CHAPTER 7

BIRD FATALITY ASSOCIATIONS AND PREDICTIVE MODELS FOR THE APWRA

7.1 INTRODUCTION

A major step toward reducing bird fatalities at wind energy generating facilities will be to identify and understand the causal factors of the fatalities. Because collisions with wind turbines are rarely observed, inferences must be drawn from patterns discernable from carcass locations found near wind turbines. Other investigators have studied such patterns (see below), but with little success, largely because of small sample sizes. Our study in the APWRA created a large enough sample size of fatalities to reveal relatively robust patterns. These patterns have resulted in the development of a predictive model based on the causal factors underlying the observed fatalities.

A robust empirical foundation is needed to attribute reliable causative factors to the bird fatality problem at wind energy generating facilities. Published and unpublished reports of the problem are replete with conclusions of the causal factors, but few are reliably based on scientific sampling, adequate sample sizes, and/or hypothesis testing (unpublished data). Many conclusions from reports are contradictory to those of other reports and some are used inappropriately to support management actions and optimistic impact estimates of proposed wind energy generating facilities or changes in existing wind energy generating facilities. The more commonly cited causal factors are cited below.

Researchers have argued that particular species or functional groups of species are inherently susceptible to collision with wind turbine blades due to typical behaviors such as migration through the area, or due to particular foraging or breeding strategies (Rogers et al. 1976; Estep 1989; Howell and DiDonato 1991; Howell and Noone 1992; Orloff and Flannery 1992, 1996; Colson 1995; Erickson et al. 1999; Hoover 2001; Strickland et al. 2001a,b; Rugge 2001; Thelander and Rugge 2001, Hunt 2002, Johnson et al. 2002) or body size (1996a,b). Some researchers have also argued that susceptibility is linked to intensity of the use of the site or numerical abundance (Howell and Noone 1992; Cade 1995; Colson 1995; Morrison 1998; Erickson et al. 1999; Anderson et al. 2001; Kerlinger and Curry 2000; Thelander and Rugge 2000a,b; Ugoretz et a. 2000; Rugge 2001; Strickland et al. 2001b); while others have concluded otherwise (Orloff and Flannery 1992, 1996; Hunt 2002).

Some have argued that all types of wind turbine and tower combinations kill birds or that the type of tower or wind turbine does not relate to bird mortality (Anderson et al. 2001; Johnson et al. 2002). Others have concluded that horizontal lattice towers (e.g., at KCS-56s) are responsible for a disproportionate number of fatalities (Orloff and Flannery 1996; Curry and Kerlinger 2000; Rugge 2001; Hunt 2002)—a conclusion that has been related to the increased perching opportunities on horizontal lattice towers, which are thought to increase the number of fatalities (Howell and DiDonato 1991; Orloff and Flannery 1992; Cade 1995; Colson 1995; Curry and Kerlinger 2000; Kerlinger and Curry 2000; Strickland et al. 2001b; Hunt 2002). However, Rugge (2001) found that birds more frequently perch on wind turbines with tubular towers, and Thelander and Rugge (2001) found that mortality was no less on tubular towers.

Rogers et al. (1976) concluded that taller towers are more dangerous to birds; whereas, Hunt (2002) concluded that taller towers are likely safer for golden eagles. Orloff and Flannery (1996) found that tower height did not relate to bird mortality, and Strickland et al. (2000b) safely concluded that the most dangerous wind turbines will be those whose rotor swept height band corresponds with the frequency of bird flights in it.

Tucker (1996b) predicted that larger-diameter rotors would be safer, which was a conclusion adopted by Kerlinger and Curry (2001). However, Orloff and Flannery (1996) found that wind turbines with larger rotor-swept areas killed more birds, and Howell (1997) concluded that the size of the rotor-swept area does not matter. Because larger-diameter rotors have been associated with slower blade motion, conclusions regarding blade tip speed correspond with those of rotor diameters. Tucker (1996b) predicted that wind turbines with slower blade tips are safer, which was also the opinion of Kerlinger and Curry (2001). However, Orloff and Flannery (1996) found that blade tip speed does not matter.

Rogers et al. (1976) predicted that wind turbines with increased rotor solidity pose greater threats to birds, where rotor solidity is the degree to which the length, depth, and speed of the blades pose an obstacle to birds flying through the rotor plane. However, Orloff and Flannery (1996) found that rotor solidity did not relate to bird mortality.

Considerable attention has been focused on the visibility of the moving turbine blades, and their lack of contrast with the background sky (Howell and DiDonato 1991; Cade 1995; Tucker 1996b; Curry and Kerlinger 2000; McIsaac 2001). Some wind turbine blades in the APWRA were painted in various patterns as a remedy and were said to be safer (Howell et al. 1991), but Orloff and Flannery (1992) found no effect. Hodos et al. (2001) reported that raptors experience motion smear, which is the inability to see the moving blades because their images moving across the birds' retinas are too large and fast to be processed by the brain. He proposed blade painting schemes to reduce motion smear, but these remain untested in the field.

Researchers concluded that wind turbines pose an obstacle to bird flights, so the more wind turbines present, the greater the threat of the wind farm to birds (Winkelman 1992; Colson 1995; Howell 1997; Hunt et al. 1998; Kerlinger and Curry 2000). Wind turbine congestion also might relate to bird mortality (Orloff and Flannery 1992). Other tall structures in the wind farm might divert flying birds into the rotor planes of operating wind turbines (Kerlinger and Curry 2001). However, Orloff and Flannery (1992) found no relationship between bird fatalities and wind turbine congestion, inter-turbine spacing, or the density of all structures around each wind turbine. Orloff and Flannery (1992) also found that bird mortality did not relate significantly to the turbine row's length, orientation, or whether it was part of a wind wall.

Orloff and Flannery (1992) found that wind turbines installed in rows (i.e. "turbine strings") forming local edges were no less dangerous than were other wind turbines.

Investigators have differed on whether fatalities are proportionately more common at mid-row wind turbines (Howell et al. 1991; Howell and Noone 1992; Anderson et al. 2001) or end-row wind turbines (Winkelman 1992; Orloff and Flannery 1992, 1996; Curry and Kerlinger 2000). Gaps in wind turbine rows have also been identified as more dangerous to birds (Curry and Kerlinger 2000; Thelander and Rugge 2001. On the other hand, Smallwood et al. (2001) found that neither ends of rows or gaps killed more birds, and Thelander and Rugge (2000a,b, 2001) concluded no more birds die at end-of-row turbines than at others.

Rogers et al. (1976) suggested that wind turbines are more dangerous on ridge crests or hill peaks, and Colson (1995) also suggested that wind turbines on ridge crests are more dangerous. Wind turbines have been considered more dangerous when located on ridge saddles or shoulders of hills (Howell and DiDonato 1991; Howell et al. 1991; Colson 1995; Curry and Kerlinger 2000), on the edges of rims (Strickland et al. 2000a), or in canyons (Orloff and Flannery 1992, 1996; Colson 1995; Kerlinger and Curry 1999). Orloff and Flannery (1992) and Rugge (2001) concluded that wind turbines at higher elevations killed more birds.

Orloff and Flannery (1992) also concluded that more raptors than non-raptors were killed at wind turbines on steep slopes, and that wind turbines with two steep slopes within 154 m also killed more raptors. Curry and Kerlinger (2000) concurred that steeper slope are more dangerous to birds, and Rugge (2001) concurred that greater topographic complexity was more dangerous. However, Orloff and Flannery (1992) concluded slope aspect was insignificant, but Rugge concluded it was significant when examined at a species-specific level.

Some researchers feel that the development of wind energy generating facilities also attracts small mammals, which then attract predatory birds to the wind farm (Hunt and Culp 1997; Hoover 2001; Curry and Kerlinger 2000; Kerlinger and Curry 2001; Hunt 2002). Roads built to access the wind turbines are thought to extend the range of distribution of ground squirrels (Colson 1995; Morrison 1996) and pocket gophers (Smallwood et al. 2001). Hunt (2002) claimed ground squirrels are more abundant where the wind turbines are located. Smallwood et al. (2001) reported golden eagle fatalities to be more common at wind turbines with at least three ground squirrel burrows within 55 m. Researchers have contended that raptors become preoccupied with hunting prey animals and therefore they inadvertently run into moving wind turbine blades (Smallwood et al. 2001; Hunt 2002). However, Hoover (2001) and Hoover et al. (2001) reported that red-tailed hawks are not attracted to ground squirrel colonies, and Orloff and Flannery (1992) reported that raptor mortality was unrelated to ground squirrel abundance.

Hunt (2002) claimed that golden eagle radio-locations from a telemetered population were more common on land parcels where rodenticides were not deployed. Cattle grazing have been thought to lower the average vegetation height, thus favoring ground squirrels (Morrison 1996). Cattle carcasses were identified as a possible attraction to golden eagles (Hoover 2001). Janss and Clave (2000) suggested carrion could attract raptors to a wind farm, and carrion is abundant in the APWRA due to the frequent deaths of cattle that are left to decompose *in situ*. Also, carrion abundance increases during the fall after the most intense ground squirrel control efforts are conducted. It is at that time that poisoned squirrels litter the hillsides, and dead squirrels and desert cottontails are clustered in and around the rock piles constructed near some turbine strings. Lastly, Kerlinger and Curry (2000) claimed that land used for cattle grazing does not attract raptors, although they provided no quantitative evidence or explanation of how they came to this conclusion.

Other factors associated with bird fatalities at wind energy generating facilities include inclement weather (Colson 1995; Johnson et al. 2002), particular seasons (Rugge 2001; Hunt 2002), and the rotor wake pushing birds into the ground (Winkelman 1995).

Most of these suggested causal factors were addressed in this study. We represented the factors with measured variables, and related them to the distribution of bird fatalities in the APWRA Our objective was to systematically test hypotheses stemming from the conclusions put forth by previous research efforts in the APWRA (and summarized in the preceding paragraphs). To do so required compiling an extensive database on bird fatalities. The ultimate aim of these association analyses was to formulate predictive models of fatalities for each of several bird species of interest.

7.2 METHODS

Methods used for fatality searches are described in Chapter 3, Section 3.2, Methods.

We collected data on each fatality along with the associated season, tower type, turbine type, tower location within the string, the aspect of the slope on which the string of turbines was situated, and attributes of the physical relief of the study plot. Except for season and weather, these same variables were recorded for all wind towers in our study area, whether or not birds were ever reported killed there. We used a global positioning system (GPS) device to record these attribute data.

7.2.1 Variables

We defined seasons of the year as spring (March 1 through May 31), summer (June 1 through September 25), fall (September 26 through November 15) and winter (November 16 through the end of February). We attributed fatalities to season of the year after projecting the actual fatality event from the date of discovery to the estimated number of days since the fatality had likely occurred. For example, if we found a carcass on October 30 and we estimated number of days since death as 45, then we attributed the fatality to September 15, which would be during summer. For estimating the association of mortality with season of the year, we only used fatalities estimated to have occurred within 90 days and to have been caused by collisions with wind turbines.

We attributed each wind turbine according to its rated output and model of manufacture. Each model and size combination also included a suite of physical characteristics such as rotor diameter and blade tip speed. The relationship between each of these variables and bird mortality usually was similar to the relationships between the other physical attributes of the wind turbine and bird mortality, because the suite of variables characteristic of each wind turbine model/size shared considerable variation.

In Chapter 1, Table 1-1 we summarized the wind turbine attributes of the wind turbines included in our sample in the APWRA. Rotor diameter equals the distance through the center and to the extremes of the rotor plane. Tip speed equals the speed of movement of the rotor at the outer tip of the blade. We tracked this variable in kilometers per hour (kph), but converted it to meters per second (m/s) for deriving the variables below.

We calculated the window of opportunity (i.e., time) when birds could fly through the rotor plane at the tips of the blades while the rotor operated at normal speed. This window was calculated as follows:

$$\text{Window} = C \div T\cdot B,$$

where C is the circumference of the rotor plane (or $2\pi r$, where r is the radius of the rotor plane, or one half the rotor diameter), T is the tip speed in m/s, and B is the number of blades on the rotor. This variable measured the number of seconds intervening blade sweeps at a particular location at the edge of the rotor plane. The values for the wind turbines in the APWRA ranged from 0.273 to 0.695 seconds. Thus, any bird taking 0.7 seconds or longer to clear the rotor plane of a normally operating wind turbine would almost certainly be injured or killed.

We calculated the area of the rotor plane swept per second by the wind turbine's blades:

$$\text{Swept rate} = TrB \div 2,$$

which, after cancellations of terms, was derived from the function:

$$\text{Swept rate} = (T/C)\cdot AB,$$

and A is the area of the rotor plane in square meters (m^2). This variable characterizes the magnitude to which the sky is disrupted by the operation of the wind turbine, or the extent that the rotor plane is an obstacle to flying birds. It is measured in m^2/s.

Blade color schemes included white, black stripes on white background, red tips, and green tips.

Tower height is measured as the distance, in meters, from the ground to the rotor. For comparison purposes, we excluded vertical axis turbines from our test of the effect of tower height on bird mortality. In one set of tests, we included vertical axis turbines, and in another set we excluded them because the movement of the blades was fundamentally different from that of the horizontal axis turbines.

Tower type was characterized, but tower type and turbine type were sometimes confounded. We compared bird mortality between vertical axis towers/turbines to both tubular and lattice towers supporting horizontal axis turbines. We performed this simplified comparison to test whether perching relates to bird mortality. Perching was assumed to be less likely on vertical axis and tubular towers than on lattice towers, although perching can occur on any tower.

We mapped the perimeters of artificially made rock piles and related bird mortality to the incidence of these piles, which had been constructed as a mitigation measure during installation of the turbines. The rocks were removed from wind turbine laydown areas and piled near the wind turbines. They were intended as den habitat for prey species of San Joaquin kit fox. We noticed that ground squirrels and desert cottontails frequently used these rock piles. It occurred to us that rock piles might draw raptors, because they tended to concentrate prey species. The incidence of rock piles at each turbine string was characterized as none, less, or equal to 0.25 piles per turbine, and > 0.25 piles per turbine.

An edge index for the wind turbine/tower laydown area was measured from the string transect while viewing the 40-m radius from the wind turbine. The index categories were: 0 = no vertical or lateral edge within 40 m of the wind turbine; 1 = some lateral edge such as the presence of a dirt road other than just the service road found at all of the wind turbines, or the presence of a cleared area adjacent to vegetated area, or area tilled for pipeline, etc.; 2 = lots of lateral edge; 3 = some vertical edge such as a road cut, road embankment, or cut into the hillside for creating a flat laydown area; 4 = lots of vertical edge, covering half or more of the area within 40 m of the wind turbine; and 5 = lots of vertical and lateral edge within 40 m of the wind turbine. The edge index was measured to test whether raptors spent disproportionate amounts of time near wind turbines with greater lateral and vertical edge, presumably for improved foraging opportunities. If such was the case, then they had a higher likelihood of being killed by operating wind turbines.

The position of each turbine in the APWRA was classified as "edge" for all those wind turbines facing a landscape devoid of wind turbines outside the APWRA, as "local edge" for all those adjacent to large spaces within the APWRA where no wind turbines occur, and as "interior" for all those not at the APWRA edge or local edge.

7.2.2 Analysis

The statistics presented here satisfy our objectives, as well as the assumptions of the corresponding hypothesis tests. For example, correlation analyses are summarized by the coefficient of determination, R^2, when prediction is the ultimate objective. They are summarized by Pearson's correlation coefficient, r_p, when the objective is simply to summarize the degree of correlation. We report weak and non-significant correlations when doing so meets our objectives, or when the measures of effect are informative despite the non-significance of the test.

Because R^2 is based on two independent factors (i.e., the steepness of the regression slope and the precision of the data relative to the regression line), we often also include the root mean square error (RMSE), which measures the latter. R^2 alone is an inefficient summary statistic for some of our hypothesis tests.

Although we use ANOVA to test some hypotheses in this study, several key assumptions of ANOVA cannot be met due to the absence of block design or related controls on treatment replication or interspersion. Even though we are studying an anthropogenic system, ours is a non-manipulative study. Our "replicates" and our degrees of interspersion of "treatments" were established by the placement of wind towers by the industry prior to our study. As a mensurative study, the chi-square family of statistical tests is, therefore, most efficient for testing many of our hypotheses (Smallwood 1993, 2002).

For all hypotheses tested, we relied on the α-level of significance of 0.05. However, we also took note of P-values less than 0.1 as indicative of trends worthy of further research or consideration. The observed/expected values derived from χ^2 tests are used as measures of effect, and need to be interpreted based on the P-value of the test, whether the expected number of observations was larger than 5 (smaller than 5 is generally regarded as unreliable), and the magnitude of the ratio. These latter considerations for assessing the significance of particular observed/expected values we leave to the reader.

For association analyses, expected values were calculated by multiplying the total number of fatalities by the incidence of the environmental element being compared in the measured set. The incidence was the proportion of the total search effort, or the sum of the time spans over which each wind turbine composing element *i* was searched, divided by the sum of the time spans over which all of the wind turbines were searched.

Search effort at the turbine level of analysis was calculated as:

$$\text{Turbine Search Effort} = Y_t \div \Sigma Y,$$

and,

$$\text{Incidence, } P_i = \Sigma \text{ (Turbine Search Effort of all wind turbines composing element } i\text{)},$$

and then,

$$\text{Expected} = N \times P_i,$$

where Y_t is the number of years during which fatality searches were performed for a given wind turbine, ΣY is the number of years of fatality searches across all wind turbines, and N represents the total number of fatalities compared within the measured set of environmental elements.

Search effort specific to season of the year was calculated as:

$$\text{Season-specific Turbine Search Effort, } Y_{t,s} = (S_s \div S_t) \times Y_t \text{ .}$$

where S_s was the number of searches made at the wind turbine during a particular season and S_t was the total number of searches made at the wind turbine. This search effort was adjusted by the searches during the next season that could document fatalities < 90 days old and that occurred during this season:

$$\text{Adjusted Season-specific Turbine Search Effort} = Y_{t,s} + 0.5 \times Y_{t,s+1} \text{ ,}$$

where $Y_{t,s+1}$ represents the search effort at the turbine during the following season. Essentially, we added half of the next season's search effort to the targeted season search effort. The sum of the adjusted season-specific turbine search effort values was divided into the sum of all these values across seasons in order to arrive at a proportion of the total search effort that was made per season across the APWRA.

Tests for relationships between bird fatalities and rodent burrow distributions were performed at the turbine string level of analysis, because we felt that our representations of burrow distributions were more robust at this level. Performing the analysis at this level introduced an additional complication of search effort, because turbine strings varied in length (i.e., number of wind turbines) and cumulative rotor swept area (we term this "windswept area"), as well as the number of years devoted to searching the wind turbines.

Figure 7-1A illustrates the strong relationship between fatalities and search effort at the string level of analysis ($r_p = 0.74$, $N = 472$, $P < 0.01$), requiring that fatality rates be adjusted by search effort. Therefore, the relative search effort devoted to each turbine string was calculated as:

$$\text{String Search Effort } (\text{m}^2 \cdot \text{years}) = N_t \times R \times Y,$$

where N_t is the number of wind turbines in the string, R is the mean rotor swept area in m^2, and Y is the number of years the string was searched.

Figure 7-1B illustrates the inverse power relationship between a fatality rate and search effort, which casts doubt on the reliability of a simple conversion of fatalities to fatality rates (mortality) for inter-string (or inter-site) comparisons and hypothesis testing. This relationship resembles the patterns in estimates of animal density related to the sizes of the area used to make the estimates (Blackburn and Gaston 1996; Smallwood and Schonewald 1996), rendering their comparisons inappropriate among study sites of varying sizes.

A more appropriate approach to factoring in differential search effort for comparing the frequencies of fatalities is to estimate expected frequencies of fatalities based on the measured set of fatalities relative to that of the element of the wind farm being associated with the fatalities (Smallwood 1993, 2002). The incidence of the compared element in the string within the measured set of searches across all the strings was calculated as:

$$\text{Effort}_i \div \Sigma \text{ Effort},$$

and was the basis upon which expected χ^2 values were estimated at the string level of analysis.

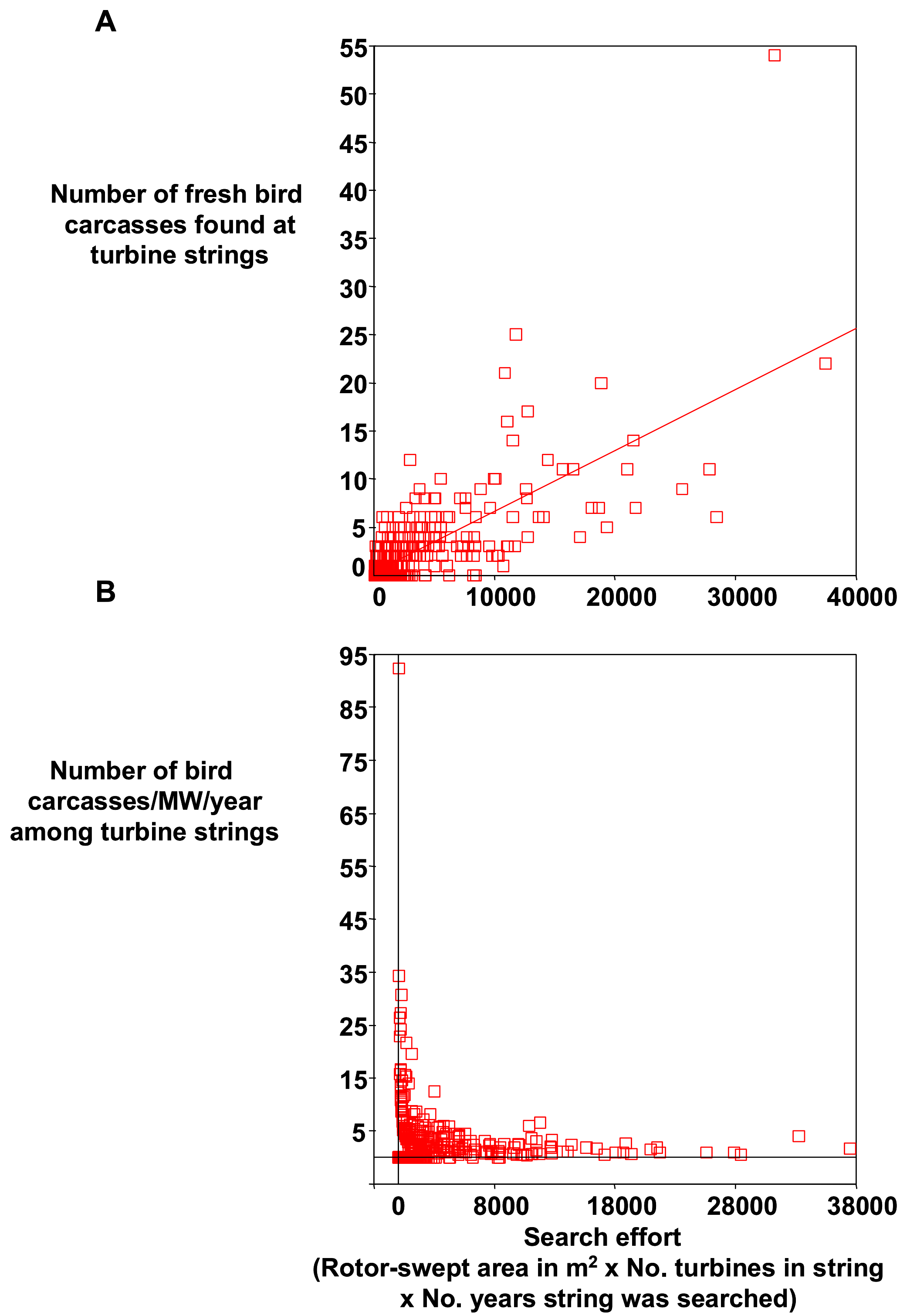


Figure 7-1. The number of fresh bird carcasses found at wind turbine strings was a linear function of carcass search effort (A) and turbine-caused bird mortality was an inverse power function of search effort (B).

7.2.3 Measures of Effect

In-depth examination of test results was based on two measures of effect. The first was the observed-divided-by-expected values, which measures the number of fatalities at that element of the measured set as a multiple of what would be expected from a uniform or random distribution of fatalities throughout the measured set. The second was the percentage of total fatalities that can be attributed to the variable's attribute in question, and is measured as the following:

$$\text{Accountable Mortality} = (\text{Observed} - \text{Expected}) \div \text{Total fatalities} \times 100\%.$$

This measure is similar to the one used in Smallwood and Erickson (1995). Positive values express the percent of the total fatalities likely killed at wind turbines due to the attribute associated with the value, and negative values express the percent of the total that were expected to have been killed if fatalities were random, but that were not killed. Thus accountable mortality ranged from -100% to 100% of the fatalities attributable to a particular category of an association variable.

7.2.4 Predictive Model

Accountable mortality values were the weightings applied to the models developed for each of twelve species. The values used were restricted to variables with significant chi-square tests for association, which were based on expected cell values mostly > 5 and which were either categorical in nature (e.g., tower type) or showed gradients in accountable mortality along a continuum (i.e., along categories that expressed a continuum, such as elevation or rotor diameter). For those variables included in the model, accountable mortality values were summed across the variables to arrive at a score:

$$\text{Predicted Impact} = \Sigma \text{ accountable mortality}.$$

Predicted impact values > 0 represented wind turbines more likely to kill individuals of the species in question. Negative or zero values represented wind turbines less likely to kill individuals of the species in question. Predicted impacts were additional to impacts that we could not account for based on the data we collected, which probably included a baseline level of impacts that were random or due simply to the fact that all wind turbines pose an inherent danger to birds because they are tall structures with moving parts into which birds can collide.

Model predictions of impact were compared to the impact we measured, where in this case the impact was the number of fatalities we recorded at the particular wind turbine. We assessed the effectiveness of the model by the percent correct classification of the wind turbines that killed birds. We also assessed the model based on the percentage of wind turbines predicted to cause greater impact (i.e., predicted impact > 0) but at which we found no fatalities during our study. It is reasonable to assume that these wind turbines will more likely kill birds, even though we did not find them yet, and this percentage informs of the level of effort needed to modify wind turbines and range management practices to substantially reduce collisions involving that species.

Lastly, we examined the percentage of the fatalities associated with the correct classification of wind turbines as those more likely to cause an impact. This percentage informs of the degree to which mortality could be reduced per species by modifying conditions expressed by the variables composing the model, assuming no interaction effects between predictor variables.

7.3 RESULTS

7.3.1 Sample Characteristics

Our sample of wind turbines and our sampling effort included mostly KCS-56 and Bonus turbines (Figure 7-2). Our sample and sampling effort of towers included mostly lattice and tubular towers (Figure 7-3). Our sample included a wide range of rotor plane areas swept per second during ordinary wind turbine operations (416 to 1246 m^2/s), although many of the wind turbines sampled swept a larger area per second (Figure 7-4). The area in the rotor plane swept per second, as well as the window of time birds could fly through the rotor plane at the blade tips, was more a function of rotor diameter than of tip speed (Figures 7-5 and 7-6).

Similarly, our sample included a wide range of tower heights, ranging from 14.0 to 43.1 m (Figure 7-7). Our sample, however, was influenced largely by 18.5 and 24.6-m towers, those supporting KCS-56 and Bonus turbines, respectively. Most of the wind turbines in our sample of turbines were designed to face the wind, but a considerable number also faced away from the wind (Figure 7-8).

The majority of the wind turbines in our sample were situated in the interior of turbine strings (Figure 7-9), and the majority was situated in the interior of the wind farm (Figure 7-10). Most were on hill slopes, ridgelines, and ridge crests (Figure 7-11), and only a relatively few wind turbines occurred within canyons (Figure 7-12). Nearly a third of the wind turbines in our sample were installed on peaks, ridge crests, and plateaus, to which no slope aspect applied, and relatively few turbines occurred on southwest and west-facing slopes (Figure 7-13).

The wind turbines ranged in elevation from 61 m to 532 m above sea level, and most occurred within two sub-ranges of elevation, from 120 to 220 m and from 280 to 450 m (Figure 7-14A). Our search effort applied to the wind turbines was more evenly distributed among elevations, however (Figure 7-14B). The wind turbines in our sample averaged 7˚ of slope, and they were right-skewed in frequency of occurrence in the sample (Figure 7-15A) but more evenly represented in the search effort (Figure 7-15B).

The number of wind turbines within 300 m of each wind turbine averaged 25, and ranged from 3 to 71 with a right-skewed frequency distribution (Figure 7-16A). The search effort generally corresponded with the frequency distribution (Figure 7-16B).

More than half of the wind turbines in our sample were within areas where rodent control was applied intensively by 2002; whereas, many of the wind turbines recently added to our sample were located on ranches where rodent control had not been conducted (Figure 7-17).

Fall was the least-sampled season of the year (Figure 7-18).

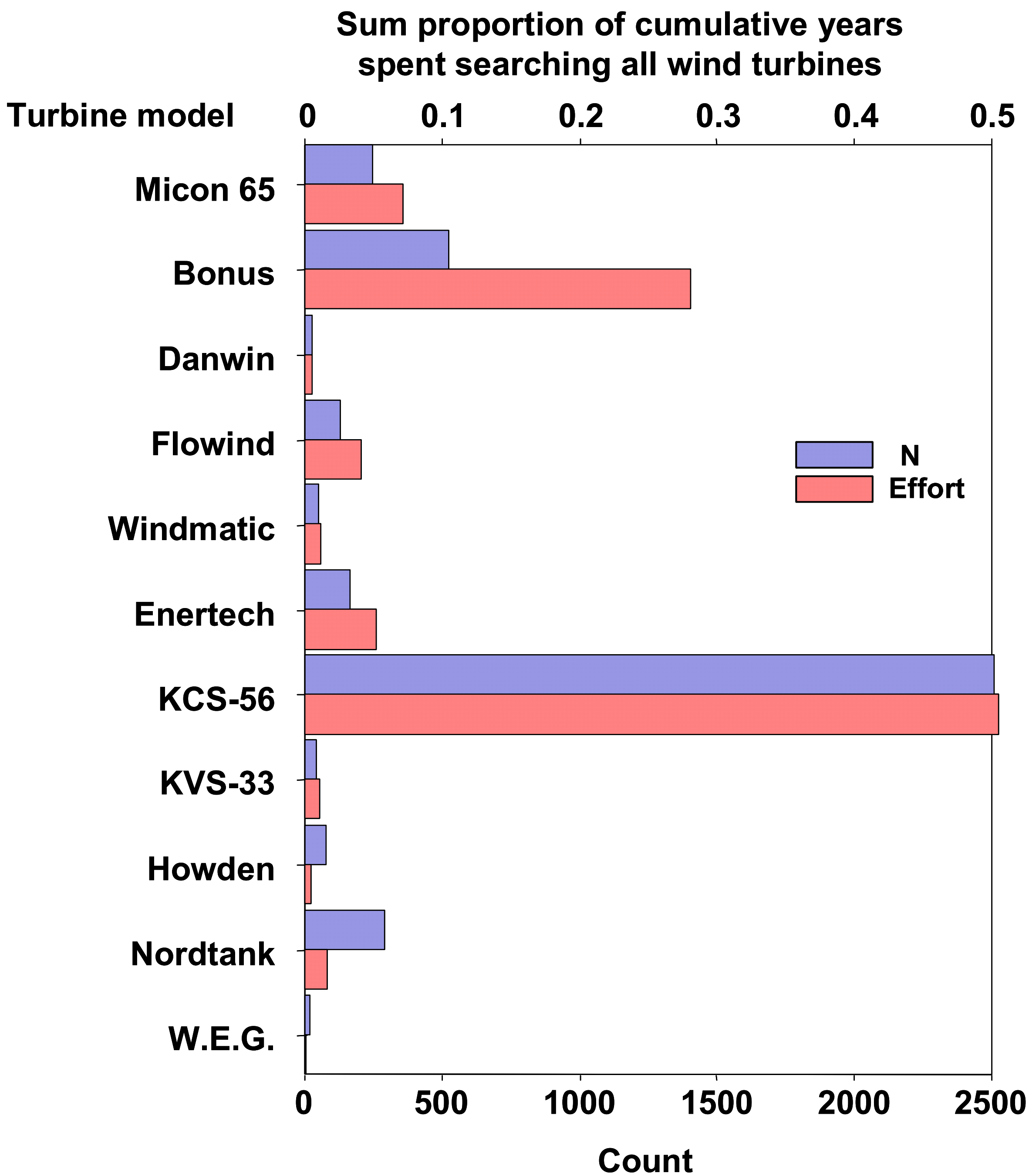


Figure 7-2. Frequency distributions of wind turbine models and search effort at those models in our sample in the APWRA

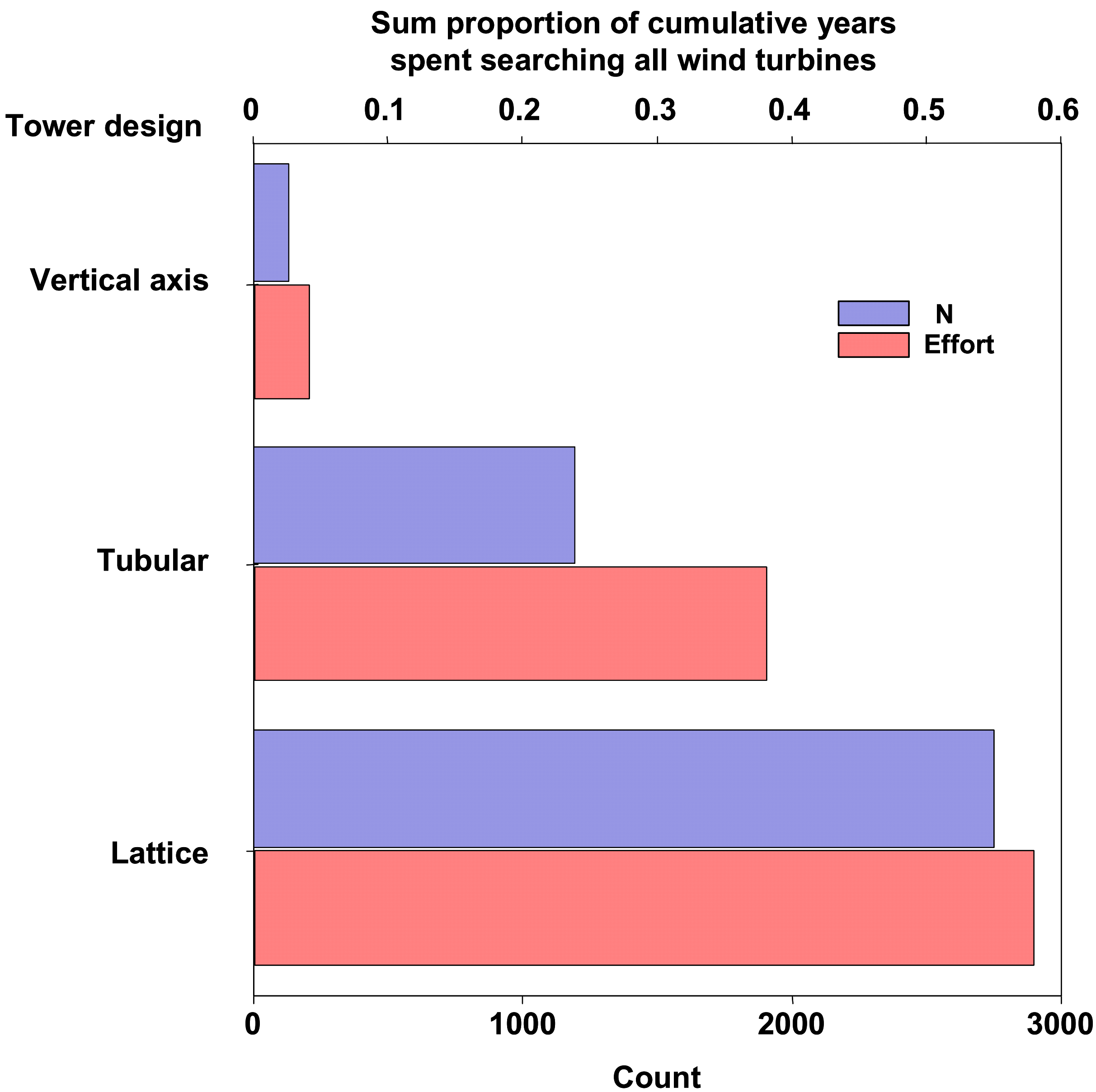


Figure 7-3. Frequency distributions of wind tower types and search effort at those tower types in our sample in the APWRA

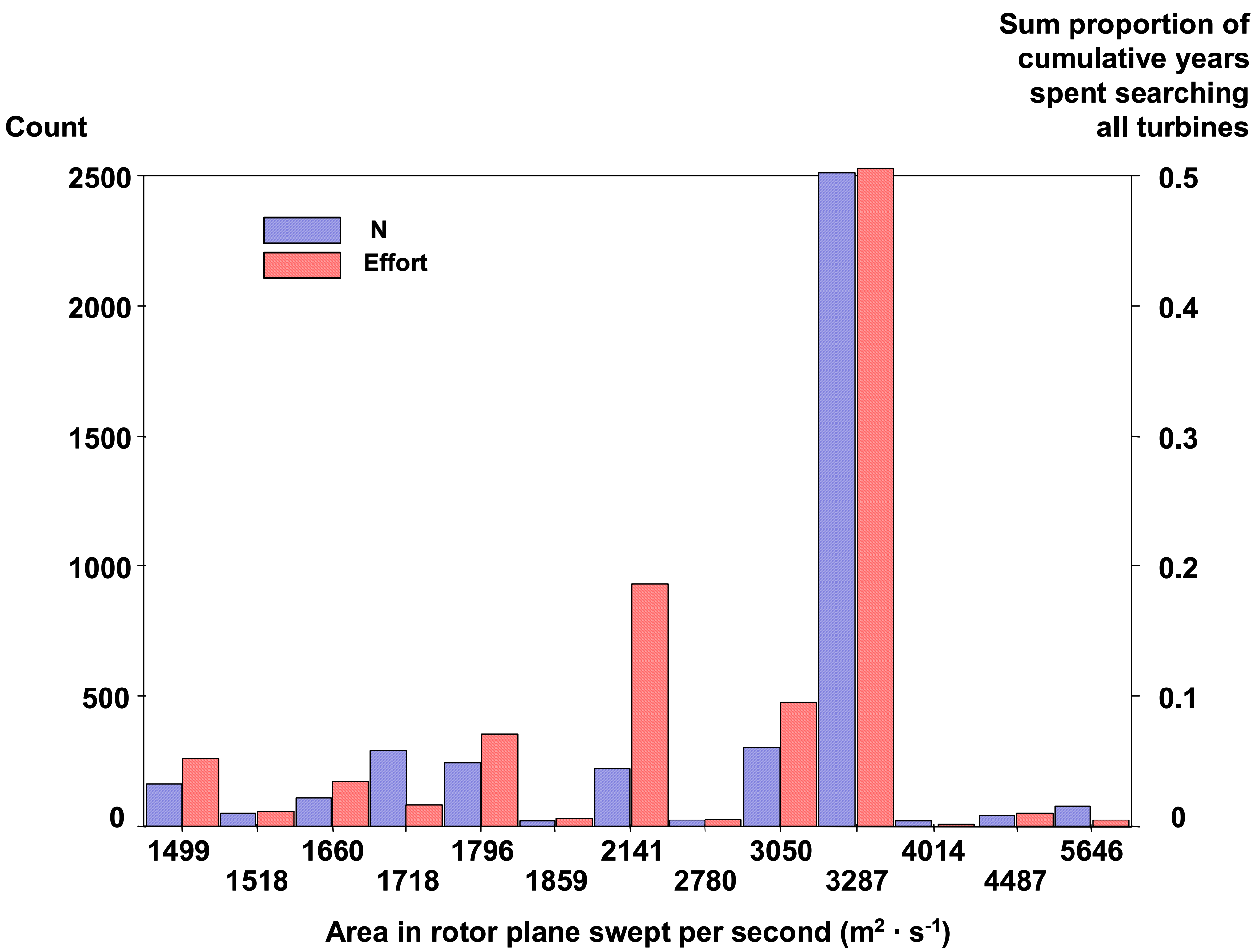
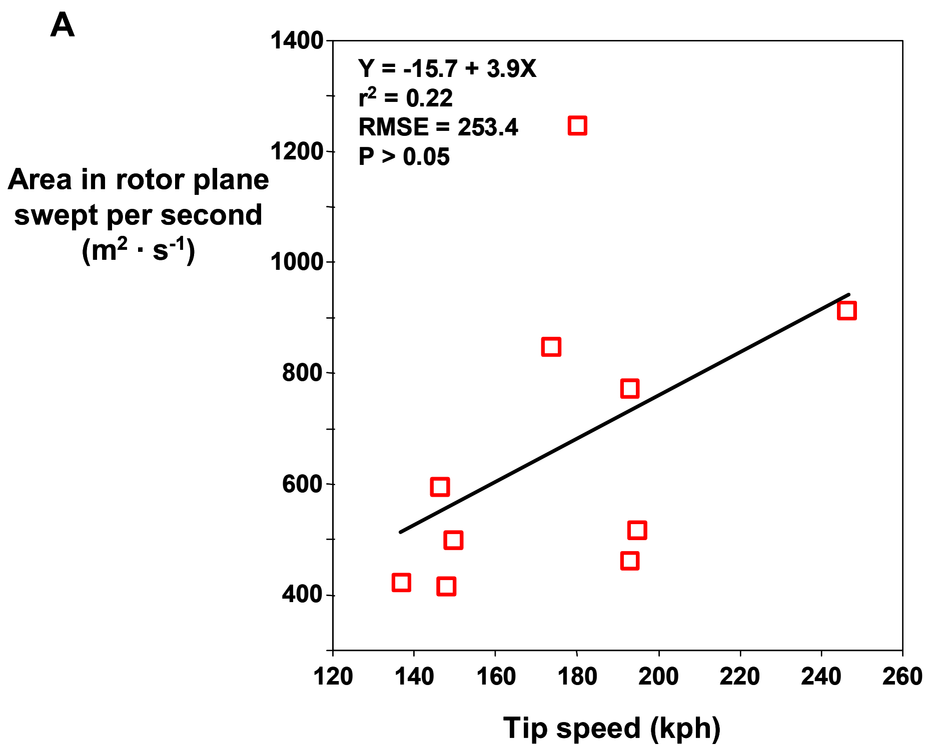


Figure 7-4. Frequency distributions of rotor swept area and search effort at those rotor swept areas characteristic of wind turbines in our sample in the APWRA



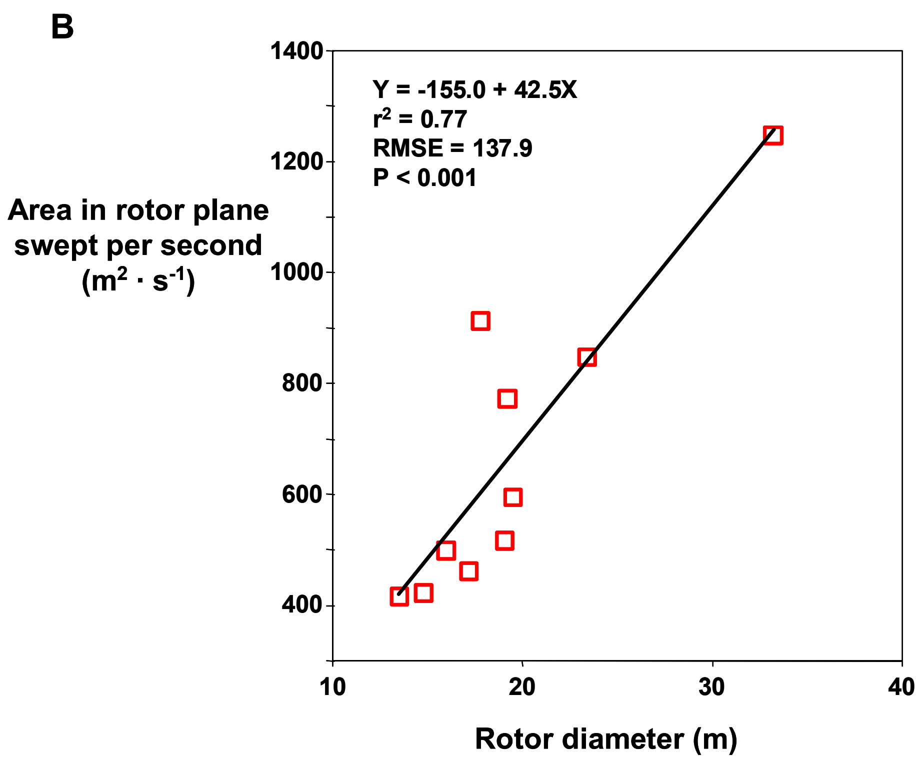


Figure 7-5. The rotor swept area swept per second was a linear function of blade tip speed among the wind turbine models in the APWRA (A), but it was more responsive and precisely related to rotor diameter (B).

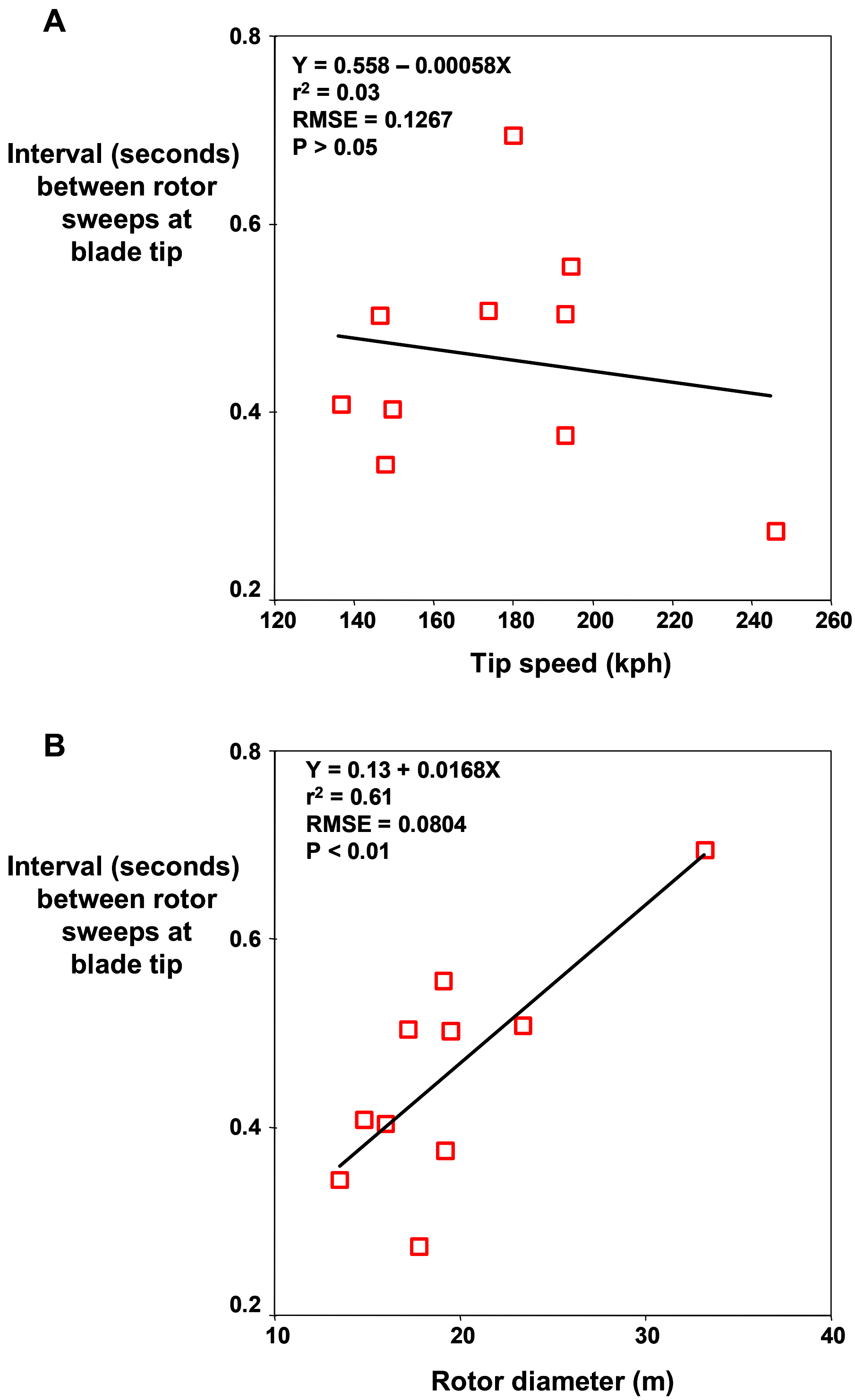


Figure 7-6. The time period intervening blade sweeps at the edge of the rotor place did not relate to blade tip speed (A), but it was a linear function of rotor diameter (B).

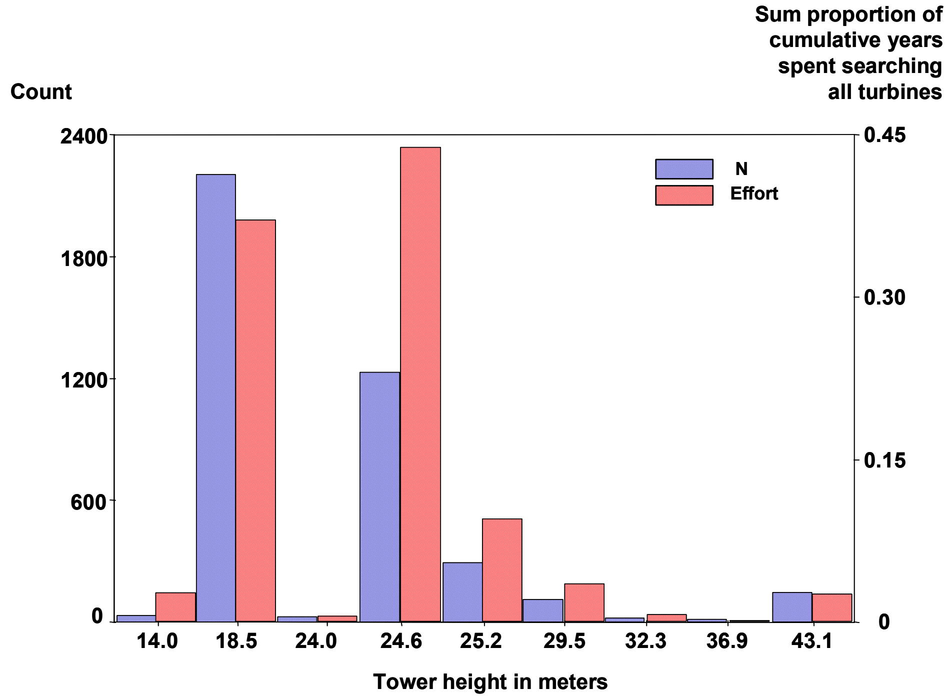


Figure 7-7. Frequency distributions of wind tower heights and search effort at those tower heights in our sample in the APWRA

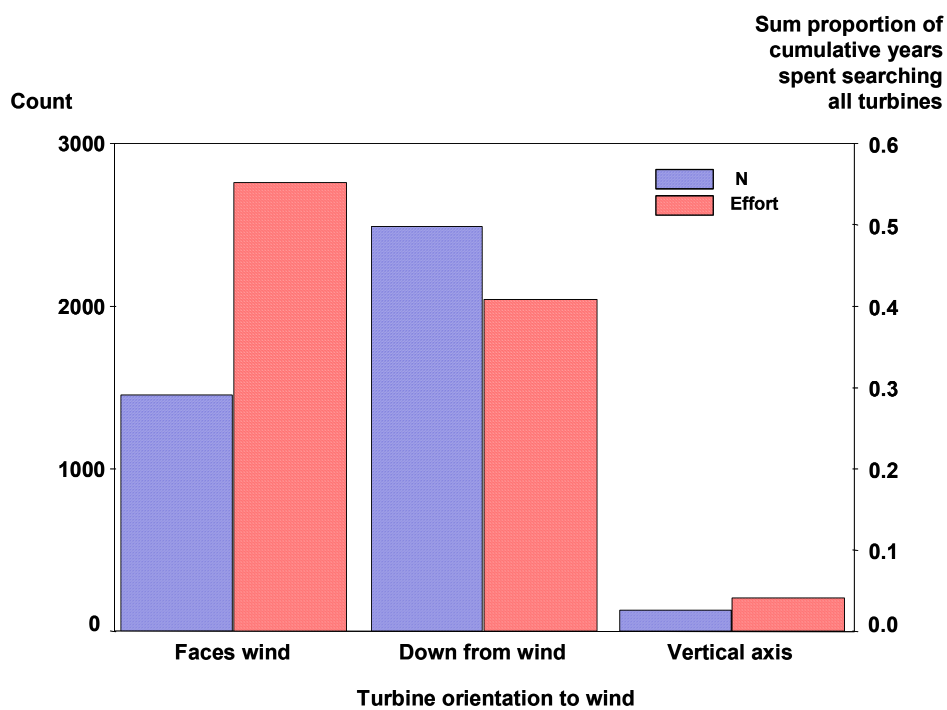


Figure 7-8. Frequency distributions of wind turbine orientations to the wind and search effort at those orientations among wind turbines in our sample in the APWRA

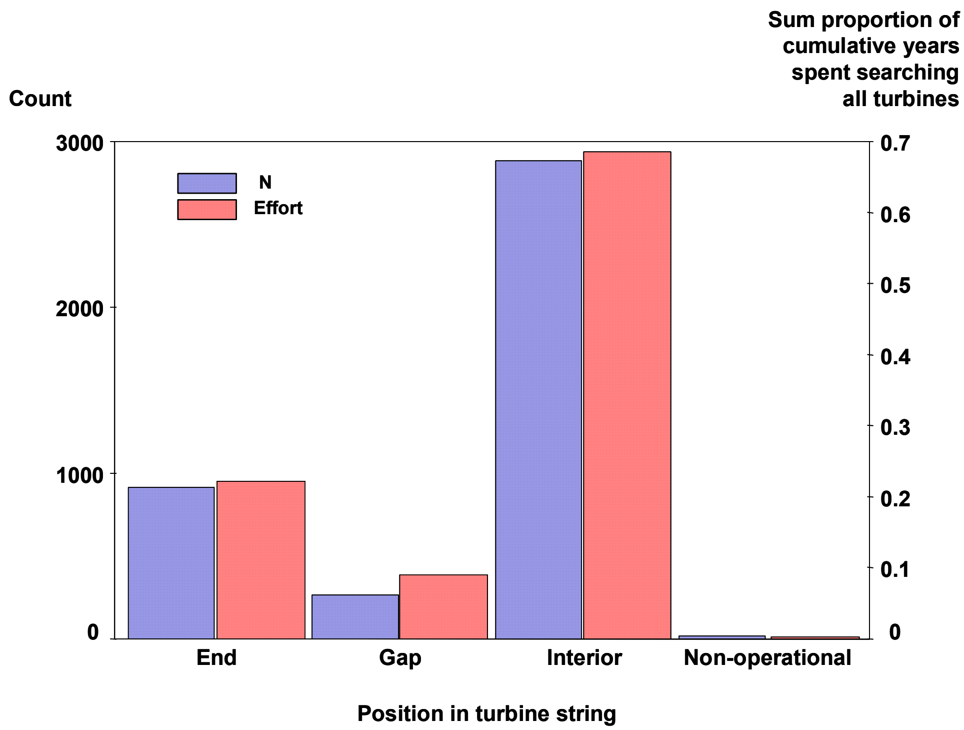


Figure 7-9. Frequency distributions of wind turbine positions in the string and search effort at positions in our sample in the APWRA

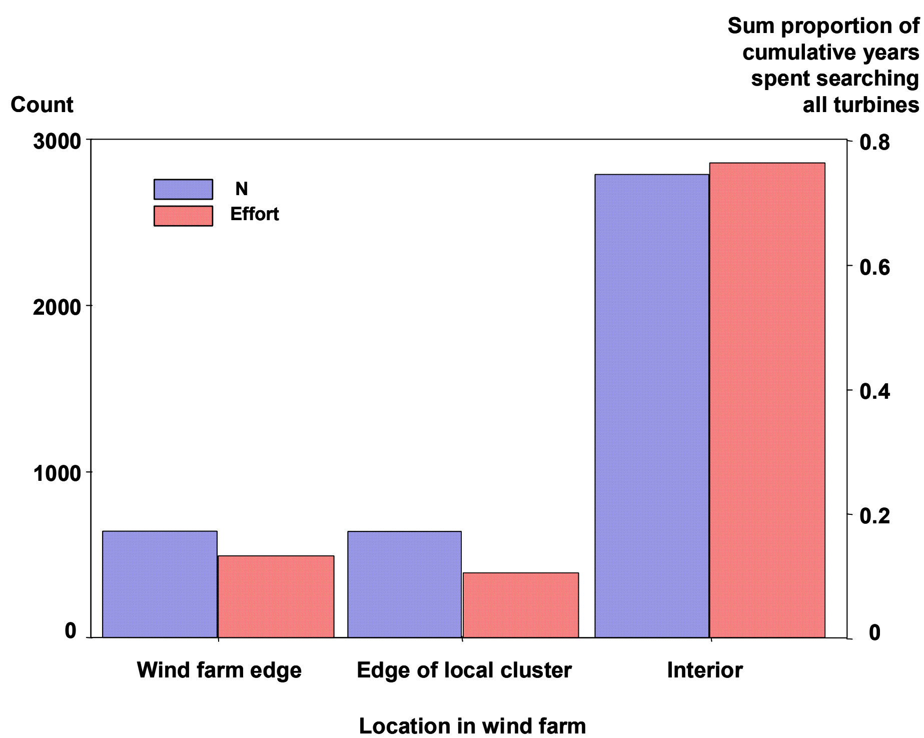


Figure 7-10. Frequency distributions of wind turbine locations in the wind farm and search effort at locations in the APWRA

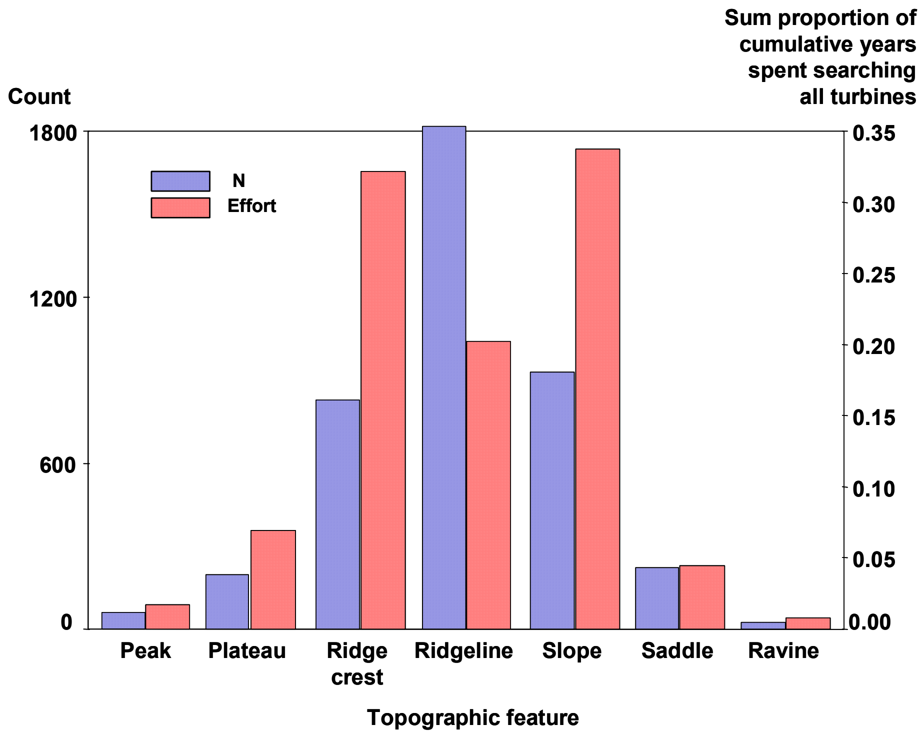


Figure 7-11. Frequency distributions of types of physical relief at wind turbines and search effort at these types of relief in the APWRA

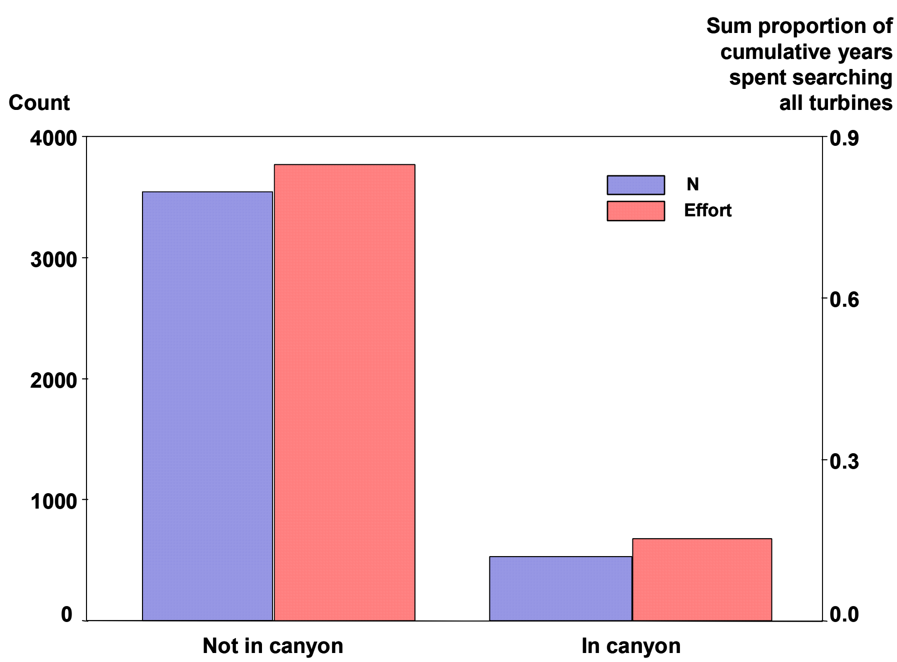


Figure 7-12. Frequency distributions of wind turbines in and out of canyons and search effort at these turbines in the APWRA

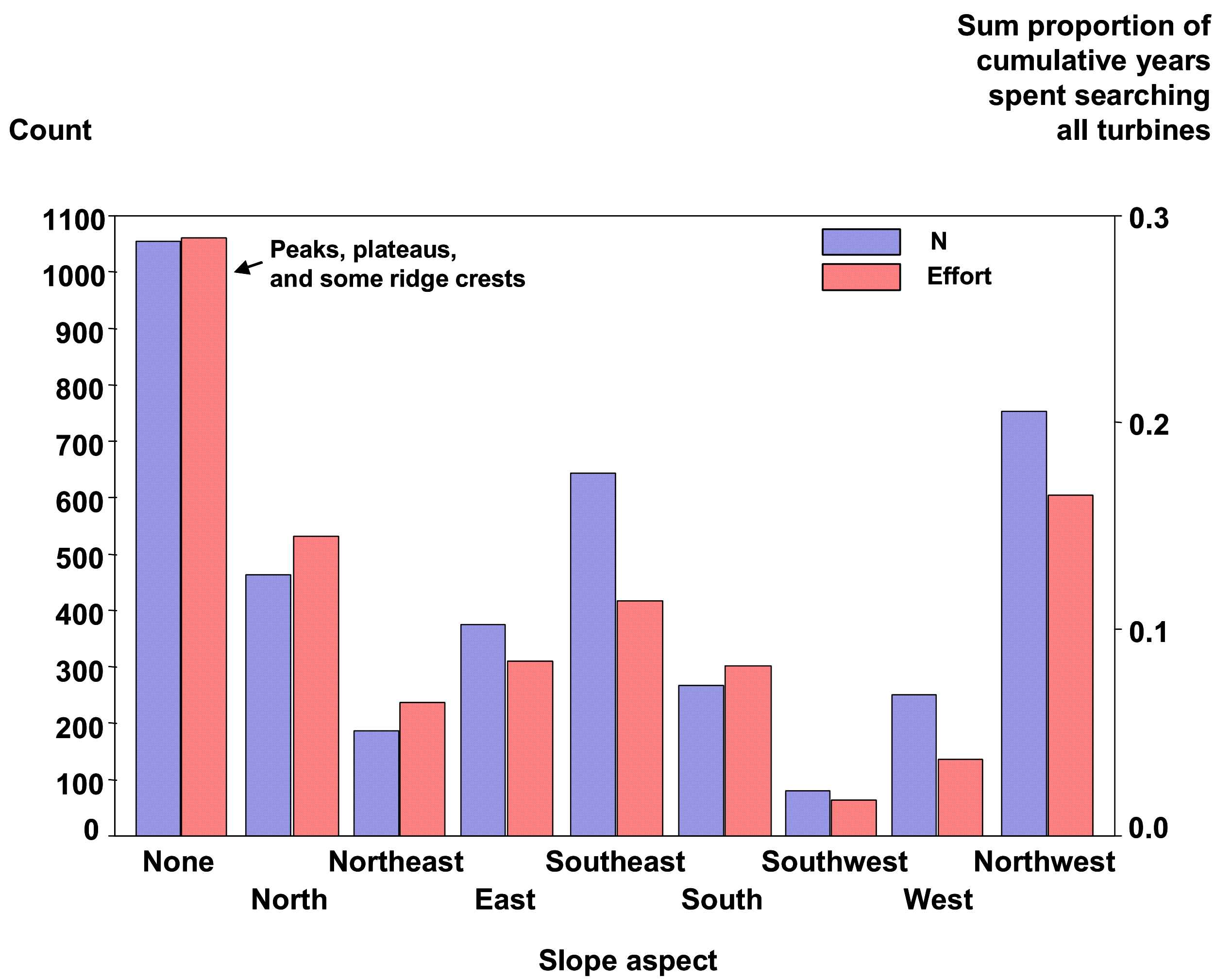


Figure 7-13. Frequency distributions of wind turbines and search effort at these turbines among slope aspects in the APWRA

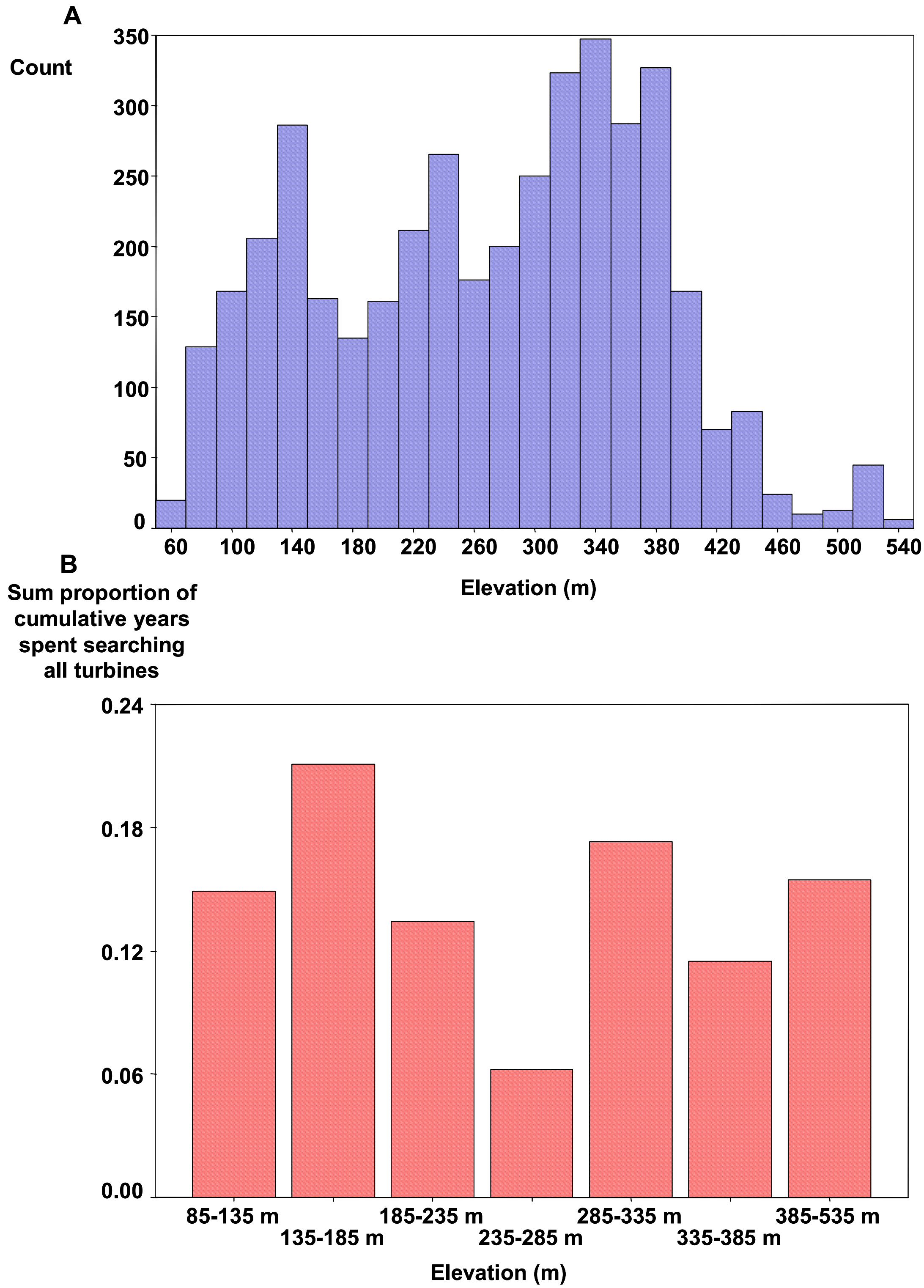


Figure 7-14. Frequency distributions of wind turbines (A) and search effort (B) at these turbines among elevations in the APWRA

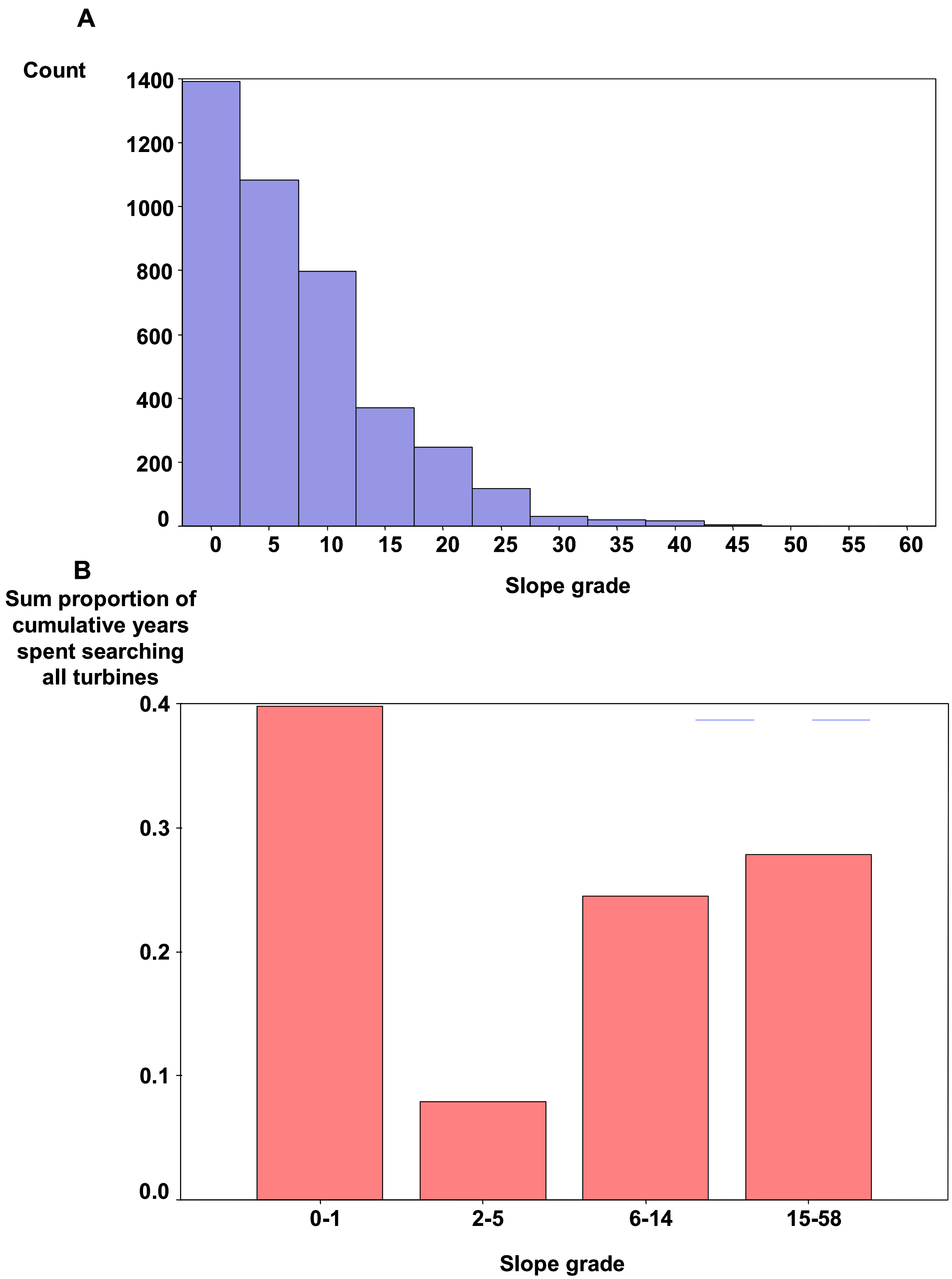


Figure 7-15. Frequency distributions of wind turbines (A) and search effort (B) at these turbines among slope grades in the APWRA

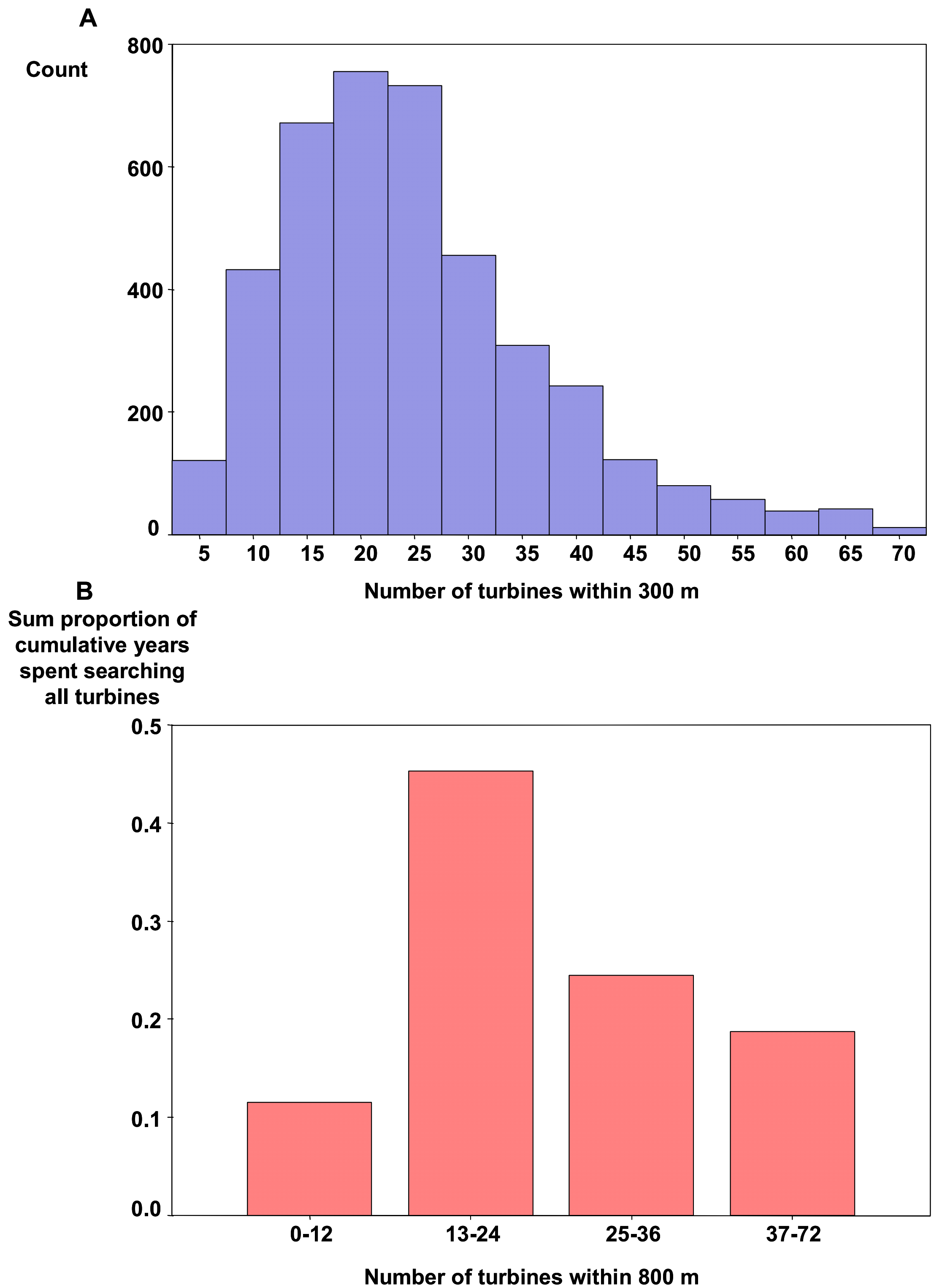


Figure 7-16. Frequency distributions of wind turbines (A) and search effort (B) at these turbines among counts of other wind turbines within 300 m of each wind turbine in the APWRA

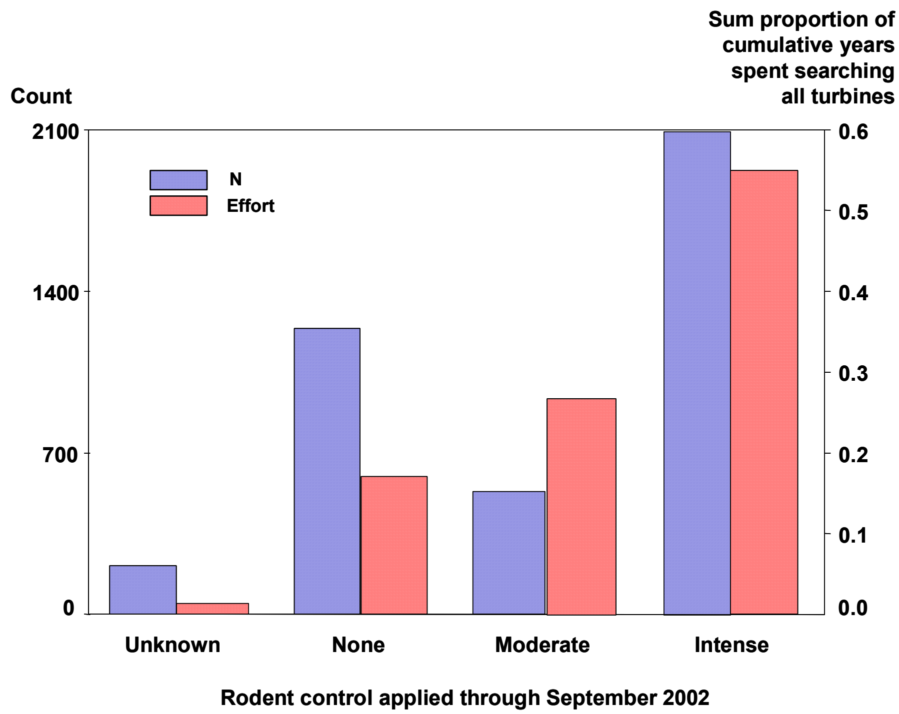


Figure 7-17. Frequency distributions of wind turbines and search effort at these turbines among levels of rodent control intensity applied in the APWRA

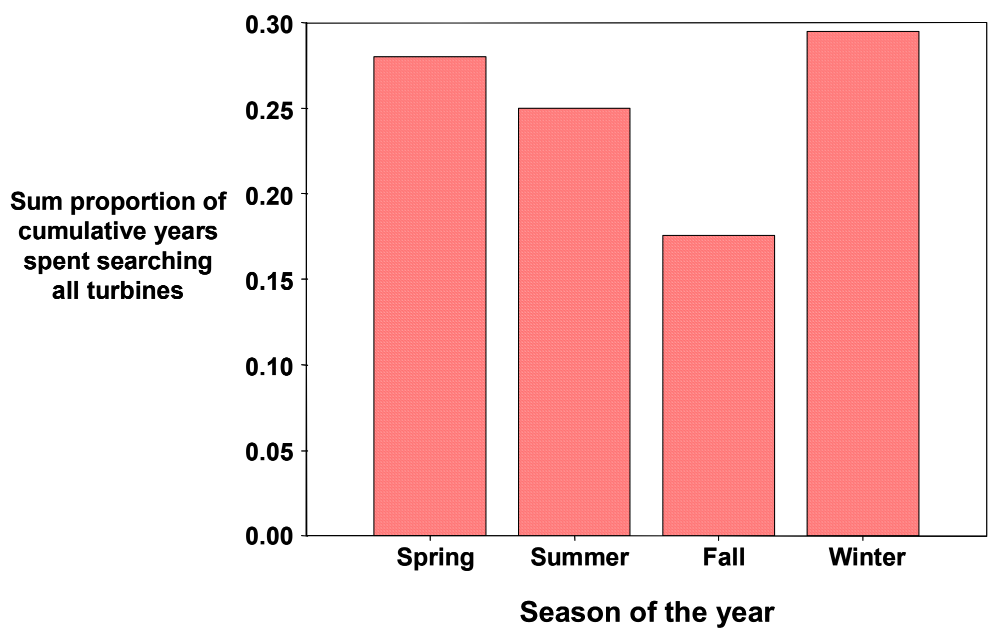


Figure 7-18. Frequency distribution of search effort at these turbines during the four seasons of the year

7.3.2 Fatality Associations

Tables 7-1 through 7-3 list the chi-square test values and their levels of statistical significance. Some variables were repeated in Table 7-3 because we aggregated the original categories into a smaller set of categories. The differences between the test results in these cases are evident in their degrees of freedom (df). For these variables, original categories were not included in Tables 7-1 and 7-2 because the smaller sample sizes of fatalities did not warrant testing of the number of original categories in the variables. When variables were aggregated in Table 7-3, only results from the aggregated categories were used in predictive model development.

Table 7-1. Chi-square values of association between the number of fatalities of raptor species and independent variables, where t denotes 0.10 > P > 0.05, * denotes P < 0.05, and ** denotes P < 0.005; and GOEA = golden eagle, RTHA = red-tailed hawk, AMKE = American kestrel, BUOW = burrowing owl, BAOW = barn owl, and GHOW = great-horned owl

Predictor Variable	df	GOEA	RTHA	AMKE	BUOW	BAOW	GHOW
Turbine model	10	17.98 [t]	20.70*	78.59**	44.59**	7.23	5.47
Turbine size	8	15.41 [t]	16.62*	74.42**	33.89**	7.07	4.82
Rotor diameter [a]	5	3.67	24.69**	50.89**	17.28**	5.21	4.5
Tip speed [a]	2	1.44	8.43*	1.94	26.75**	1.67	3.32
Window [a]	2	0.66	2.19	0.72	27.43**	5.86 [t]	3.45
Rotor-swept area/sec [a]	3	4.83	9.72*	40.71**	24.83**	2.70	4.08
Tower type	2	2.34	6.74*	2.71	34.37**	0.56	1.87
Tower height [a]	4	11.47*	9.34 [t]	3.22	24.41**	6.17	5.03
Orientation to wind	2	8.81*	6.42*	2.25	21.24**	0.54	2.09
Blade color scheme	4	4.59	21.50**	35.37**	1.69	24.13**	3.76
Perch guard	1	3.44 [t]	14.12**	0.20	0.76	0.54	3.34 [t]
Derelict turbine	2	0.22	4.87 [t]	3.22	3.39	2.92	0.70
Low reach of blades [a]	4	21.74**	5.78	12.42*	22.01**	2.52	6.64
High reach of blades [a]	3	15.05**	16.29**	2.69	9.79*	3.82	4.04
Whether in wind wall	1	6.64*	0.14	0.07	9.05**	0.13	0.10
Position in string	3	9.95*	15.77**	1.23	28.05**	6.82 [t]	1.95
Position in farm	2	8.25*	18.96**	2.59	3.21	7.70*	1.38
Turbine congestion	3	10.42*	17.44**	2.12	6.04	10.75*	1.24
Elevation	6	9.78	11.56 [t]	14.5*	57.78**	8.05	10.27
Slope grade	3	6.79	9.26 [t]	2.37	2.08	11.80*	1.89
Physical relief	6	17.39*	9.99	10.93 [t]	5.67	9.15	19.5**
Whether in canyon	1	6.56*	38.42**	0.00	2.25 [t]	24.79**	1.31
Slope aspect	8	10.84	19.50*	9.69	10.49	24.05**	7.03
Slope aspect	4	7.76	11.56*	4.32	1.38	17.93**	3.84
Edge index	5	47.56**	31.48**	3.33	7.21	1.86	3.49
Rock piles	2	1.01	3.30	4.12	2.75	1.22	3.73
Rodent control	3	9.32*	7.61 [t]	2.16	23.45**	6.02	4.61
Rodent control	3	11.09*	10.06*	2.52	23.42**	5.32	4.91
Cattle pats, grass	3	2.67	9.20*	0.13	7.29 [t]	18.40**	8.99*
Cattle pats, turbines	3	7.12 [t]	3.18	3.98	9.87*	3.30	1.17
Cottontails, grass	2	0.27	5.14 [t]	0.48	0.35	0.33	1.68
Cottontails, turbines	2	0.16	5.40 [t]	0.57	2.49	3.45	1.07
Vegetation height	3	8.00*	3.90	3.52	0.63	3.89	1.03
Season of the year	3	3.29	32.70**	8.83*	26.21**	5.87	3.59

[a] Categories of variable were aggregated to reduce degrees of freedom.

Table 7-2. Chi-square values of association between the number of fatalities of non-raptor species and independent variables, where t denotes 0.10 > P > 0.05, * denotes P < 0.05, and ** denotes P < 0.005; and MALL = mallard, WEME = western meadowlark, HOLA = horned lark, MODO = mourning dove, RODO = rock dove, and EUST = European starling

Predictor Variable	df	MALL	WEME	HOLA	MODO	RODO	EUST
Turbine model	10	25.02*	31.02**	5.99	65.36**	92.63**	22.70*
Turbine size	8	31.55**	25.10**	17.25*	55.67**	58.75**	19.13*
Rotor diameter [a]	5	29.14**	16.53*	14.65*	32.50**	60.11**	17.66**
Tip speed [a]	2	20.49**	19.48**	5.98 [t]	10.82**	19.23**	2.43
Window [a]	2	14.78**	18.59**	2.20	28.73**	37.57**	12.13**
Rotor-swept area/sec [a]	3	2.21	12.48*	9.82*	18.73**	19.83**	12.29*
Tower type	2	18.43**	16.17**	3.47	5.36 [t]	5.36 [t]	0.86
Tower height [a]	4	8.17 [t]	14.45*	3.43	3.47	19.06**	4.83
Orientation to wind	2	8.94*	12.33**	0.34	2.20	19.43**	1.75
Blade color scheme	4	0.81	6.29	0.56	1.63	4.78	8.28 [t]
Perch guard	1	0.36	1.05	0.25	0.37	16.50**	0.74
Derelict turbine	2	1.35	4.44	4.97 [t]	4.78 [t]	3.80	0.05
Low reach of blades [a]	4	8.76 [t]	12.93*	1.81	5.54	64.44**	6.12
High reach of blades [a]	3	13.4**	8.81*	11.02*	1.48	44.6**	6.49 [t]
Whether in wind wall	1	5.38*	4.81*	0.54	5.55*	4.83*	3.60 [t]
Position in string	3	20.43**	10.43*	9.20*	12.68*	3.82	0.30
Position in farm	2	2.40	1.45	2.33	8.37*	19.99**	0.70
Turbine congestion	3	9.81*	2.72	2.08	5.83	23.19**	2.26
Elevation	6	32.74**	24.64**	2.35	50.99**	80.86**	12.99*
Slope grade	3	14.58*	15.24**	5.75	4.02	10.46*	3.23
Physical relief	6	13.19*	7.50	0.87	15.43*	65.04**	10.15
Whether in canyon	1	33.59**	16.62**	0.76	3.31 [t]	1.30	0.17
Slope aspect	8	13.71 [t]	6.29	7.22	21.49*	30.19**	5.46
Slope aspect	4	5.44	1.38	0.38	15.80**	24.95**	1.15
Edge index	5	4.26	6.32	6.18	10.09 [t]	13.06*	3.42
Rock piles	2	1.48	0.67	0.62	2.85	2.86	1.28
Rodent control	3	18.52**	5.52	0.76	17.32**	12.67*	11.38*
Rodent control	3	16.20**	5.67	0.62	14.62**	11.84*	8.03*
cattle pats, grass	3	3.00	1.30	0.84	1.99	11.37*	1.88
cattle pats, turbines	3	9.98*	3.71	3.61	4.22	16.68**	2.56
Cottontails, grass	2	2.03	0.82	0.24	4.22	12.14**	2.24
Cottontails, turbines	2	5.48 [t]	16.31**	2.84	3.85	20.92**	8.81*
Vegetation height	3	6.58 [t]	3.47	2.97	1.98	20.88**	2.69
Season of the year	3	9.70*	14.65**	10.53*	33.02**	45.75**	1.07

[a] Categories of variable were aggregated to reduce degrees of freedom.

Table 7-3. Chi-square values of association between the number of fatalities of bird species and independent variables, where t denotes 0.10 > P > 0.05, * denotes P < 0.05, and ** denotes P < 0.005

Predictor Variable	df	Hawks	Raptors	All birds
Turbine model	10	23.48*	41.50**	70.06**
Turbine size	8	15.89*	38.63**	66.71**
Rotor diameter [a]	5	23.29**	40.58**	53.99**
Tip speed	11	35.99**	51.07**	68.41**
Tip speed [a]	2	6.41*	11.56**	12.34**
Window	12	36.2**	51.56**	71.35**
Window [a]	2	2.13	7.11*	20.07**
Rotor-swept area/sec	12	36.2**	51.56**	71.35**
Rotor-swept area/sec [a]	3	7.23 [t]	17.10**	15.90**
Tower type	2	7.89*	8.18*	23.82**
Tower height	8	23.66**	24.27**	25.39**
Tower height [a]	4	11.97*	10.90*	19.57**
Orientation to wind	2	9.09*	1.48	6.83*
Blade color scheme	4	23.65**	32.90**	20.29**
Perch guard	1	10.99**	7.33*	12.45**
Derelict turbine	2	4.58	0.30	1.49
Low reach of blades	16	32.84*	53.60**	82.49**
Low reach of blades [a]	4	6.44	6.98	16.14**
High reach of blades	17	32.96*	53.62**	82.55**
High reach of blades [a]	3	14.02**	15.99**	4.98
Whether in wind wall	1	0.15	6.10*	15.26**
Position in string	3	20.39**	52.95**	75.33**
Position in farm	2	12.96**	23.50**	33.56**
Turbine congestion	3	14.41**	24.73**	5.17
Elevation	6	11.97 [t]	14.74*	114.83**
Slope grade	4	9.77*	9.44 [t]	14.59*
Physical relief	6	8.95	19.91**	41.31**
Whether in canyon	1	32.50**	47.22**	41.49**
Slope aspect	8	19.95*	28.57**	27.18**
Slope aspect	4	9.82*	15.52**	19.71**
Edge index	5	26.99**	45.06**	31.57**
Rock piles	2	2.47	4.00	4.97 [t]
Rodent control	3	7.74 [t]	13.38**	20.34**
Rodent control	3	8.96*	16.91**	21.10**
Cattle pats, grass	3	11.43*	4.54	1.90
Cattle pats, turbines	3	2.77	5.66	4.23
Cottontails, grass	2	6.85*	3.42	6.57*
Cottontails, turbines	2	5.13 [t]	2.49	8.56*
Vegetation height	3	5.7	7.83*	11.42*
Season of the year	3	30.81**	49.50**	65.26**

[a] Categories of variable were aggregated to reduce degrees of freedom.

Appendix C presents the χ^2 tests between the distribution of bird fatalities and factors measured in the APWRA for particular species. Appendix B presents the tests for groups of species, including all hawks, all raptors, and all bird species combined. In considering these test values, we also considered the percentage of expected values < 5—the greater the percentage, the less reliable the test result. The test values were similar across wind turbine attributes, including wind turbine model, its rated speed, typical tip speed, rotor diameter, the window of time between blade sweeps of the same location at the blade tips, and the area in the rotor plane that is swept per second. Therefore, we attempted to identify the strongest association between the fatalities of a given species and turbine attributes, and we used only this strongest association in the predictive model.

Figures 7-19 through 7-21 depict the locations of wind turbines where golden eagles, red-tailed hawks, and burrowing owls had been found killed.

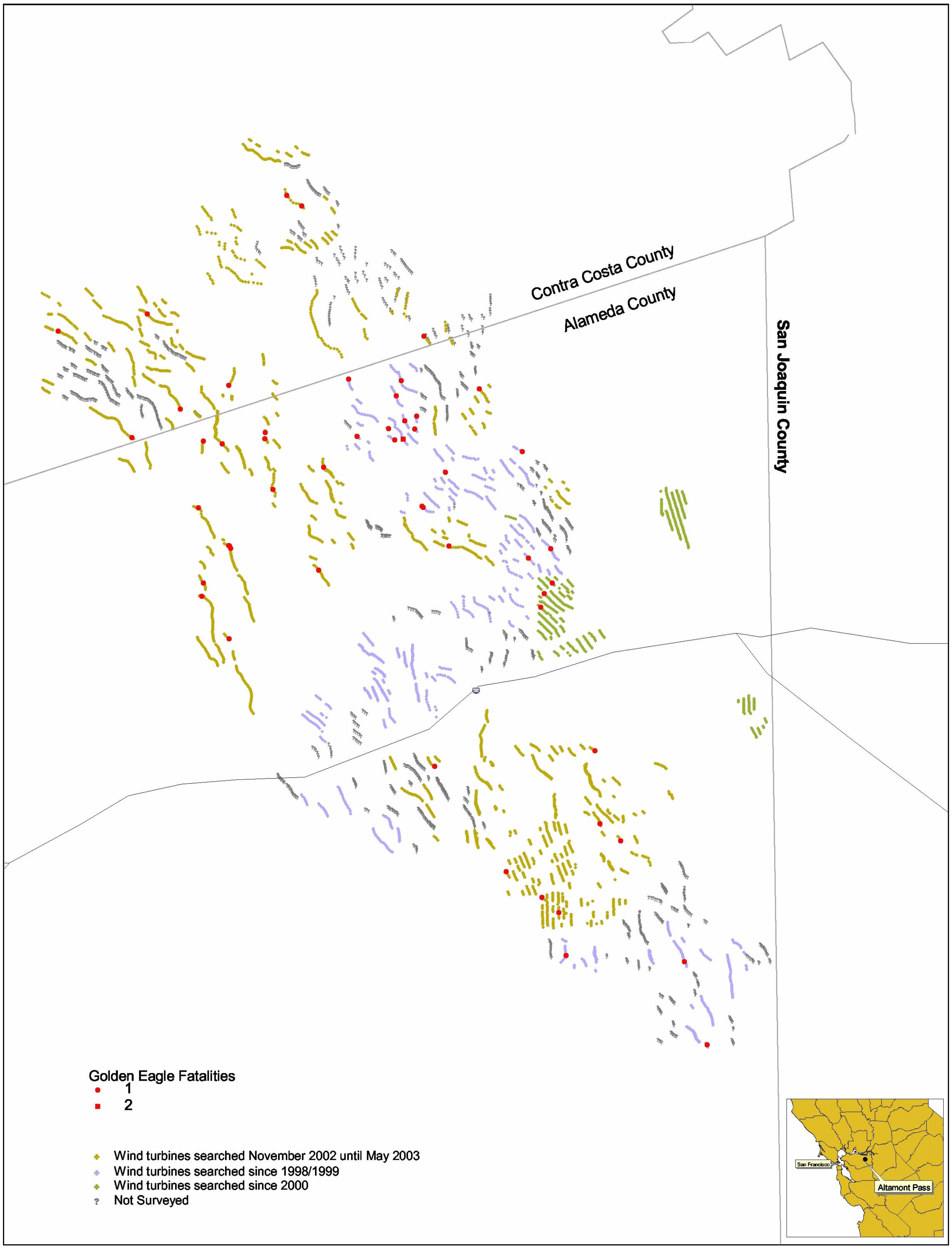


Figure 7-19. Golden eagle fatalities relative to search effort applied to wind turbines in the APWRA

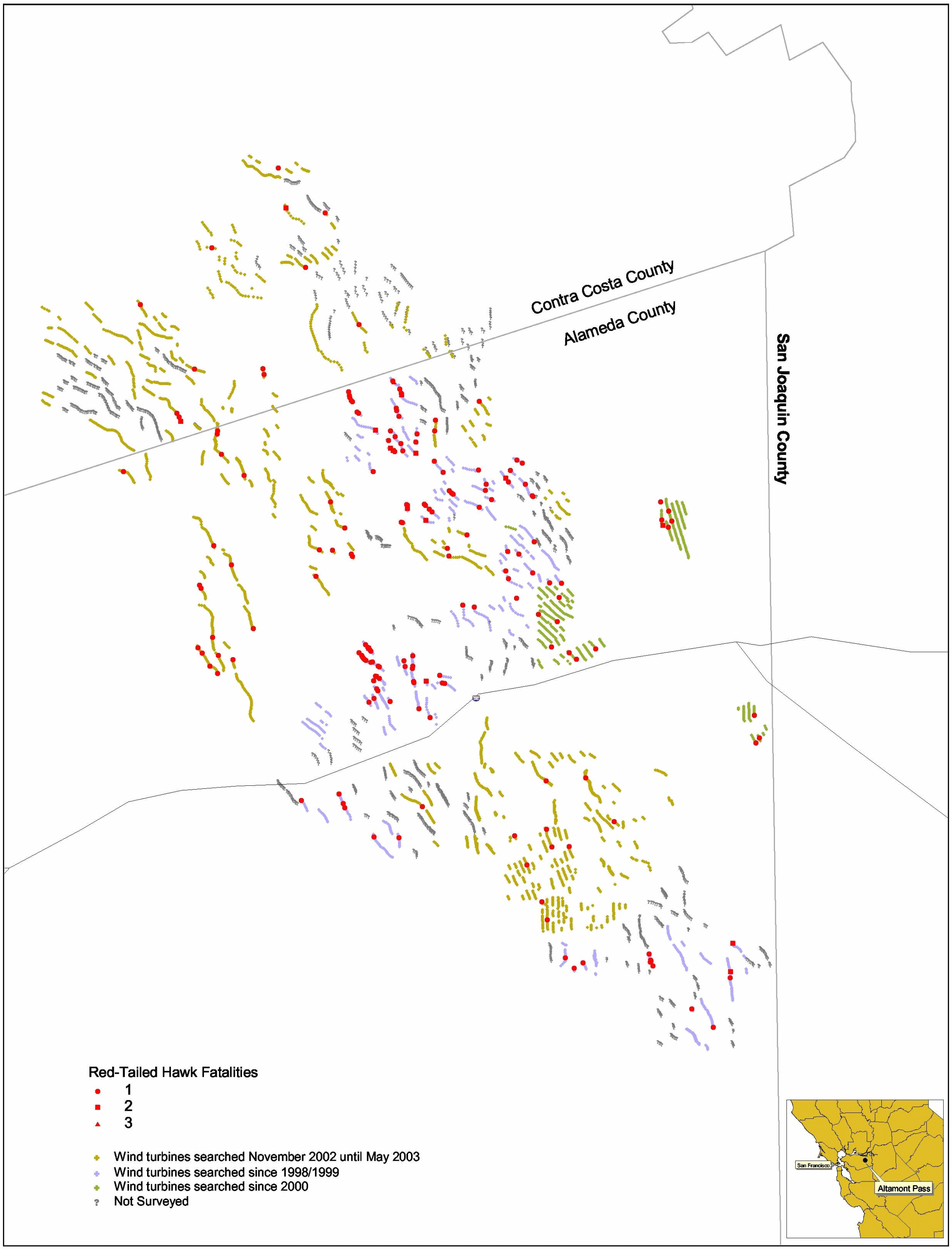


Figure 7-20. Red-tailed hawk fatalities relative to search effort applied to wind turbines in the APWRA

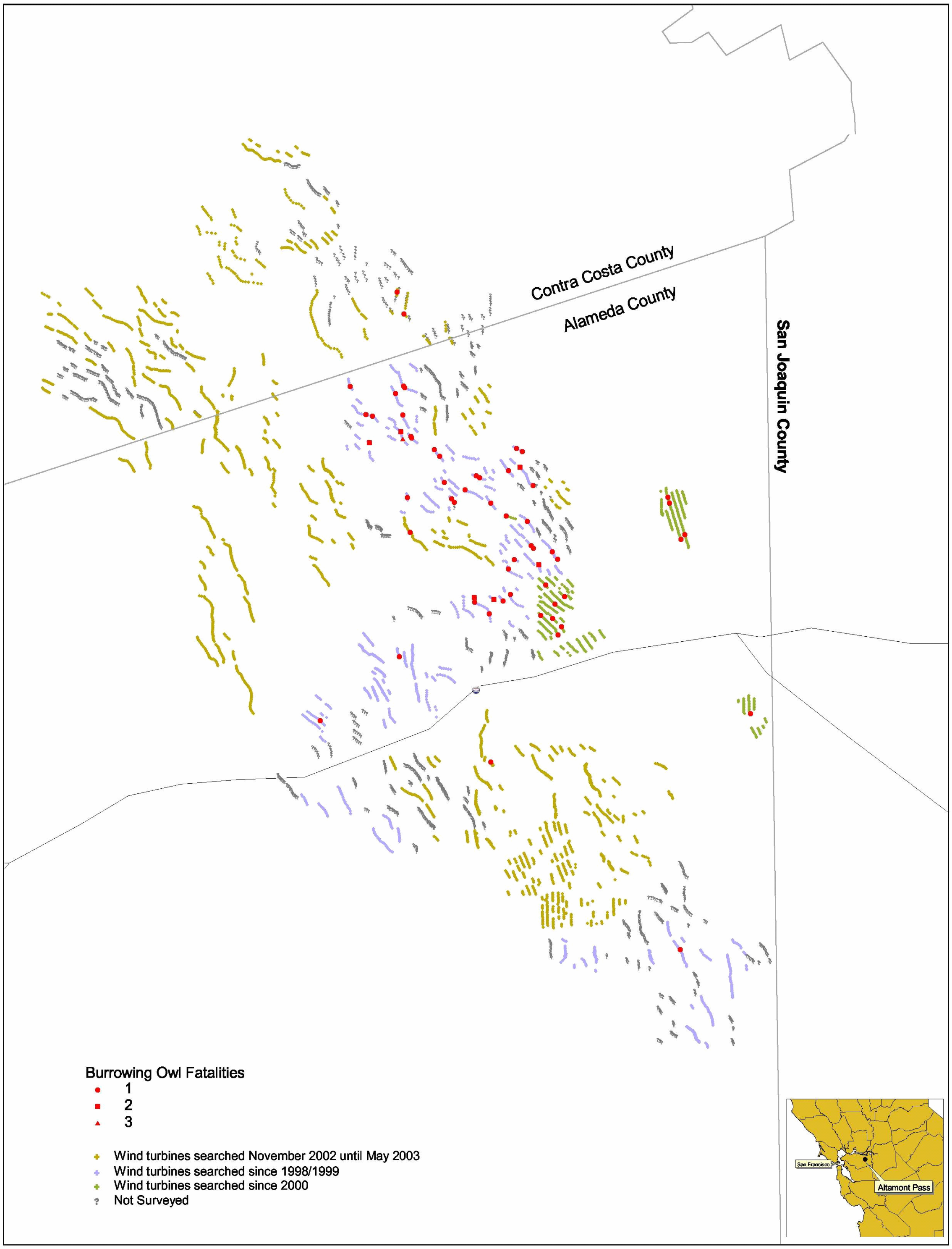


Figure 7-21. Burrowing owl fatalities relative to search effort applied to wind turbines in the APWRA

Wind Turbine Attributes

Table 7-4 presents the directions and magnitudes of the χ^2 test results involving wind turbine attributes, most of which were used for model development. Variables not used for model development included rated speed of the wind turbine, turbine size (rated power output), and turbine model. Bonus turbines associated with a greater than expected number of golden eagle fatalities, as well as fatalities of American kestrel, burrowing owl, mallard, western meadowlark, and mourning dove (Table 7-4). KVS-33 turbines killed more than the expected number of American kestrels, and KCS-56 turbines killed more than the expected number of golden eagles and American kestrels. Enertech and Flowind turbines also killed more than the expected number of burrowing owls, and Windmatic turbines took a disproportionate toll on mourning doves. Micon turbines killed more than the expected number of mourning doves, as well as European starlings and Rock doves.

Table 7-4. The directions and magnitudes of the associations between wind turbine-caused fatalities and attributes of the turbine or tower, and identified from the most reliable statistical test results.

Species	Magnitude of increase in mortality
Wind turbine model	
Golden eagle	5% at KCS-56, 3% at Bonus, 3% at Howden
Red-tailed hawk	6% at Bonus, 2% at Nordtank
American kestrel	11% at KVS-33, 5% at KCS-56, 3% at Nordtank
Burrowing owl	17% at Bonus, 10% at Flowind, 4% at Micon, 3% at Enertech
Mallard	26% at Bonus, 11% at Micon
Western meadowlark	11% at Bonus, 4% at Nordtank, 4% at Flowind
Mourning dove	25% at Micon, 5% at Windmatic, 5% at Howden
Rock dove	16% at Micon
European starling	9% at Micon, 4% at Nordtank
All hawks	6% at Bonus
All raptors	5% at Bonus
All birds	5% at Micon, 2% at Bonus
Rotor Diameter	
Red-tailed hawk	10% at turbines with larger rotor diameters
Rock dove	15% at turbines with smaller rotor diameters
All hawks	9% at turbines with the largest rotor diameters
All raptors	7% at turbines with the largest rotor diameters
Tip speed	
Mourning dove	25% at turbines with slowest tip speeds
All hawks	5% at turbines with intermediate tip speeds
All raptors	5% at turbines with intermediate tip speeds
All birds	5% at turbines with intermediate to slowest tip speeds

Table 7-4. (cont'd)

Species	Magnitude of increase in mortality
Seconds per rotor sweep at blade tip	
Burrowing owl	30% at turbines with longer time per rotor sweep at blade tip
Barn owl	10% at turbines with longest time per rotor sweep at blade tip
Mallard	32% at turbines with longer time per rotor sweep at blade tip
Western meadowlark	22% at turbines with longer time per rotor sweep at blade tip
All raptors	5% at turbines with longer time per rotor sweep at blade tip
All birds	5% at turbines with longer time per rotor sweep at blade tip
Rotor-swept area/sec.	
American kestrel	10% at turbines with larger area swept/second
Horned lark	25% at turbines with low-medium area swept/second
European starling	17% at turbines with least area swept/second
All hawks	7% at turbines with larger area swept/second
All raptors	3% at turbines with larger area swept/second
All birds	4% at turbines with least area swept/second
Rotor orientation	
Rock dove	15% at turbines with rotor blades facing wind
All hawks	9% at turbines with rotor blades facing wind
All birds	4% at turbines with rotor blades facing wind
Tower type	
Red-tailed hawk	7% at tubular towers
Burrowing owl	19% at tubular towers, 10% at vertical axis towers
Mallard	35% at tubular towers
Western meadowlark	15% at tubular towers, 4% at vertical axis towers
Mourning dove	18% at tubular towers
All hawks	7% at tubular towers
All raptors	6% at tubular towers
All birds	7% at tubular towers
Blade color scheme	
Red-tailed hawk	2% at turbines with red stripes/tips on blades
American kestrel	5% at turbines with black stripes, 3% at turbines with colored blade tips
Barn owl	3% at turbines with red stripes/tips on blades
European starling	4% at turbines with colored blade tips
All hawks	3% at turbines with red stripes/tips on blades
All raptors	2% at turbines with colored blade tips
All birds	2% at turbines with colored blade tips

Table 7-4. (cont'd)

Species	Magnitude of increase in mortality
Perch deterrent	
Golden eagle	3% at towers with perch deterrents
Red-tailed hawk	3% at towers with perch deterrents
Great horned owl	4% at towers with perch deterrents
Rock dove	3% at towers with perch deterrents
All hawks	2% at towers with perch deterrents
Tower height	
Burrowing owl	16% at towers of medium height
All hawks	10% at towers of medium height
All raptors	6% at towers of medium height
All birds	5% at towers of medium height
Height of lowest blade reach	
Golden eagle	25% at turbines with lower reaches of blades
Rock dove	24% at turbines with fairly high reach of blades
All birds	3% at turbines with fairly high reach of blades
Height of highest blade reach	
Red-tailed hawk	9% at turbines with *highest* reaches of blades
Mallard	23% at turbines with *highest* reaches of blades
Horned lark	27% at turbines with *medium* reaches of blades
Western meadowlark	13% at turbines with *higher* to highest reaches of blades
European starling	14% at turbines with *lowest* reaches of blades
All hawks	8% at turbines with *highest* reaches of blades
All raptors	6% at turbines with *highest* reaches of blades

At the multi-species level of analysis, Bonus turbines killed disproportionately more hawks, raptors, and all birds (Table 7-4). Micon turbines killed disproportionately more birds than any other wind turbine model. KCS-56 turbines killed fewer than the expected number of raptors and all birds.

Larger rotor diameters associated with disproportionately more fatalities of red-tailed hawks, all hawks, and all raptors; whereas, shorter diameter wind turbines killed substantially more than the expected number of rock doves (Table 7-4).

Wind turbines with slower-moving blades associated with a significantly larger proportion of fatalities of mourning doves, all hawks, all raptors, and all birds considered together. Wind turbines with intermediate to longer windows of opportunity to fly through the rotor plane (i.e., 0.5–0.7 seconds) associated with a significantly larger proportion of fatalities of burrowing owl, mallard, and western meadowlark. Wind turbines with the longest windows of opportunity to fly through the rotor plane associated with a significantly larger proportion of barn owl fatalities.

At the multi-species level of analysis, wind turbines with longer windows of opportunity to fly through the rotor plane associated with a significantly larger proportion of fatalities of all raptors and all birds. The converse of the window of opportunity to fly through the rotor plane is the rate at which the rotor plane is swept.

Larger rotor areas swept per second associated with disproportionately more numbers of fatalities of American kestrel, all hawks, all raptors, and all birds; whereas, the intermediate and small rotor swept areas per second associated with disproportionately more horned lark and European starling fatalities.

Rotors facing the wind killed disproportionately more rock doves, all hawks, and all birds combined (Table 7-4). Tubular towers killed disproportionately more red-tailed hawks, burrowing owls, mallards, western meadowlarks, mourning doves, all hawks, all raptors, and all birds than expected by chance, whereas vertical axis turbines killed more burrowing owls and western meadowlarks than expected.

Wind turbines with blades painted colors other than white ended up killing disproportionately more red-tailed hawks, American kestrels, barn owls, European starlings, and all hawks, all raptors, and all birds (Table 7-4). We found no evidence for any species that indicated colored blade tips or striped blades associated with fewer than the expected number of fatalities.

Lattice towers with perch deterrents associated with increased mortality of golden eagle, red-tailed hawk, great-horned owl, rock dove, and all hawks (Table 7-4). Wind turbines with perch deterrents did not associate with less mortality for any species in the study area. Positive associations might have resulted for one or more reasons. It is possible that perch deterrents were put on lattice towers with a history of killing disproportionately more birds, and that the perch deterrents failed to eliminate mortality at these turbines. It is also possible that birds that are used to perching on lattice towers might approach them to perch on them and at the last moment discover the perch deterrents, which are simply chicken wire tied around horizontal structures normally used for perching. Upon discovering the perch deterrents, these birds might take evasive or corrective flights, which sometimes take them into the rotor plane.

Towers of intermediate height associated with disproportionately more fatalities of burrowing owl, all hawks, all raptors, and all birds (Table 7-4). Turbines with blades that reach lower toward the ground killed disproportionately more golden eagles, and those with lowest reaches that were relatively high compared to other turbines killed more than the expected number of rock doves and all birds considered together. Of all the wind turbine and tower attributes, the lowest reach of the turbine blades associated most strongly with golden eagle mortality.

Wind turbines with blades reaching highest into the sky killed disproportionately more red-tailed hawks, mallards, all hawks, and all raptors. Higher blade reaches also took disproportionately more western meadowlarks.

Wind Turbine Location Attributes

Wind turbine-caused fatalities of most species were more often than expected at wind turbines not belonging to wind walls, including golden eagle, burrowing owl, mallard, western meadowlark, European starling, all raptors, and all birds (Table 7-5). One exception was rock dove. Wind turbines with fewer other wind turbines occurring within 300 m killed disproportionately more golden eagles, red-tailed hawks, barn owls, mallards, and all hawks and all raptors combined (Table 7-5). Only rock doves were killed disproportionately more often at wind turbines within denser turbine fields.

Whereas adjacency of wind turbines to derelict turbines appeared to be a significant factor in our analysis of a smaller set of data (Smallwood and Thelander, in review), it did not appear to be a significant factor using the larger data set now available to us. Only horned lark and mourning dove were killed at wind turbines next to derelict wind turbines in disproportionate numbers (Table 7-5). Mourning doves also died disproportionately at derelict turbines, suggesting that at least this species collides with non-operating turbines and tower structures with fatal consequences.

Wind turbines at the ends of turbine rows killed more than the expected number of golden eagles, red-tailed hawks, burrowing owls, barn owls, mallards, western meadowlarks, and mourning doves, and wind turbines at the edges of gaps in the row killed more than the expected number of mallards and horned larks (Table 7-5). Overall, wind turbines at the ends of rows and at gaps killed disproportionately more hawks, raptors, and all bird species combined than did interior turbines (Table 7-5). Similarly, wind turbines at the edges of local clusters of wind turbines killed disproportionately more golden eagles, red-tailed hawks, barn owls, and mourning doves (Table 7-5). At the multi-species level of analysis, wind turbines at the edges of local clusters of wind turbines killed significantly more than the expected number of hawks, raptors, and all bird species combined.

Wind turbines on ridgelines killed disproportionately more golden eagles, American kestrels, and all raptors combined; whereas, those on plateaus killed disproportionately more great-horned owls, mallards, and mourning doves; and those on slopes also killed disproportionately more mallards and mourning doves (Table 7-5). Those in canyons killed disproportionately more golden eagles, red-tailed hawks, burrowing owls, barn owls, mallards, western meadowlarks, and mourning doves—as well as all hawks combined, all raptors, and all birds (Table 7-5). Wind turbines on slopes facing north or northwest killed disproportionately more red-tailed hawks and barn owls, as well as all hawks and all raptors combined (Table 7-5). Wind turbines on slopes facing southwest and west killed more than the expected number of mourning doves.

Wind turbines at mid elevation killed disproportionately more red-tailed hawks; whereas, those at highest and lowest elevations killed disproportionately more American kestrels. Those at the lowest elevations in the APWRA killed disproportionately more burrowing owls, mallards, western meadowlarks, mourning doves, rock doves, European starlings, and all raptors and all birds (Table 7-5). Those on steeper slopes killed disproportionately more golden eagles, red-tailed hawks, barn owls, and western meadowlarks; whereas, those on shallower slopes killed more rock doves (Table 7-5). At the interspecific level of analysis, wind turbines on steeper slopes also killed disproportionately more hawks, raptors, and all birds.

Within the first set of 1,526 wind turbines searched for carcasses, the presence of rock piles assembled near wind turbine strings associated with significantly more than the expected number of fatalities of golden eagle, red-tailed hawk, American kestrel, burrowing owl, barn owl, horned lark, western meadowlark, and rock dove (Smallwood and Thelander in review). However, adding the additional 2,548 wind turbines changed the relationship. With our larger sample size, the number of rock piles near wind turbines did not associate with the number of fatalities of any species we examined.

Table 7-5. The directions and magnitudes of the associations between wind turbine-caused fatalities and attributes of the turbine's location, and identified from the most reliable statistical test results

Species	Magnitude of increase in mortality
Whether in wind wall	
Golden eagle	12% at turbines *not* in wind walls
Burrowing owl	13% at turbines *not* in wind walls
Mallard	14% at turbines *not* in wind walls
Western meadowlark	8% at turbines *not* in wind walls
Mourning dove	14% at turbines *not* in wind walls
Rock dove	5% at turbines *in* wind walls
European starling	8% at turbines *not* in wind walls
All raptors	4% at turbines *not* in wind walls
All birds	4% at turbines *not* in wind walls
Whether adjacent to derelict turbine	
Horned lark	9% at turbines next to derelict turbines
Mourning dove	5% at turbines next to derelict turbines, 5% at derelict turbines
Position in turbine string	
Golden eagle	17% at the string end, 2% next to gaps
Red-tailed hawk	11% at the string end, 1% next to gaps
Burrowing owl	24% at the string end
Barn owl	6% at the string end, 3% next to gaps
Mallard	18% next to gaps, 14% at the string end
Horned lark	17% next to gaps, 4% at the string end
Western meadowlark	11% at the string end, 2% next to gaps
Mourning dove	25% at the string end
All hawks	13% at the string end or edge of gap
All raptors	14% at the string end or edge of gap
All birds	11% at the string end or edge of gap

Table 7-5. (cont'd)

Species	Magnitude of increase in mortality
Location in wind farm	
Golden eagle	12% at local cluster of turbines
Red-tailed hawk	9% at local cluster of turbines
Barn owl	12% at local cluster of turbines
Mourning dove	16% at edge of wind farm
Rock dove	8% at local cluster of turbines, 5% at edge of wind farm
All hawks	7% at local cluster of turbines
All raptors	7% at local cluster of turbines
All birds	6% at local cluster of turbines or at edge of wind farm
Wind turbine congestion	
Golden eagle	21% at turbines more sparsely distributed
Red-tailed hawk	8% at turbines more sparsely distributed
Barn owl	23% at turbines more sparsely distributed
Mallard	13% at turbines more sparsely distributed, 6% at most crowded turbines
Rock dove	17% at turbines more densely distributed
All hawks	7% at turbines more sparsely distributed
All raptors	8% at turbines more sparsely distributed
Physical relief	
Golden eagle	21% on ridgeline
American kestrel	10% on ridgeline, 5% on ridge crest
Great horned owl	21% on plateau, 5% in ravine, 2% on ridgeline
Mallard	12% on slope, 11% on plateau
Mourning dove	19% on slope, 11% on plateau
Rock dove	10% on plateau, 7% in saddle
All raptors	6% on ridgeline
All birds	3% on plateau, 2% on slope
Whether in a canyon	
Golden eagle	13% *in* canyon
Red-tailed hawk	15% *in* canyon
Burrowing owl	6% *in* canyon
Barn owl	26% *in* canyon
Mallard	36% *in* canyon
Western meadowlark	15% *in* canyon
Mourning dove	11% *in* canyon
All hawks	13% *in* canyon
All raptors	11% *in* canyon
All birds	7% *in* canyon

Table 7-5. (cont'd)

Species	Magnitude of increase in mortality
Slope aspect	
Red-tailed hawk	5% on north/northwest slopes, 4% on south/southeast slopes
Barn owl	24% on north/northwest slopes, 5% on west/southwest slopes
Mourning dove	15% on west/southwest slopes
Rock dove	7% on west/southwest slopes, 4% on flat terrain
All hawks	7% on northwest slopes, 3% on southern slopes
All raptors	5% on northwest slopes, 3% on southern slopes
All birds	7% on southeast to west-facing slopes
Elevation	
Red-tailed hawk	8% at mid elevation
American kestrel	12% at highest elevation, 5% at lowest elevation
Burrowing owl	44% at lowest elevation
Mallard	47% at lowest elevation
Western meadowlark	20% at lowest elevation
Mourning dove	46% at lowest elevation
Rock dove	19% at lowest elevation
European starling	14% at lowest elevation
All raptors	6% at lower elevations
All birds	12% at lower elevations
Slope grade	
Golden eagle	13% on steeper slopes
Red-tailed hawk	11% on steeper slopes
Barn owl	23% on steeper slopes
Western meadowlark	12% on steepest slopes
Rock dove	11% on shallower slopes
All hawks	9% on steeper slopes
All raptors	9% on steeper slopes
All birds	3% on steepest slopes
Edge index	
Golden eagle	27% at sites with greater vertical edge
Red-tailed hawk	13% at sites with greater vertical edge
Mourning dove	12% at sites with lots of vertical edge, 10% at sites with little or no edge
Rock dove	10% at sites with lateral but no vertical edge
All hawks	11% at sites with greater vertical edge
All raptors	11% at sites with greater vertical edge
All birds	5% at sites with greater vertical edge

Wind turbines with greater levels of vertical edge around its tower base killed disproportionately more golden eagles, red-tailed hawks, and mourning doves—as well as all hawks, all raptors, and all birds combined (Table 7-6).

Range Conditions

Had the rodent control program achieved the objective of reducing mortalities, then disproportionately more wind turbine-caused fatalities would have occurred where no rodent control was implemented during our study. In fact, wind turbines in areas of no rodent control killed disproportionately more golden eagles, mourning doves, rock doves and European starlings (Table 7-6).

Wind turbines in areas with rodent control killed disproportionately more red-tailed hawks, burrowing owls, mallards, and at the interspecific level of analysis, more hawks and raptors. The golden eagle association we obtained in this study differs from that of Smallwood and Thelander (in review), probably because the largest number of wind turbines in an area of no control occurs in the northwestern portion of the wind farm, and it corresponds with the intensive use of the wind farm by golden eagles. There is no evidence that the rodent control program, or lack thereof, had any influence on the spatial variation in the intensity of use of the wind farm by golden eagles (see Chapter 8).

Cattle pats were counted only at the original set of 1,526 wind turbines, so our analysis is limited to those. Wind turbines with more cattle pats nearby killed disproportionately more golden eagles, burrowing owls, and mallards (Table 7-6), although the association with mallard fatalities was likely spurious, because we can think of no ecological explanation for mallards to fly by wind turbines with greater levels of cattle visitation.

Table 7-6. The directions and magnitudes of the associations between wind turbine-caused fatalities and attributes of the range conditions surrounding the wind turbine, identified from the most reliable statistical test results

Species	Magnitude of increase in mortality
Rodent control	
Golden eagle	14% in areas with no control
Red-tailed hawk	8% in areas with moderate level of control
Burrowing owl	24% in areas with moderate level of control
Mallard	31% in areas with moderate level of control
European starling	8% in areas with no control
All hawks	7% in areas with moderate level of control
All raptors	7% in areas with moderate level of control
All birds	4% in areas with moderate level of control, 3% in areas with no control
Cattle pats at wind turbines	
Golden eagle	19% at turbines with more cattle pats
Burrowing owl	18% at turbines with more cattle pats
Mallard	22% at turbines with more cattle pats
Rock dove	13% at turbines with fewer or no cattle pats

Seasonality

For most species, summer and winter were most often associated with more than the expected number of fatalities; however, spring was associated with a disproportionate number of mallard fatalities, and fall was associated disproportionately with red-tailed hawk fatalities (Table 7-7). Significant associations between number of fatalities and season of the year are depicted in Figures 7-22 and 7-23.

Table 7-7. The directions and magnitudes of the associations between wind turbine-caused fatalities and season of the year, identified from the most reliable statistical test results

Species	Magnitude of increase in mortality with season of the year
Red-tailed hawk	10% in winter, 6% in fall, 5% in summer
American kestrel	18% in winter
Burrowing owl	21% in summer, 6% in winter
Mallard	20% in spring, 3% in summer
Western meadowlark	17% in winter
Horned lark	30% in summer
Rock dove	21% in summer
All hawks	10% in winter, 6% in fall, 4% in summer
All raptors	8% in summer, 8% in winter
All birds	8% in summer, 4% in winter

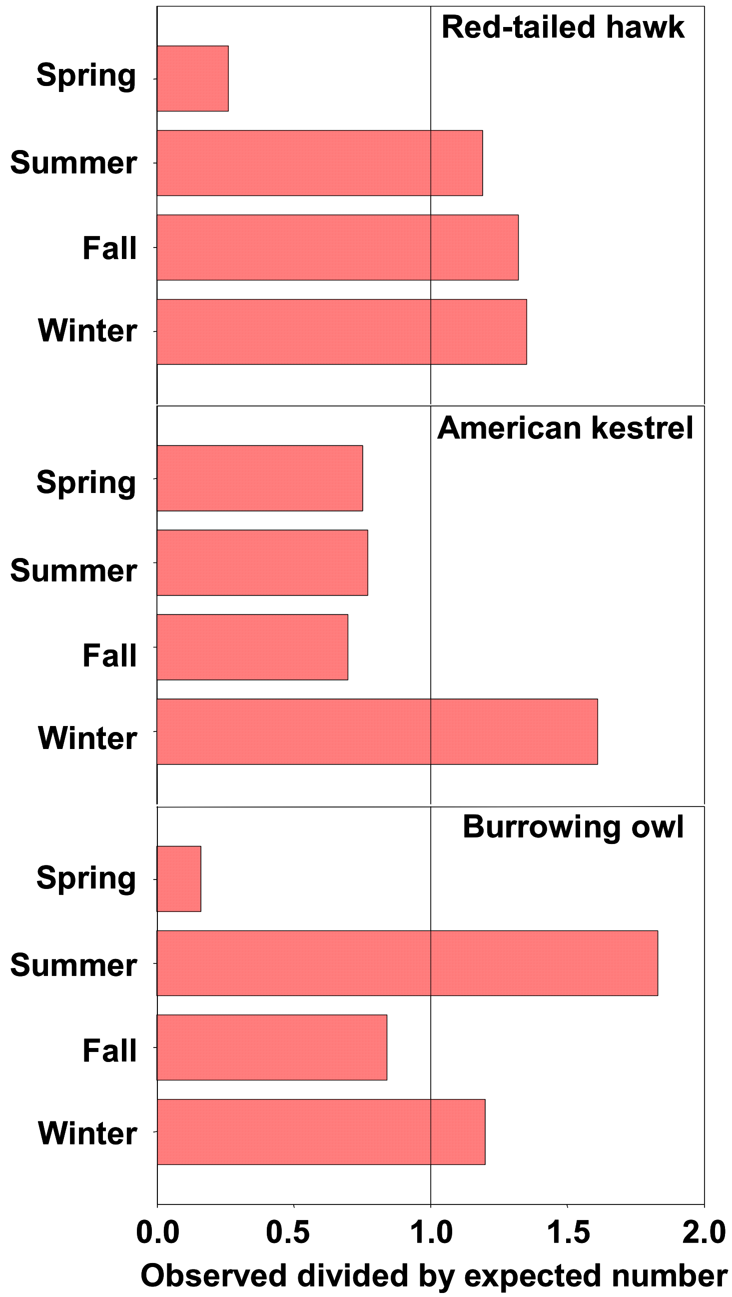


Figure 7-22. Observed-divided-by-expected number of fatalities of raptor species during each season of the year during our study in the APWRA. All associations shown were significant ($P < 0.05$).

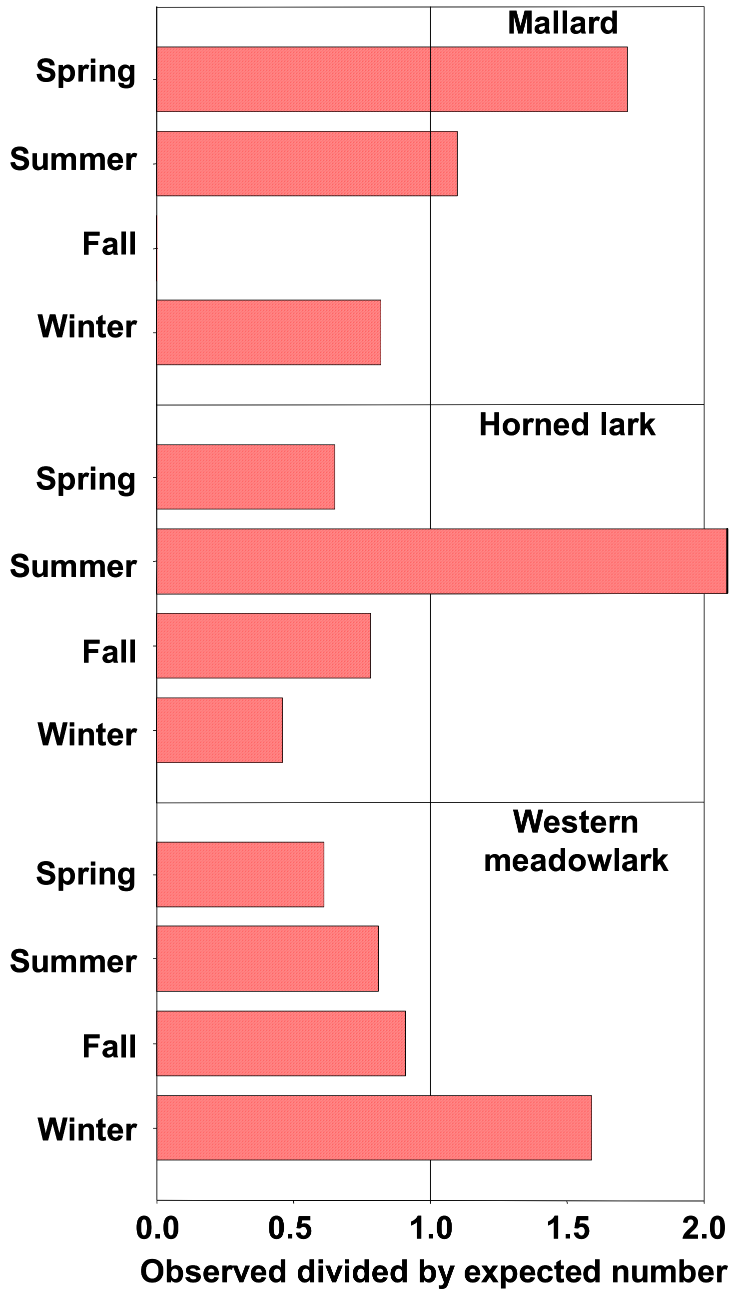


Figure 7-23. Observed–divided-by-expected number of fatalities of non-raptor species during each season of the year during our study in the APWRA. All associations shown were significant ($P < 0.05$).

7.3.3 Predictive Models of Mortality

Table 7-8 summarizes the associations between variables and species that were most reliable for use in model development. Some variables were not used for model development because doing so would be nonsensical from an ecological standpoint. For example, season of the year did not fit into models built around all of the data, including from all four seasons, considered together. Other variables not entered into the models included perch deterrent and blade color schemes. Turbine size (i.e., power output) was not used because it correlated strongly with other turbine attributes that were already used.

The empirical models developed were tested only against the database of the 4,074 wind turbines from which the data were obtained for model development. The remaining 1,326 wind turbines in the APWRA (which were not included in our study) cannot be subjected to model predictions, because we have not yet characterized those wind turbines based on the variables measured in our study.

The number of wind turbines that the model predicted to be more dangerous to each species was many more than the number where we actually found carcasses of each species. Assuming our predictive models are relatively precise, this discrepancy indicates that continued carcass searches would likely add many more wind turbines to the pool of wind turbines documented to have actually killed members of each species. Also, we note that our designation of "dangerous" is a relative one, meaning that these wind turbines are predicted to more likely kill members of the species in question. However, all wind turbines remain dangerous to some degree to every bird species.

Table 7-8. Chi-square test results that were significant, composed of expected cell values mostly > 5, and resulting in accountable mortality values that formed distinct gradients across categories or levels of the association variable. Numbers in the table are the largest accountable mortality values calculated from the chi-square tests between the association variable and the mortality of the species, where GOEA = golden eagle, RTHA = red-tailed hawk, AMKE = American kestrel, BUOW = burrowing owl, BAOW = barn owl, GHOW = great-horned owl, MALL = mallard, WEME = western meadowlark, HOLA = horned lark, MODO = mourning dove, RODO = rock dove, and EUST = European starling.

Predictor Variable	df	GOEA	RTHA	AMKE	BUOW	BAOW	GHOW	MALL	WEME	HOLA	MODO	RODO	EUST
Rotor diameter	5		10									15	
Tip speed	2										25		
Window	2				30	10		32	22				
Rotor-swept area/sec	3			10						25			17
Tower type	2		7		29			37	19		18		
Tower height	4				16								
Orientation to wind	2											15	
Derelict turbine	2									9			
Low reach of blades	4	25										24	
High reach of blades	3		9					23	13	27			14
Part of wind wall?	1	12			13			14	8		14	5	8
Position in string	3	19	12		25	9		32	14	21	25		
Position in farm	2	12	9			12					17	13	
Turbine congestion	3	21	8			23						17	
Elevation	6			17	44			47	20		46	25	14
Slope grade	3	20	11			23			12			11	
Physical relief	6	22		18			28	23			30	20	
Whether in canyon	1	13	15		6	26		36	15		11		
Slope aspect	4		11			29					15	11	
Edge index	5	27	13									10	
Rock piles	2												
Rodent control	3		10		24								12
Cattle pats, grass	3		7										
Cattle pats, turbines	3				18							13	
Cottontails, grass	2												
Cottontails, turbines	2								15				17
Vegetation height	3												

Golden Eagles

The only wind turbine attributes that reliably associated with fatalities of golden eagles was the height of the lowest reach of the turbine blades. This attribute accounted for 25% of the fatalities (Table 7-9). Other strong associations included wind turbines surrounded by greater levels of vertical edge (e.g., tower laydown areas cut into hill slopes), those on ridgelines, those that are more isolated from other wind turbines, and those with more cattle pats near the tower bases. Overall, it appears that wind turbines are most dangerous when they are isolated and located on ridgelines within canyons or deeper ravines where golden eagles forage by contour flying over areas that are relatively more exposed due to intense cattle grazing.

Table 7-9. The directions and magnitudes of the associations between wind turbine-caused golden eagle fatalities and levels within independent variables

Variable	Magnitude of increase in mortality
Height of lowest blade reach	25% at turbines with lower reaches of blades
Whether in wind wall	12% at turbines *not* in wind walls
Position in turbine string	17% at the string end, 2% next to gaps
Location in wind farm	12% at local cluster of turbines
Wind turbine congestion	21% at turbines more sparsely distributed
Physical relief	21% on ridgeline
Whether in canyon	13% in canyon
Slope grade	13% on steeper slopes
Edge index	27% at sites with greater vertical edge
Rodent control	14% in areas with no control
Cattle pats at wind turbines	19% at turbines with more cattle pats

The model correctly predicted wind turbines to be dangerous where 82% of the golden eagle fatalities actually occurred (Table 7-10). About 50% of the wind turbines were predicted to be dangerous to golden eagles. Model predictions are also depicted in Figure 7-24. The more dangerous wind turbines were distributed widely across the wind farm (Figure 7-25).

Table 7-10. The distribution of known golden eagle fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the nine variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	2007	2014	50% of turbines
1	10	42	81% of turbines
2	0	1	100% of turbines
Total fatalities	10	44	82% of fatalities

Red-tailed Hawks

No variable we measured could alone account for more than 15% of the red-tailed hawk fatalities (Table 7-11). Red-tailed hawk fatalities most strongly associated with wind turbines located on steep canyon slopes at the ends of turbine strings or edges of clusters of wind turbines, as well as those that are more isolated from other wind turbines and those with larger rotor diameters on tubular towers.

Table 7-11. The directions and magnitudes of the associations between wind turbine-caused red-tailed hawk fatalities and level within independent variables

Variable	Magnitude of increase in mortality
Rotor diameter	10% at turbines with larger rotor diameters
Tower type	7% at tubular towers
Height of highest blade reach	9% at turbines with *highest* reaches of blades
Position in turbine string	11% at the string end, 1% next to gaps
Location in wind farm	9% at local cluster of turbines
Wind turbine congestion	8% at turbines more sparsely distributed
Whether in canyon	15% in canyon
Slope aspect	5% on north/northwest slopes, 4% on south/southeast slopes
Elevation	8% at mid elevation
Slope grade	11% on steeper slopes
Edge index	13% at sites with greater vertical edge
Rodent control	8% in areas with moderate level of control

The model correctly predicted wind turbines to be dangerous where 37% of the red-tailed hawk fatalities actually occurred (Table 7-12), which indicates poor predictive power. Only 16% of the wind turbines were predicted to be dangerous to red-tailed hawks. Model predictions are also depicted in Figure 7-26. The more dangerous wind turbines were distributed in three main clusters within the wind farm (Figure 7-27).

Table 7-12. The distribution of known red-tailed hawk fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the eleven variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	3267	613	16% of turbines
1	125	51	29% of turbines
2	5	12	71% of turbines
3	0	1	100% of turbines
Total fatalities	135	78	37% of fatalities

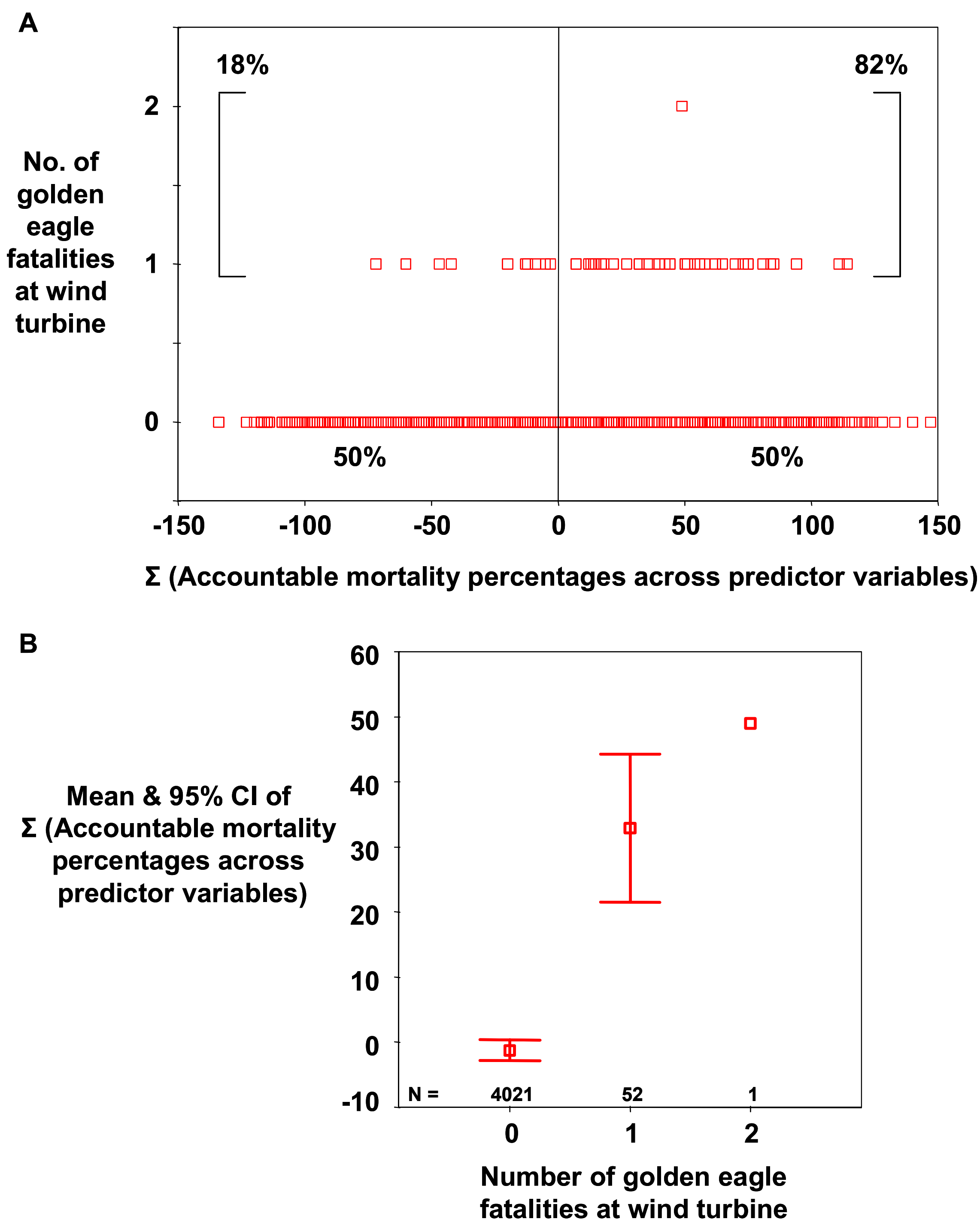


Figure 7-24. Most of the wind turbines documented to have killed golden eagles were correctly classified as more dangerous to golden eagles by the empirical model we developed (A), the mean values of which increased with the actual number of golden eagles killed by the wind turbine (B).

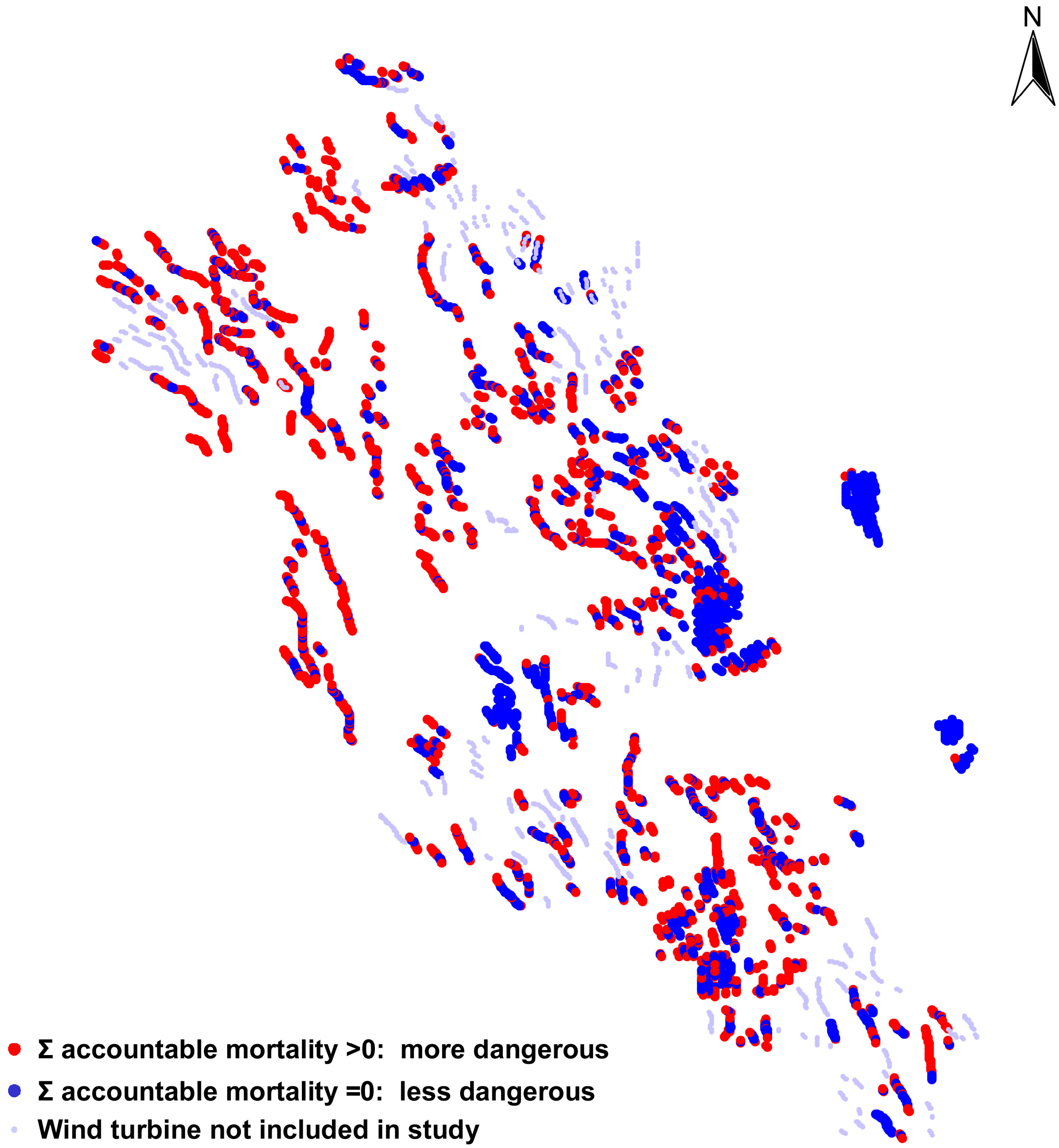


Figure 7-25. Wind turbines predicted by our model to be more dangerous to golden eagles are widely distributed across the APWRA.

American Kestrels

KVS-33 turbines were more dangerous to American kestrels than were other turbine types (because they had the larger rotor-swept area/second), and so were wind turbines on ridge lines and ridge crests at the highest and lowest elevations. Wind turbines on steeper slopes with more vertical edge around the tower laydown area also were dangerous (Table 7-13).

Table 7-13. The directions and magnitudes of the associations between wind turbine-caused American kestrel fatalities and levels within independent variables

Variable	Magnitude of increase in mortality
Rotor-swept area/second	10% at turbines with larger area swept/second
Physical relief	10% on ridgeline, 5% on ridge crest
Elevation	12% at highest elevation, 5% at lowest elevation
Slope grade	11% on steeper slopes
Edge index	13% at sites with greater vertical edge
Rodent control	8% in areas with moderate level of control

The model correctly predicted wind turbines to be dangerous where 75% of the American kestrel fatalities actually occurred (Table 7-14), which indicates solid predictive power. However, 66% of the wind turbines were predicted to be dangerous to American kestrels, meaning that continued carcass searches would continue to turn up American kestrel fatalities at wind turbines not previously documented to have killed this species. Model predictions are summarized in Figure 7-28. The more dangerous wind turbines were distributed widely across the wind farm (Figure 7-29).

Table 7-14. The distribution of known American kestrel fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the three variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	1353	2661	66% of turbines
1	15	42	74% of turbines
2	0	1	100% of turbines
Total fatalities	15	44	75% of fatalities

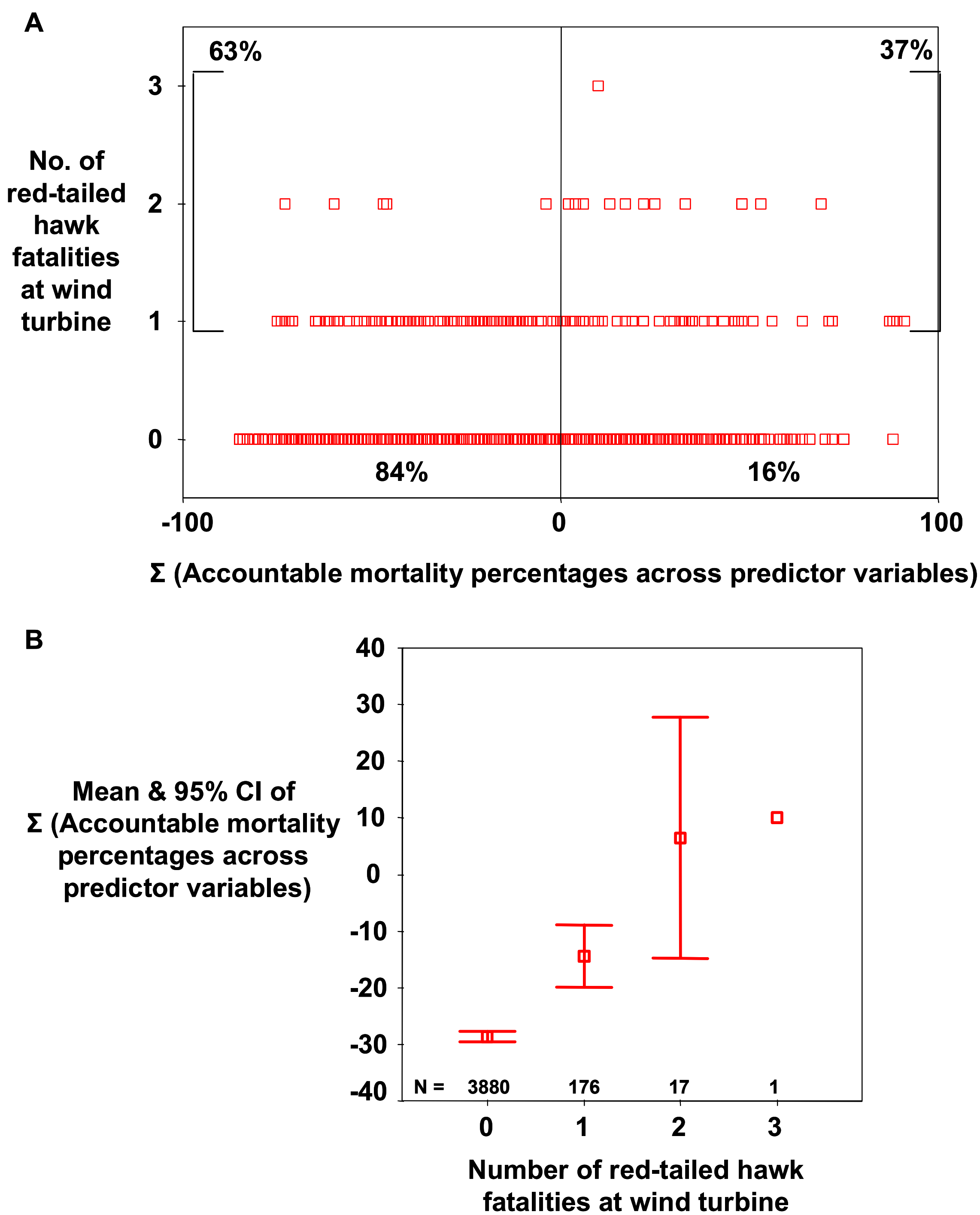


Figure 7-26. Most of the wind turbines documented to have killed red-tailed hawks were incorrectly classified as more dangerous to red-tailed hawks by the empirical model we developed (A), the mean values of which increased with the actual number of red-tailed hawks killed by the wind turbine (B).

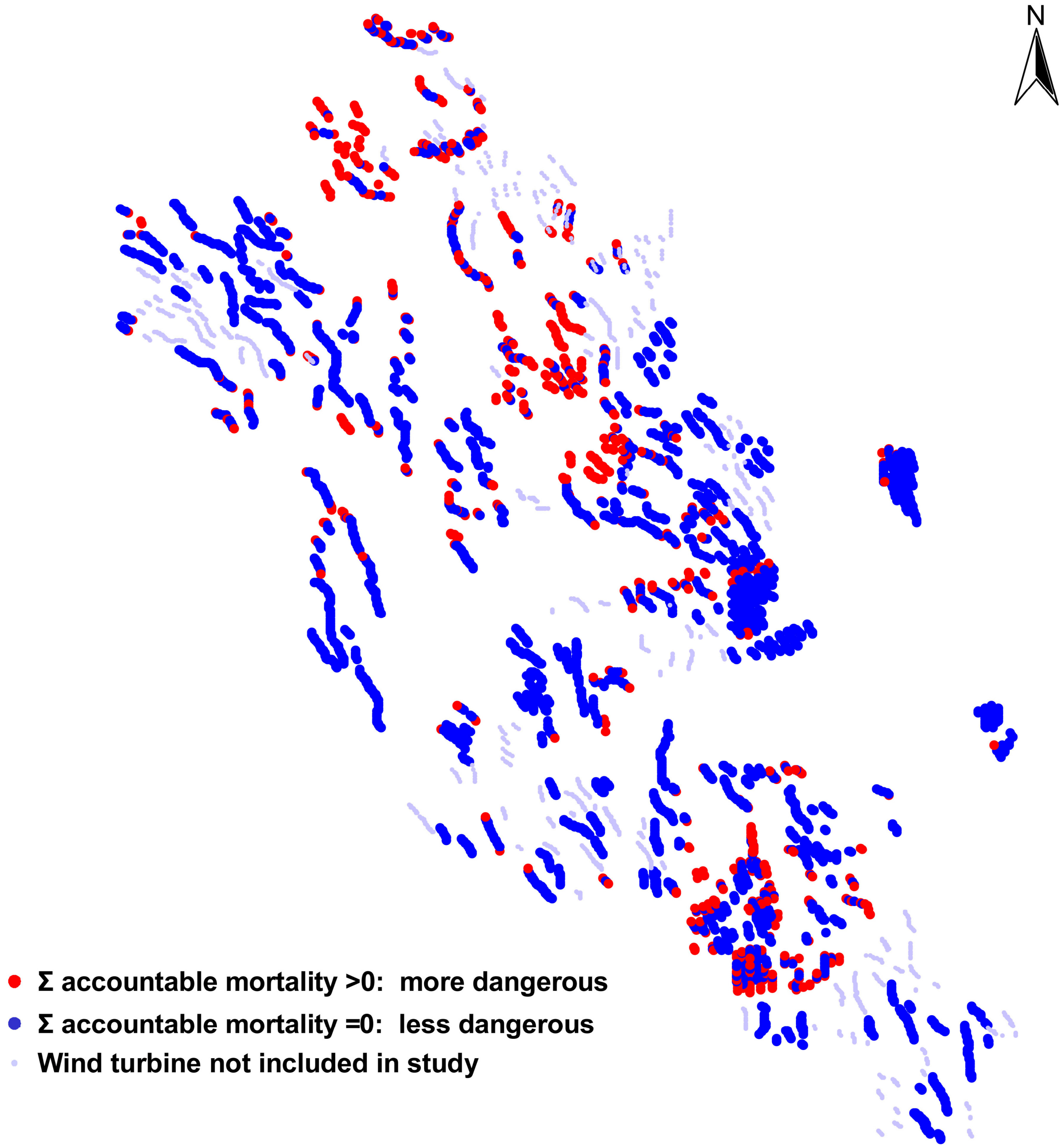
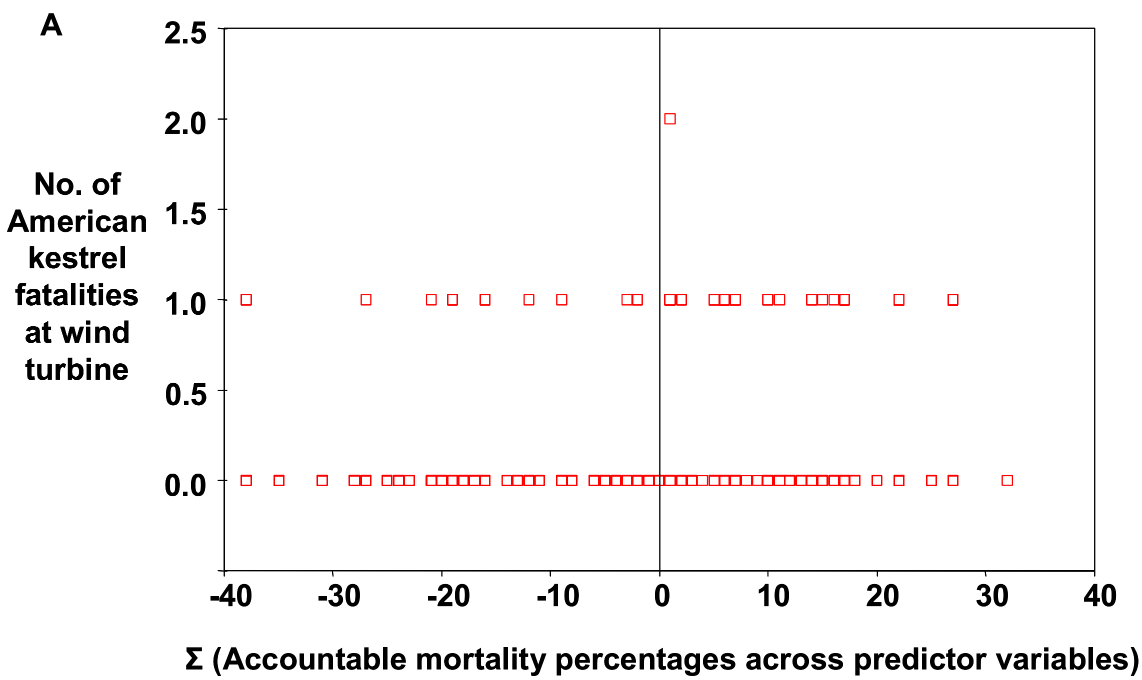


Figure 7-27. Wind turbines predicted by our model to be more dangerous to red-tailed hawks are distributed less widely across the APWRA than we actually documented.



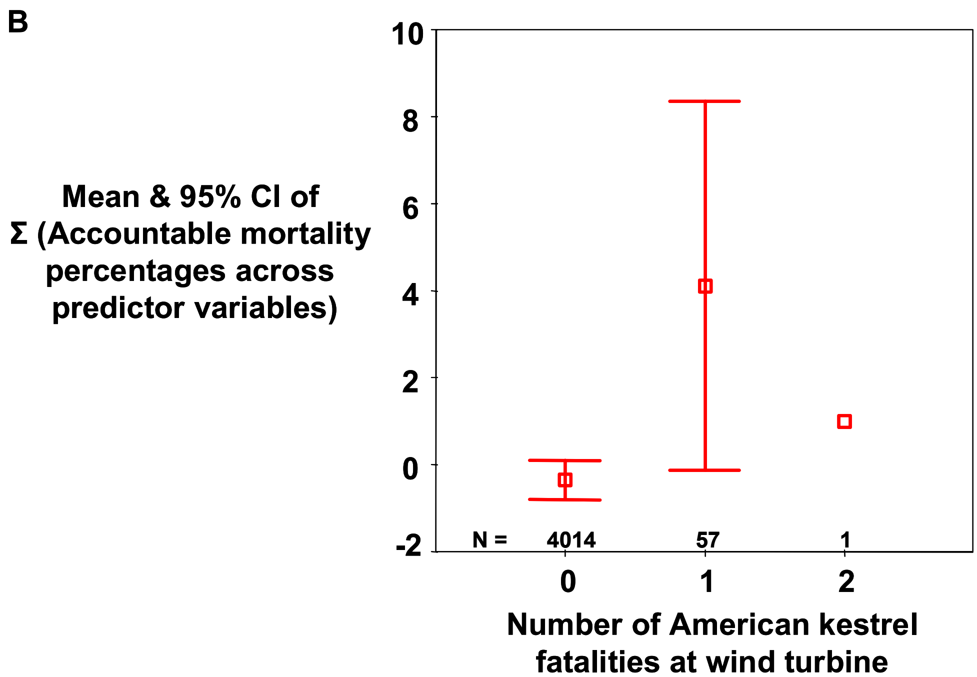


Figure 7-28. Most of the wind turbines documented to have killed American kestrels were incorrectly classified as more dangerous to American kestrels by the empirical model we developed (A), the mean values of which generally increased with the actual number of American kestrels killed by the wind turbine (B).

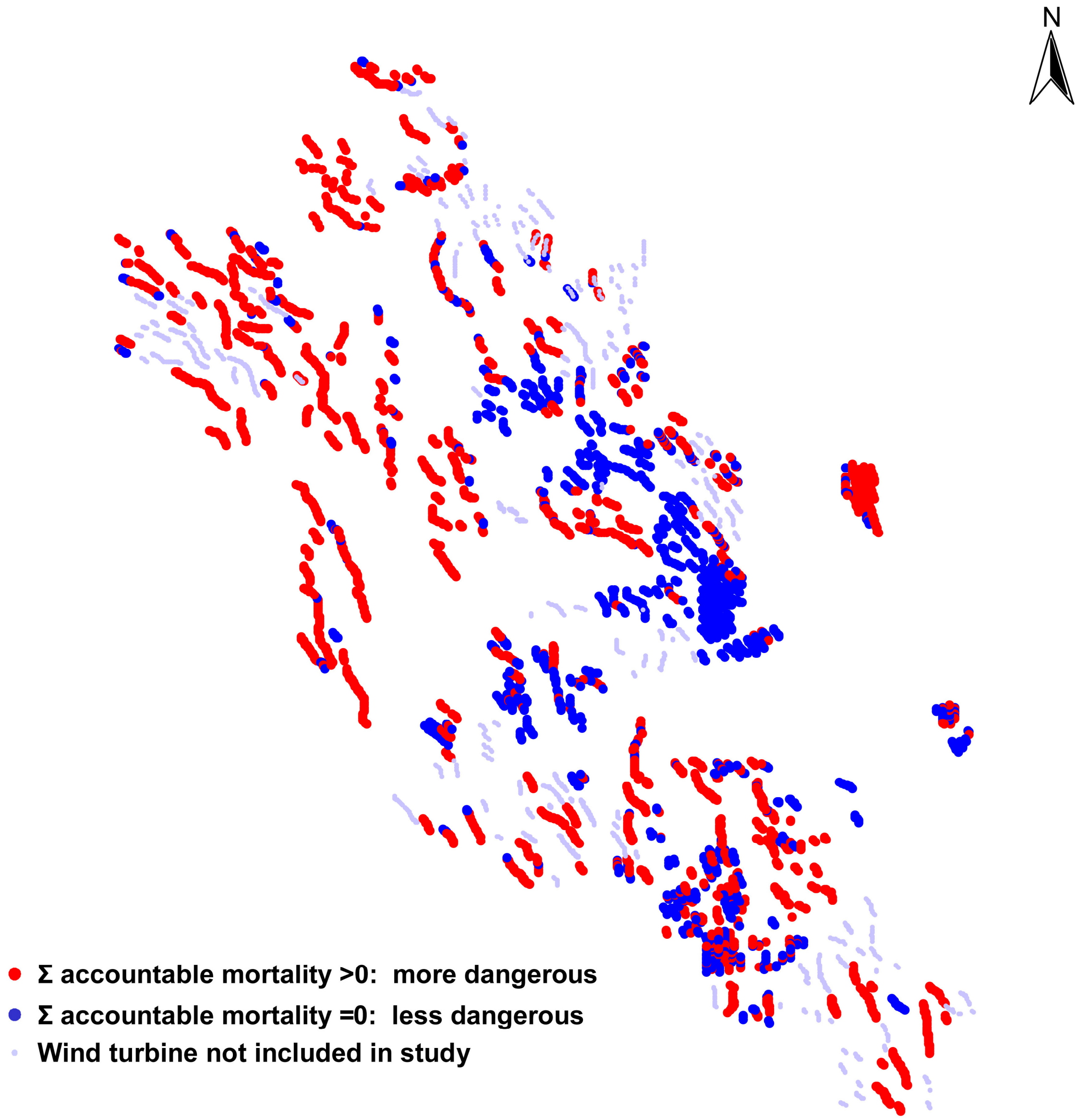


Figure 7-29. Wind turbines predicted by our model to be more dangerous to American kestrels are widely distributed across the APWRA.

Burrowing Owls

Wind turbines with longer intervals between rotor sweeps at the blade tip made burrowing owls most vulnerable, as did wind turbines located at the lowest elevations of the wind farm, turbines on tubular towers, at the ends of strings, and where rodent control was being implemented (Table 7-15). Also, wind turbines with more cattle pats nearby were more dangerous to burrowing owls, as were turbines outside of wind walls and those in canyons.

Table 7-15. The directions and magnitudes of the associations between wind turbine-caused burrowing owl fatalities and levels within independent variables

Variable	Magnitude of increase in mortality
Sec/rotor sweep at blade tip	30% at turbines with longer time per rotor sweep at blade tip
Tower type	19% at tubular towers, 10% at vertical axis towers
Tower height	16% at towers of medium height
Whether in wind wall	13% at turbines *not* in wind walls
Position in turbine string	24% at the string end
Whether in canyon	6% in canyon
Elevation	44% at lowest elevation
Rodent control	24% in areas with moderate level of control
Cattle pats at wind turbines	18% at turbines with more cattle pats

The model correctly predicted wind turbines to be dangerous where 71% of the burrowing owl fatalities actually occurred (Table 7-16), which indicates solid predictive power. Only 29% of the wind turbines were predicted to be dangerous to burrowing owls (Figure 7-30). The more dangerous wind turbines were distributed mostly along a low-elevation band across the wind farm, but also between the Patterson Pass and the Highway 205 corridor (Figure 7-31). This region of the APWRA possibly supports the greatest number of burrowing owls.

Table 7-16. The distribution of known burrowing owl fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the eight variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	2,838	1,172	29% of turbines
1	16	38	70% of turbines
2	2	4	67% of turbines
3	0	1	100% of turbines
Total fatalities	20	49	71% of fatalities

Key Raptors

The model correctly predicted wind turbines to be dangerous where 47% of the golden eagle, red-tailed hawk, American kestrel, and burrowing owl fatalities actually occurred (Table 7-17). Only 23% of the wind turbines were predicted to be dangerous to these species collectively. The more dangerous wind turbines were distributed mostly along a north-south oriented low-elevation band across the wind farm, but also at the ends of some turbine strings and at the edges of local clusters of wind turbines (Figure 7-32).

Table 7-17. The distribution of known golden eagle, red-tailed hawk, American kestrel, and burrowing owl fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	2,884	850	23% of turbines
1	179	112	38% of turbines
2	12	23	66% of turbines
3	2	7	78% of turbines
6	0	1	100% of turbines
Total fatalities	209	185	47% of fatalities

Barn Owls

The model correctly predicted wind turbines to be dangerous where 57% of the barn owl fatalities actually occurred (Table 7-18). Only 20% of the wind turbines were predicted to be dangerous to barn owls.

Table 7-18. The distribution of known barn owl fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the six variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	3,194	823	20% of turbines
1	18	25	58% of turbines
2	2	1	33% of turbines
Total fatalities	20	27	57% of fatalities

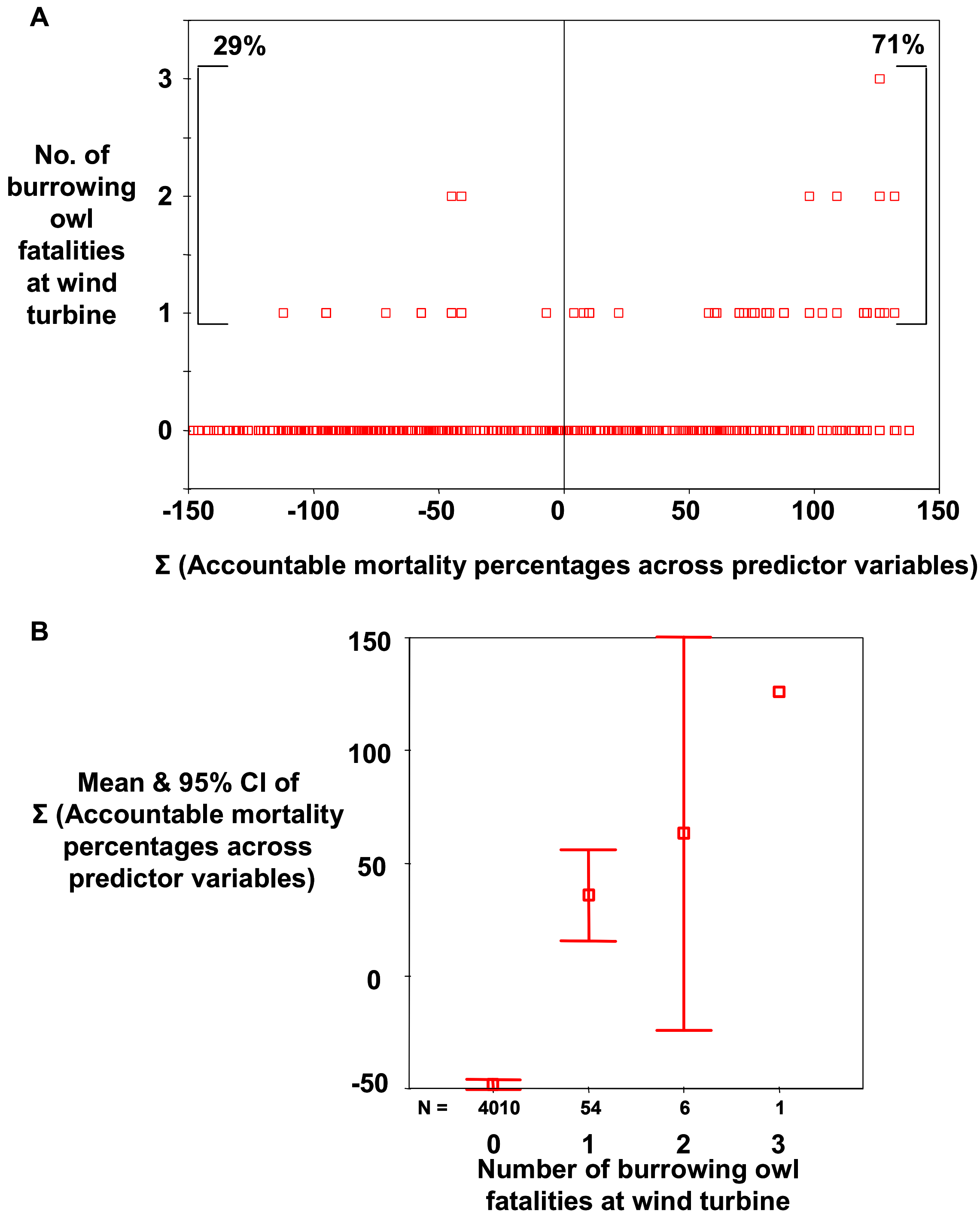


Figure 7-30. Most of the wind turbines documented to have killed burrowing owls were correctly classified as more dangerous to burrowing owls by the empirical model we developed (A), the mean values of which increased with the actual number of burrowing owls killed by the wind turbine (B).

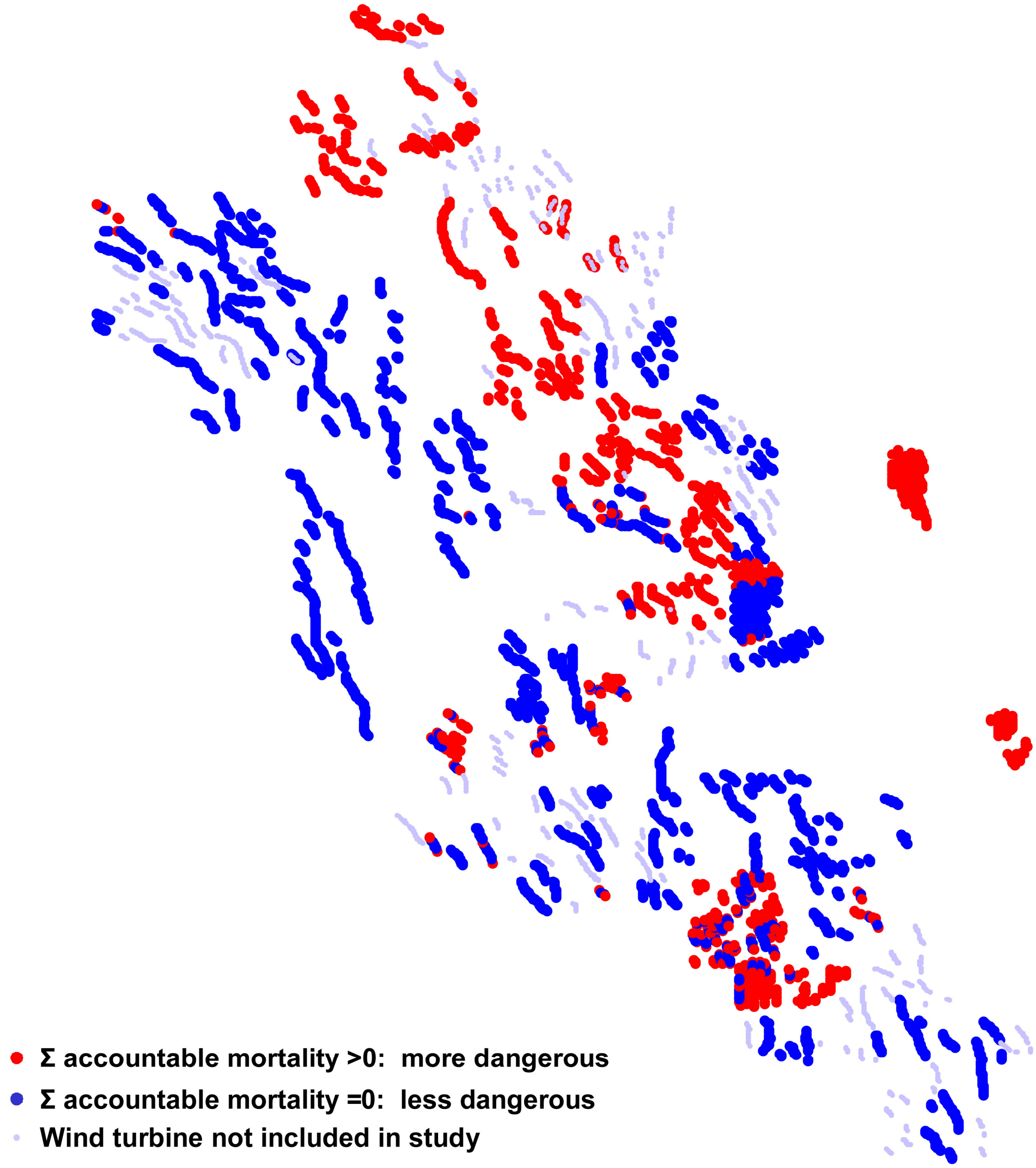


Figure 7-31. Wind turbines predicted by our model to be more dangerous to burrowing owls are distributed rather narrowly across the APWRA.

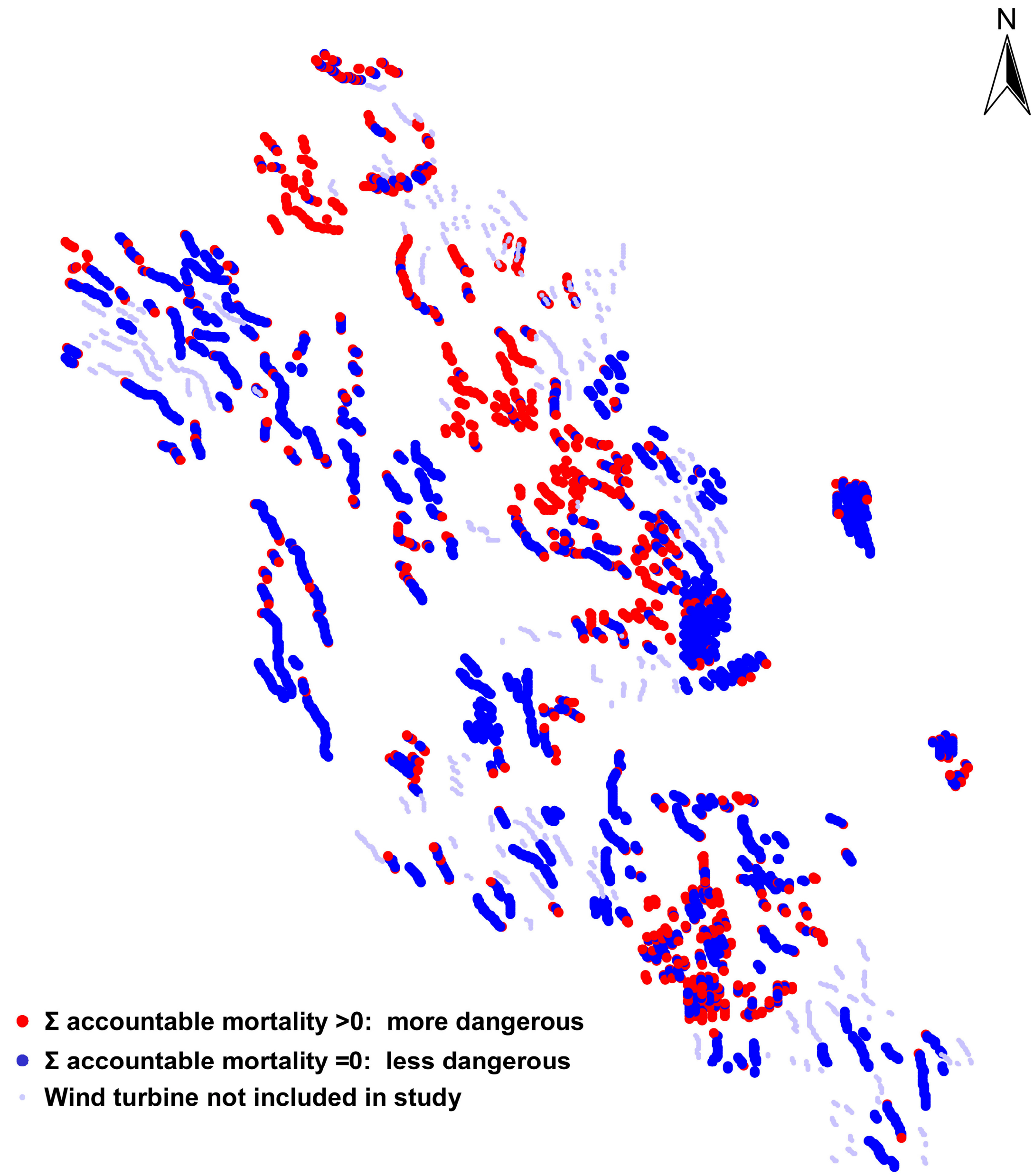


Figure 7-32. Wind turbines predicted by our model to be more dangerous in combination to golden eagles, red-tailed hawks, American kestrels, and burrowing owls are distributed relatively narrowly across the APWRA.

Great Horned Owls

The model, which was based on only a single independent variable, correctly predicted wind turbines to be dangerous where 56% of the great horned owl fatalities actually occurred (Table 7-19). Half of the wind turbines were predicted to be dangerous to great horned owls.

Table 7-19. The distribution of known great horned owl fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the one variable chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	2,028	2028	50% of turbines
1	8	8	50% of turbines
2	0	1	100% of turbines
Total fatalities	8	10	56% of fatalities

Mallards

The model correctly predicted wind turbines to be dangerous where 79% of the mallard fatalities actually occurred (Table 7-20). Only 25% of the wind turbines were predicted to be dangerous to mallards.

Table 7-20. The distribution of known mallard fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the eight variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	3,036	1,005	25% of turbines
1	7	20	74% of turbines
2	0	3	100% of turbines
Total fatalities	7	26	79% of fatalities

California Horned Lark

The model correctly predicted wind turbines to be dangerous where 48% of the California horned lark fatalities actually occurred (Table 7-21). Only 6% of the wind turbines were predicted to be dangerous to California horned larks.

Table 7-21. The distribution of known California horned lark fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the four variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	3,787	263	6% of turbines
1	12	11	48% of turbines
Total fatalities	12	11	48% of fatalities

Western Meadowlarks

The model correctly predicted wind turbines to be dangerous where 56% of the western meadowlark fatalities actually occurred (Table 7-22). Only 23% of the wind turbines were predicted to be dangerous to western meadowlarks.

Table 7-22. The distribution of known western meadowlark fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the eight variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	3,050	927	23% of turbines
1	42	48	53% of turbines
2	0	3	100% of turbines
Total fatalities	42	54	56% of fatalities

Mourning Doves

The model correctly predicted wind turbines to be dangerous where 82% of the mourning dove fatalities actually occurred (Table 7-23). Only 29% of the wind turbines were predicted to be dangerous to mourning dove.

Table 7-23. The distribution of known mourning dove fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the ten variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	2,867	1,164	29% of turbines
1	6	26	81% of turbines
2	0	1	100% of turbines
Total fatalities	6	28	82% of fatalities

Rock Doves

The model correctly predicted wind turbines to be dangerous where 53% of the rock dove fatalities actually occurred (Table 7-24). Only 20% of the wind turbines were predicted to be dangerous to rock dove.

Table 7-24. The distribution of known rock dove fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the ten variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	3,112	788	20% of turbines
1	78	57	42% of turbines
2	5	11	69% of turbines
3	1	4	80% of turbines
4	0	3	100% of turbines
Total fatalities	91	103	53% of fatalities

European Starlings

The model correctly predicted wind turbines to be dangerous where 74% of the European starling fatalities actually occurred (Table 7-25). Two-thirds of the wind turbines were predicted to be dangerous to European starling.

Table 7-25. The distribution of known European starling fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the five variables chosen for inclusion in the model.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	1,337	2,673	67% of turbines
1	15	43	74% of turbines
2	1	3	75% of turbines
Total fatalities	17	49	74% of fatalities

All Birds

The model correctly predicted wind turbines to be dangerous where 39% of the bird fatalities actually occurred (Table 7-26). Only 20% of the wind turbines were predicted to be more dangerous to birds.

Table 7-26. The distribution of known bird fatalities between wind turbines classified according to their relative likelihoods of causing the fatalities. These likelihoods are represented by the sum of the percent accountable fatalities from the variables chosen for inclusion in the combined model for all birds.

No. of fatalities at wind turbine	No. of wind turbines less likely to cause fatalities (scored ≤ 0)	No. of wind turbines more likely to cause fatalities (scored > 0)	Percent correctly classified as > 0
0	2,557	711	20% of turbines
1	395	176	31% of turbines
2	96	62	39% of turbines
3	15	29	66% of turbines
4	8	10	56% of turbines
5	2	2	50% of turbines
6	3	3	50% of turbines
7	1	0	0% of turbines
Total fatalities	699	455	39% of fatalities

7.4 DISCUSSION

7.4.1 Model Predictions

Our model predictions are somewhat simplistic, because we were unable to account for interaction effects between independent variables. The number of fatalities in our sample and the differential sampling effort precluded a reliable analysis of interaction effects or the use of multivariate statistics. Even had we attempted such analyses, we found that our sampling was incomplete for characterizing the distribution of fatalities of each and all species among wind turbines. Continued carcass searches would undoubtedly have expanded the number and variety of wind turbines that caused fatalities, although it is also possible that the representation of the associations identified in this study would have remained largely unchanged.

We can explain only a fraction of the variation in bird fatalities caused by wind turbines in the APWRA. All birds lumped together (and assuming additive effects from the factors entered into the model), the elimination of 20% of the wind turbines might reduce mortality on the order of 40%. We can do better for certain species—including burrowing owl, mallard, California horned lark, and mourning dove—for which elimination of a portion of the wind turbines in the APWRA would likely reduce most of the mortality. Nevertheless, for other species, such as golden eagle, red-tailed hawk, and American kestrel, if shutting down turbines was the only management treatment considered (but we recommend multiple treatments, see Chapter 9), it would be necessary to remove most or all of the currently operating wind turbines for mortality to substantially lessen.

Future plans to repower much of the APWRA (i.e., replace older turbines with newer ones at a ratio of 7:1) will require new siting criteria to be applied (Alameda County 1998). It may be that such a program is needed sooner than later, so that the most dangerous sites for turbine installations can be decommissioned and the new turbines can be installed in areas less likely to be dangerous, based on the results presented here. Regardless, extensive monitoring would be needed after turbine installation, to determine if the program, in fact, resulted in reduced bird mortality.

It is also possible that the percentage of accountable mortality of certain factors is misleading, and that mitigation measures taken to reduce the impact of particular factors might be more effective than suggested by the model predictions. For example, it is conceivable that translocating the existing wind turbines out of canyons and off of steep slopes, then clustering them into wind walls (or other aggregations) would reduce mortality to a much greater extent than suggested by the percentages resulting from our statistical tests. In fact, it is our opinion that a combination of such measures would indeed reduce mortality to levels that are lower than suggested by the models.

For certain species, our analysis suggests that we either did not characterize the key factors that are most important to predicting wind turbine-caused fatalities, or that there is a relatively equal threat posed by each and every wind turbine in the APWRA. For example, red-tailed hawk mortality appeared almost random in occurrence; no single variable that we measured could explain more than 15% of the variation. Red-tailed hawks appear to be highly susceptible to collisions with wind turbines.

However, red-tailed hawk mortality might be influenced more significantly by some variables we measured in a limited capacity but that we could not use in the predictive models. For example, early tests for association between red-tailed hawk mortality and the degree of pocket gopher clustering around wind turbines appeared promising, but we were able to measure this clustering only around 70 turbine strings, not around the 472 strings that were used for developing the model. Complicating matters further was the rodent control program, which was undoubtedly changing the numerical and spatial distributions of small mammals in the APWRA while we were attempting to explain the variation in raptor mortality. We also did not include in the predictive model the steps taken by the wind industry to reduce mortality, namely, rodent control, painting turbine blades, installing perch guards, and installing tubular towers in place of lattice towers during a later addition to the APWRA. Notably, each of these steps associated with greater levels of mortality, not lesser.

7.4.2 Wind Turbine/Tower Attributes

Bonus, Micon, and KVS-33 turbines were the most dangerous wind turbines to birds within our study area at the APWRA. Generally speaking, the taller towers supporting wind turbines with a larger rotor diameter and slower to intermediate blade tip speeds were the most dangerous wind turbines to birds. Also, tubular towers associated with more avian fatalities than did lattice or vertical axis towers. The test for association between fatalities and tower type indicated that perching on towers might be less of an issue than previously believed. Also, taller towers, or at least turbines with higher blade reaches, are more dangerous to a larger suite of bird species than previously claimed. This set of results supports the need to monitor any future repowering program in order to observe how wind turbines with larger diameter blades mounted on taller towers affect bird mortality.

Also, our results contradict the claims made in the repowering Draft Environmental Impact Report (DEIR) (Alameda County 1998) that slower-moving blades on taller, tubular towers will be safer for birds in the APWRA. We found that the vulnerability of birds in the APWRA is increased by taller towers, the slower-moving blades, and the longer time spans with which birds have to fly through the rotor plane. Of course, our results are interpreted only within the context of the APWRA and the range of conditions represented by our sample of wind turbines and fatalities.

The strong association between burrowing owl mortality and Flowind (vertical axis) turbines was most likely the result of an artifact of the higher densities of burrowing owl occurring where these wind turbines operated. Similarly, it was likely an artifact of flyways that mallards were disproportionately killed by Windmatic turbines. Despite these likely artifacts of location, burrowing owls and mallards were also killed more often than expected by chance by Bonus turbines on tubular towers.

Rotors facing the wind associated with a significantly greater mortality of birds, either because this rotor orientation is also associated with other wind turbine attributes that cause more fatalities or because there is a mechanism specific to the rotor orientation that causes more fatalities to occur. We were unable to determine which of these scenarios is more likely.

Mitigation measures implemented by the wind industry in an attempt to reduce fatalities, including painting turbine blades, installing perch deterrents, and shifting to tubular towers, associated with increased mortality. This increased mortality might be caused by the mitigation measures in some cases, such as birds flying up into moving turbine blades while averting landings on lattice towers just discovered to be blocked by chicken wire, or American kestrels for some reason being attracted to the green and red tips moving at the outer edge of the rotor plane. However, it is also possible that these particular wind turbines were located where vulnerability was greater for other reasons.

In summary, wind turbines were generally more dangerous when they swept larger portions of the sky, moved slower, reached higher into the sky, and were supported on tubular towers. But there were species-specific exceptions, such as wind turbines with lower reaches of the blade sweep killing disproportionately more golden eagles.

7.4.3 Physiography

Generally wind turbines at the lowest elevations and on canyon slopes were more dangerous to birds in our study area, especially on steeper slopes. The effect of wind turbines installed in canyons was one of the most consistently significant factors tested in our study. Ridge crests and peaks appeared to kill no more birds than one would expect of a random distribution of wind turbine strikes, but turbines on ridgelines and slopes did kill disproportionately more of certain key species.

Another factor that related strongly to bird fatalities was the presence of rock piles created by the wind industry when it cleared rocks from wind turbine laydown areas. This factor was only significant, however, for the original set of 1,526 wind turbines sampled in our study. Wind turbines with these rock piles nearby killed more raptors, and disproportionately more western meadowlarks and horned larks.

Rock piles likely attract raptors because they harbor ground squirrels and cottontails, the latter of which use these rock piles as principal den sites. Horned larks and western meadowlarks likely approach and use the rock piles for their elevated displays and calls, which are typical behaviors of these species in grasslands. Rock dove fatalities also associated with the presence of rock piles, but this relationship is likely spurious, given the behavior of rock doves in the APWRA.

The addition of 2,548 wind turbines in 2002/2003 to our sample changed the association test results involving rock piles. We noted during our data collection that the areas where we added wind turbines to our study included many natural rock piles and rock outcrops, which likely provided many opportunities for raptor prey species to find refuge and for bird species to perch and display upon.

The presence of rock piles was only significant for the original set of 1,526 wind turbines we sampled. Wind turbines with these rock piles nearby killed more raptors, and disproportionately more western meadowlarks and horned larks. The addition of 2,548 wind turbines in 2002-03 to our sample changed the association test results involving rock piles. We noted during field studies that the areas where we added wind turbines included many natural rock piles and rocky outcrops, which likely provided many opportunities for raptor prey species to find refuge and for bird species to perch upon.

7.4.4 Wind Farm Configuration

The most dangerous wind turbines in our study were located at the ends of rows, next to gaps in rows, and at the edge of a local cluster of wind turbines within the wind farm. Overall, wind walls are safer for birds, as are the wind turbines situated in the interiors of clusters of wind turbines. Also, wind turbines that are more isolated from other wind turbines kill disproportionately more birds. These results suggest that birds recognize wind turbines and towers as obstacles and attempt to avoid them while flying, which is consistent with our behavioral observations, but fatalities occur where birds are surprised by wind turbines situated at the edges of local wind turbine clusters or alone.

An excellent example of a threatening wind turbine is the Micon 65-kW turbine sited alone at the northwest corner of the wind field we refer to as ”Mountain House” (String 179; ID = 1307 in our database). It is situated on a steep, northwest-facing slope. We estimated the mortality of this one wind turbine to be between 4 and 11 birds per year, adjusted for search detection biases and scavenger removal rates (see Chapter 3).

7.4.5 Rodent Control and Burrowing Animals

Rodent control did not associate with lesser bird mortality, except for golden eagles. Chapter 6 addressed the effects of the rodent control program in detail. Also, we provide measures of association between mortality and the abundance and distribution of small mammal burrow systems in the Appendices, but we did not build any predictive models based on these associations. Too few of the wind turbines were included in the burrow mapping efforts to contribute substantially to the development of predictive models for application across the entire APWRA.