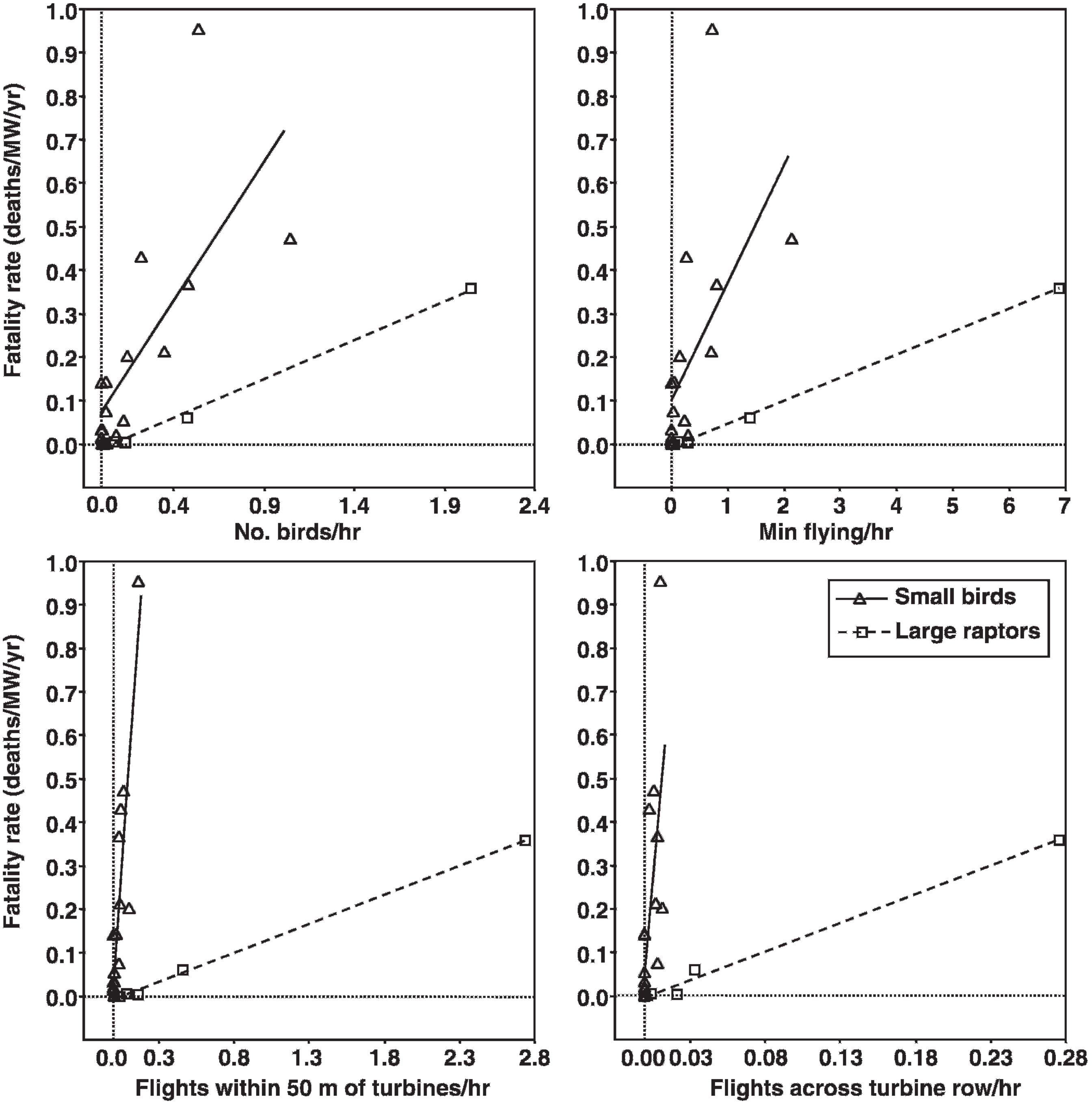

Figure 11. Response of mean adjusted fatality rate at wind turbines to rates of utilization and flight behaviors in the Altamont Pass Wind Resource Area, California, USA, 1998–2002 (fatality rate) and 1998–2000 (behavior).

fatality rates of American kestrels correlated with flights in the rotor zone, and those of western meadowlark did so while flights were at rotor height.

Contrary to correlations we observed between fatality and utilization rates both inter-specifically and seasonally, we failed to find strong correlations when we compared these rates spatially. Spatial comparisons of these rates were likely confounded by variable plot sizes and the strong decreases in utilization rates with increasing distance from the observer of the turbine rows. However, even after accounting for the effect of distance from the observer, fatality rates still did not correlate with utilization rates among turbine rows. Among observation plots, fatality and utilization rates correlated only for burrowing owl, mallard, and all birds as a group.

Orloff and Flannery (1992) found no relationship between fatality and utilization rates among their observation plots in the APWRA, which was consistent with our finding for most species examined. Perhaps these fatality and utilization rates do not correlate spatially, but we suspect the correlation eluded us and Orloff and Flannery (1992) due to the strong, species-specific effect of distance from the observer on estimating utilization rates. We failed to record small-bodied bird species beyond 400 m or 500 m, whereas

Table 8. Models of mean adjusted fatality rate (deaths/megawatt/yr) regressed on rates of utilization and bird flights and perching among observation plots in the Altamont Pass Wind Resource Area, California, USA, during 1998–2002 (fatality rate) and 1998–2000 (behavior).

Fatality rate	Observation records/hr	r^2	SE	*P*	*a*	*b*
Large raptors	No. birds	1.00	0.01	<0.001	−0.0081	0.1770
	Flight time	1.00	0.01	<0.001	−0.0046	0.0524
	Perch time	1.00	0.01	<0.001	0.0032	0.0390
	Close flights	1.00	0.01	<0.001	−0.0052	0.1330
	No. birds at blade ht	1.00	0.01	<0.001	−0.0006	0.6220
	Flight time at blade ht	0.99	0.01	<0.001	0.0044	0.1360
	Close flights at blade ht	0.99	0.01	<0.001	0.0025	0.9330
	Crossing turbines at blade ht	0.99	0.02	<0.001	0.0022	2.4270
Small birds	No. birds	0.52	0.18	<0.01	0.0734	0.6370
	Flight time	0.35	0.21	<0.05	0.1030	0.2680
	Perch time	0.13	0.25	>0.05	0.1600	0.0254
	Close flights	0.77	0.13	<0.001	0.0400	4.9120
	Crossing turbines	0.42	0.20	<0.01	0.0624	38.4240

we often recorded some conspicuous birds 800 m to 1,000 m distant. Due to this strong effect of distance from the observer, we also suggest that past comparisons of fatality and utilization rates among wind farms were of dubious value (Erickson et al. 2001, Young et al. 2003, Smallwood and Thelander 2004, Johnson et al. 2006, Whitfield and Madders 2006). Comparisons of fatality and utilization rates between sites will probably yield no useful patterns until methods are standardized to account for how the size of the area surveyed affects utilization rates.

On the other hand, temporal comparisons of fatality and utilization rates were often significant, likely because comparing utilization in the same plot through time cancels the effect of distance between birds and observer. High seasonal variation in flight activity among species suggested to us that pre- and postconstruction utilization monitoring needs to span all seasons and probably should do so for several years to account for interannual variation in relative abundance of species. Erickson et al. (W. Erickson, Western Ecosystems Technology, Inc., unpublished report) concluded that bird observations are not needed beyond one season of the year, but we disagree. Had we restricted our observations to summer, for example, we would have grossly mischaracterized utilization of the APWRA by red-tailed hawk, golden eagle, burrowing owl, etc. Utilization and behavior surveys also need to be extended into the night to detect nocturnal species and diurnal species that sometimes may be active at night.

MANAGEMENT IMPLICATIONS

Managers can now use the relationships we reported between fatality and utilization rates to forecast avian fatality rates at proposed wind farms, so long as adequate preconstruction utilization surveys are performed and adjustments made for differences in local conditions and wind turbine model and size. For example, if a large-bodied raptor species was seen flying at blade height within a proposed wind farm at the rate of 10 birds/hour, then the appropriate model (Table 8) would predict a fatality rate of 6.2 birds/MW/year, assuming no effect of differences in turbine size between the APWRA and the proposed wind farm.

A seasonal shutdown of wind turbines would reduce fatality rates of some but not all species due to considerable interspecific variation in seasonal activity patterns. However, a seasonal shutdown, such as a winter shutdown in the APWRA, can make sense as a tradeoff measure, balancing bird fatality reductions with minimizing loss of power generation in the wind farm. Shutting down wind turbines during high wind speeds also might reduce fatality rates, but unknown effects of this measure would warrant an experimental implementation.

Because birds almost never perch on operating turbines, perching on them did not relate to fatality rates. However, some species with high fatality rates often interacted among defunct turbines and vacant towers, so removing vacant towers, repairing broken turbines, and synchronizing turbine operations within a row might help reduce hazardous use of the rotor zone, thereby reducing collisions. Another measure to minimize or reduce fatality rates would be to leave sufficiently large gaps between groups of turbines to allow birds to travel and forage without having to necessarily fly close to wind turbines.

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