APPENDIX A

MEASURING IMPACTS TO BIRDS CAUSED BY WIND TURBINES

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1.0 INTRODUCTION

Differential composition of wind turbines at wind energy generating facilities (e.g., the number of turbines installed, differences in height, energy output, rotor diameter, turbine manufacturer, and tower type) is a source of confusion when comparing bird mortality within and among wind energy generating facilities. The standard measurement of mortality currently being used is the number of fatalities per wind turbine per year (Anderson et al. 1999). This metric has little meaning to those lacking experience with bird mortality at wind energy generating facilities. More importantly, it has lost much of its usefulness for comparing the effects of wind energy generating facilities as more facilities have been installed because the newer wind turbines are much larger than the older ones and each sweeps a much larger area of the sky.

We propose that bird mortality at wind energy generating facilities and other energy generating facilities should be reported in the future as the number of fatalities/megawatt (MW)/year, where MW is the amount of electrical energy generated by the facility that was sampled for bird fatalities. Where the actual energy generated cannot be determined, MW would be based on the rated output of the sampled wind turbines. This measure of mortality would be applicable to other types of energy generating facilities, thus facilitating comparisons between various sources of energy generation (e.g., see Erickson et al. 2001). Replacing the number of wind turbines with MW in the mortality measure will facilitate consumer-oriented measurements, such as the number of fatalities/household/year. Also, it would allow the number and composition of wind turbines to be used as predictor variables that can then be related to bird mortality.

2.0 METHODS

The field methods and most data management and analysis methods we used are described in Chapter 3, *Bird Mortality in the Altamont Pass Wind Resource Area*.

We divided the number of recent wind turbine-caused fatalities (i.e., < 90 days since death) in the APWRA by: (1) the number of wind turbines composing any particular turbine string, and (2) the rated generation output in megawatts of the turbines in the string. Each of these ratios was then divided by the span of years during which carcass searches were performed. Ninety days was added to all year spans in order to include the 90 days preceding the initiation of the searches on each string, during which fresh carcasses could have accumulated. The metrics generated were the number of fatalities/turbine/year and the number of fatalities/MW/year. These two metrics were then compared to each other using scatterplots and linear regression analysis to reveal how they related to each other.

3.0 RESULTS

Bird mortality caused by wind turbines can be measured on a per-megawatt or per-turbine basis, with nearly the same precision. However, the relationship between the number of fatalities per MW and the number of fatalities per wind turbine is a function of the size of the generating capacity of the wind turbine(s) (Figures A1 and A2). One measurement can be derived directly from the other if the analyst knows the composition of the models and generating capacity of the wind turbines making up the sample.

The number of fatalities per wind turbine can be misleading when the sample of wind turbines includes turbines built by different manufacturers that generate different amounts of energy, or have different rotor-swept areas (RSA) due to differences in blade length. Also, mortality expressed in terms of MW relates more precisely to mortality in terms of the windswept area of the turbine string (sum of the RSAs among turbines in the string) (Figure A3A) than mortality expressed in terms of the number of wind turbines (Figure A3B).

Assume a comparison between two wind energy generating facilities of equal power generation. One facility is composed of ten 400-kW wind turbines. The other facility is composed of 100 40-kW turbines. In the wind farm composed of the larger turbines, 10 dead birds found in one year will result in a calculated mortality of one death/wind turbine/year. In the wind farm composed of smaller turbines, 10 dead birds result in a calculated mortality of 0.1 deaths/wind turbine/year. In this comparison the mortality will appear greater at the wind farm with larger turbines, based on the number of wind turbines in the facility. However, mortality would appear equal between the two sites if it were measured as the number of deaths/MW/year; that is, mortality would be calculated as 2.5 deaths/MW/year at either site.

Figure A1 illustrates that the metric based on deaths/wind turbine/year is more sensitive to changes in number of fatalities as the component wind turbines' rated power generation increases. This is true, if one assumes that fewer but larger wind turbines are installed in a given wind farm. Conversely, deaths/MW/year is more sensitive to changes in the number of fatalities as the component wind turbines' rated power generation lessens, assuming that more of these smaller wind turbines would be deployed in a wind farm to generate an equivalent total output. In the APWRA, it is likely that smaller turbines will be replaced with fewer, larger turbines. This process of replacing older equipment with newer models is termed "repowering."

Based on our data from the APWRA put to multiple regression analysis, the number of fatalities/wind turbine/year accounted for a larger proportion of the regression sum of squares of bird mortality than did the number of fatalities/MW/year (Table A1), which suggests that the former measure of mortality is more efficient than the latter. In one of these regressions, we entered MW as a predictor variable first and the number of wind turbines in the sample second. In the other, we entered the number of wind turbines first and the MW second. Entering the number of MW first into the regression model left 33%

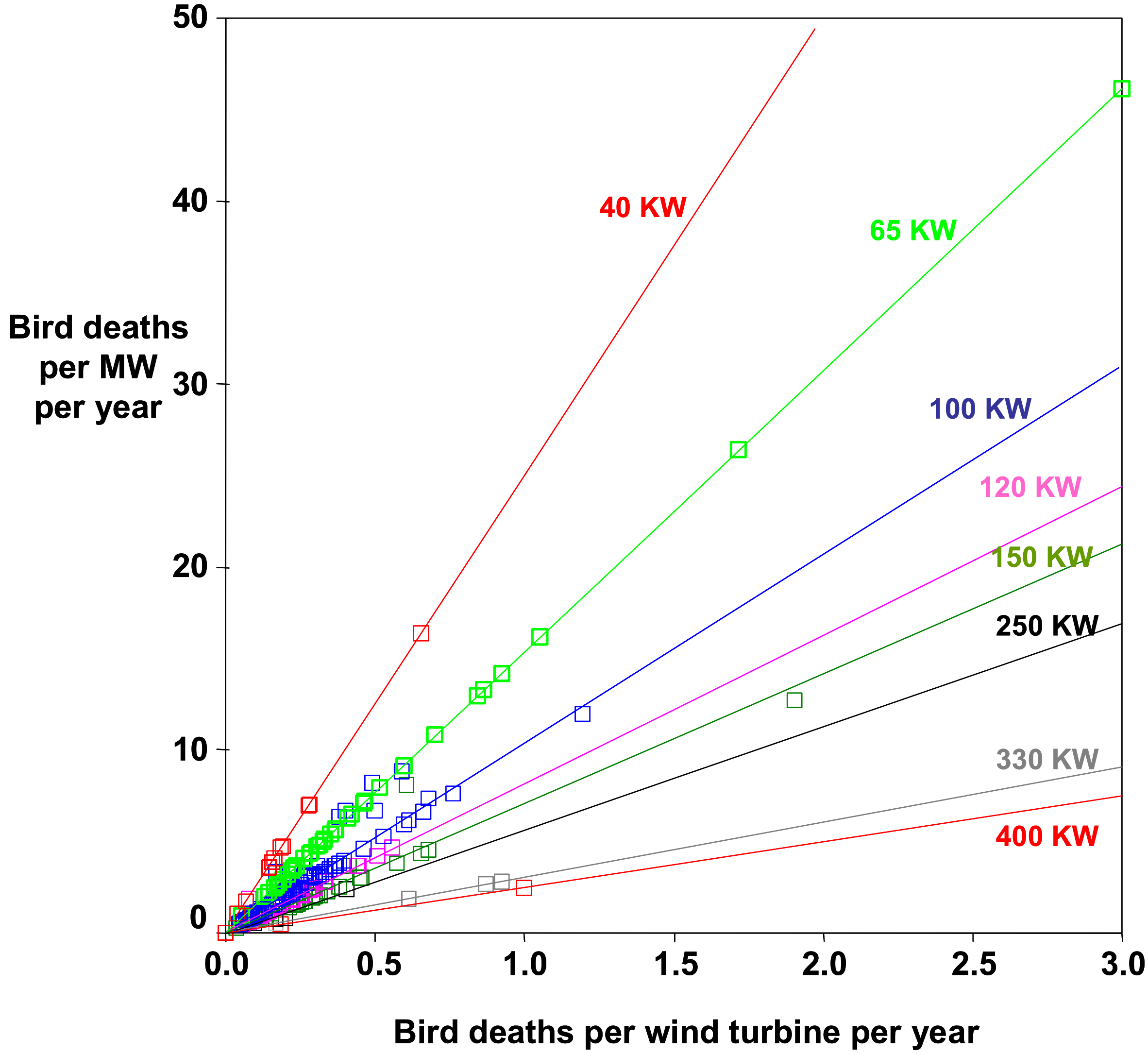

Figure A1. Mortality measured as per-MW increases linearly with mortality measured as per-wind turbine, but the linear relationship is unique to the size of the wind turbine. This uniqueness is expressed as the slope of the regression.

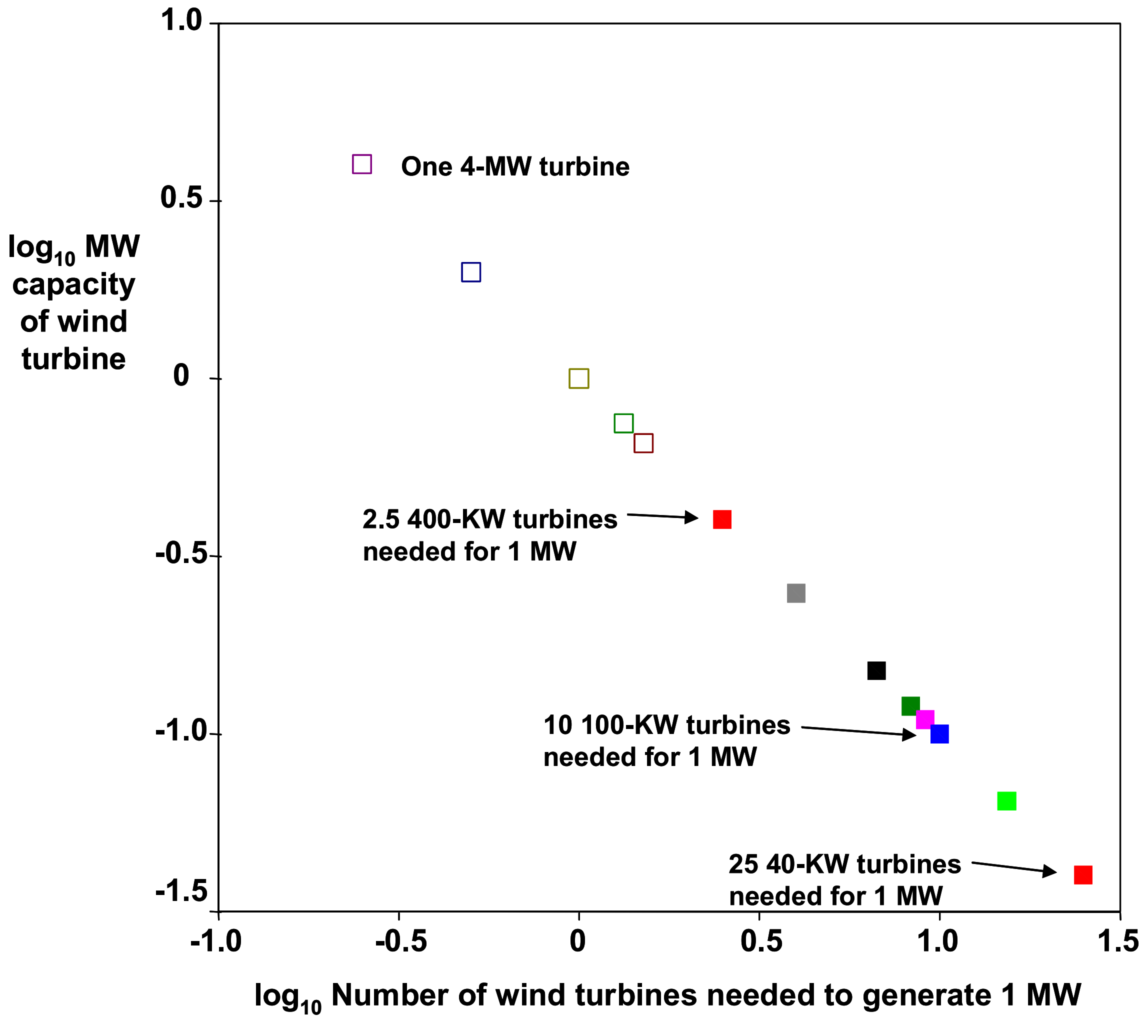

Figure A2. The slope of mortality measured as per-MW regressed on mortality measured as per-turbine is the generating capacity of the wind turbine, and relates as an inverse power function to the number of wind turbines needed to generate 1 MW of electrical energy.

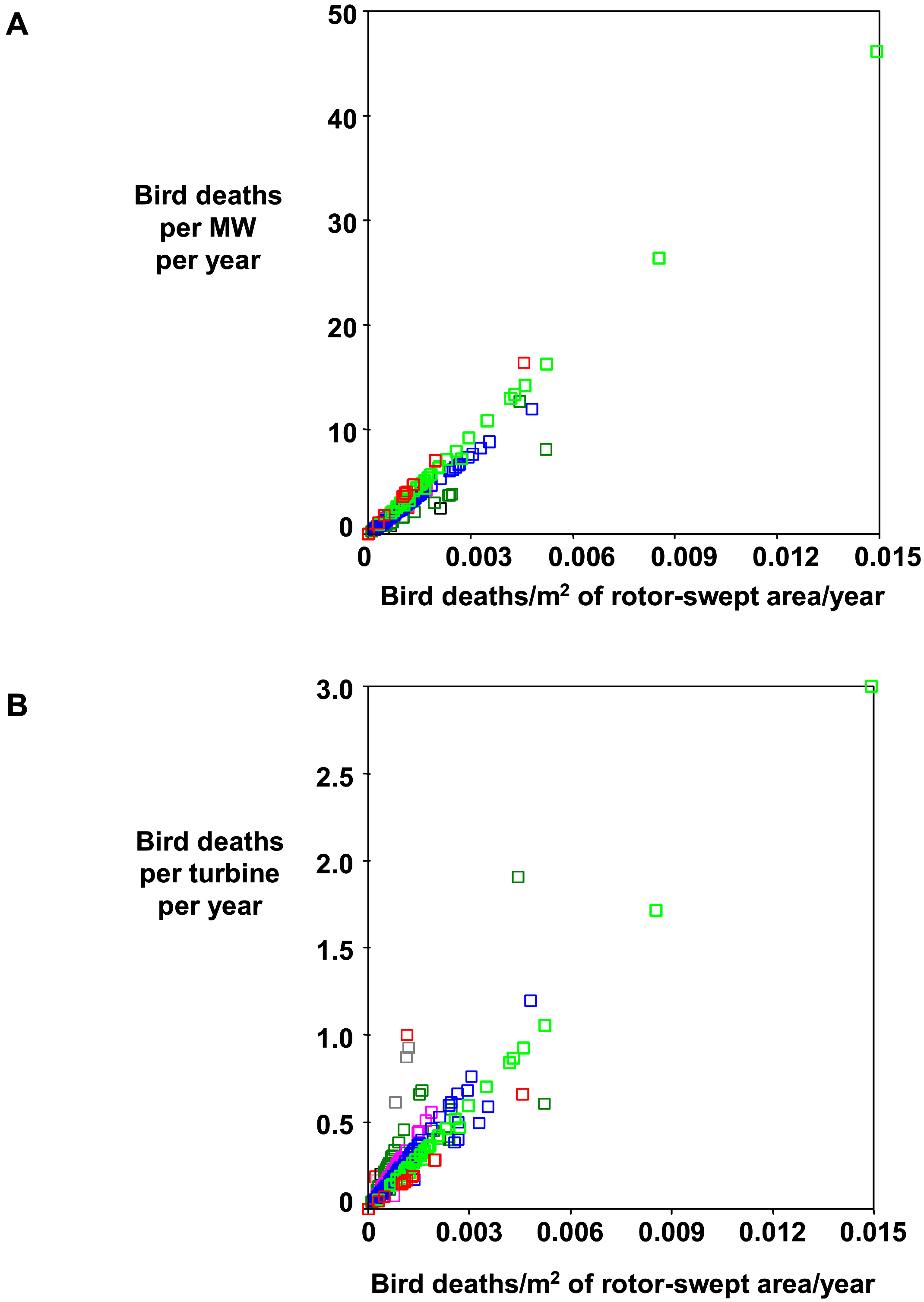

Figure A3. Mortality in terms of MW related to mortality in terms of rotor-swept area (A) more precisely than mortality in terms of number of wind turbines (B).

Table A1. Multiple regression models of bird fatalities/year, in which MW entered first left 33% of the 653.207 sum of squares to be explained by number of wind turbines in the sample, and entered second added only 0.63% of those 653.207 sum of squares.

Source	Regression sum of squares	df	Mean square	F	P
Model 1					
MW	437.840	1	437.840	133.163	~0
No. turbines	653.207	2	326.603	115.409	~0
Model 2					
No. turbines	649.110	1	649.111	229.150	~0
MW	653.207	2	326.603	115.409	~0
Either model					
Error	1310.271	463	2.830		
Total	1963.478	465			

of the variation in bird fatalities per year to be explained by the number of wind turbines, whereas entering the number of wind turbines into the model first left only 0.6% of the variation in bird fatalities per year to be explained by MW.

However, the number of fatalities/MW/year is nearly equally efficient at measuring raptor mortality as the number of fatalities/wind turbine/year (Table A2). Entering MW into the model first left the number of wind turbines to explain 8.2% of the variation in number of raptor fatalities per year, but entering the number of wind turbines first left 5.8% of the variation to be explained by MW. The difference between these percentages is inconsequential, and so the metrics are equally efficient.

An important point to consider when comparing any standardized measure of mortality between sites is whether the variation in mortality was partly a function of the duration of monitoring used to derive the mortality estimate. Variation in mortality estimates will decline as the monitoring duration increases, and this decline will be most rapid for estimates derived from monitoring that lasts less than a year (Figure A4A). The reason for this pattern is largely mathematical. Considering MW (or number of turbines) as a constant in the metric, the numerator (fatalities) and the second denominator (years of monitoring) are variable, but the variability of the number of fatalities is likely to be less than that of the number of years. When a fatality is found, mortality will relate to number of years of fatality searches as an inverse power function until the next fatality is found, and then this relationship will apply to the new mortality estimate until the next fatality is found (Figure A4B). Given enough time, wind turbines where no fatalities were found initially will kill birds eventually, and non-zero mortality estimates will be added to a growing pool of non-zero estimates (Figures A4B and A5).

Table A2. Multiple regression models of raptor fatalities/year, in which MW entered first left 8.2% of the 229.017 sum of squares to be explained by number of wind turbines in the sample, and entered second added 5.8% of those 229.017 sum of squares.

Source	Regression sum of squares	DFdf	Mean square	F	P
Model 1					
MW	210.338	1	210.338	123.738	~0
No. turbines	229.017	2	114.509	68.849	~0
Model 2					
No. turbines	215.787	1	215.787	127.826	~0
MW	229.017	2	114.509	68.849	~0
Either model					
Error	770.059	463	1.663		
Total	999.076	465			

Our data indicate that an asymptote in the percentage of wind turbine strings that caused fatalities is reached after three years of monitoring (Figure A6). We found that the number of fatalities increases with increasing proportion of the total time the turbines in the sample were searched (Figure A7A). This latter pattern is consistent with the pattern depicted in Figure A6. It serves to suggest that most of the wind turbines were not sampled long enough to robustly estimate mortality. The matter of robustness relates here not to whether the estimates are too high or too low, but rather to their reliability and precision. It also indicates that long term monitoring improves the precision of mortality estimates. Figure A7B, which is consistent with Figures A4 and A5, shows the transformation of estimates of both high mortality values and zero values into a narrower value range as more time was devoted to search effort. Looking to the bottom right of the scatterplot, one can see that given sufficient search time all turbines generate non-zero mortality values, i.e., all wind turbines eventually kill birds in the APWRA.

Mortality estimates based on less than one year of searching are more variable and should be cautiously interpreted when comparing mortality between sites. However, we found that the mean mortality did not change through time, indicating that the larger estimates of mortality in shorter-duration monitoring periods are offset by the larger number of zero values (Figure A8). The real significance of the effect of monitoring period is in the error term, which is inflated by short-duration monitoring periods.

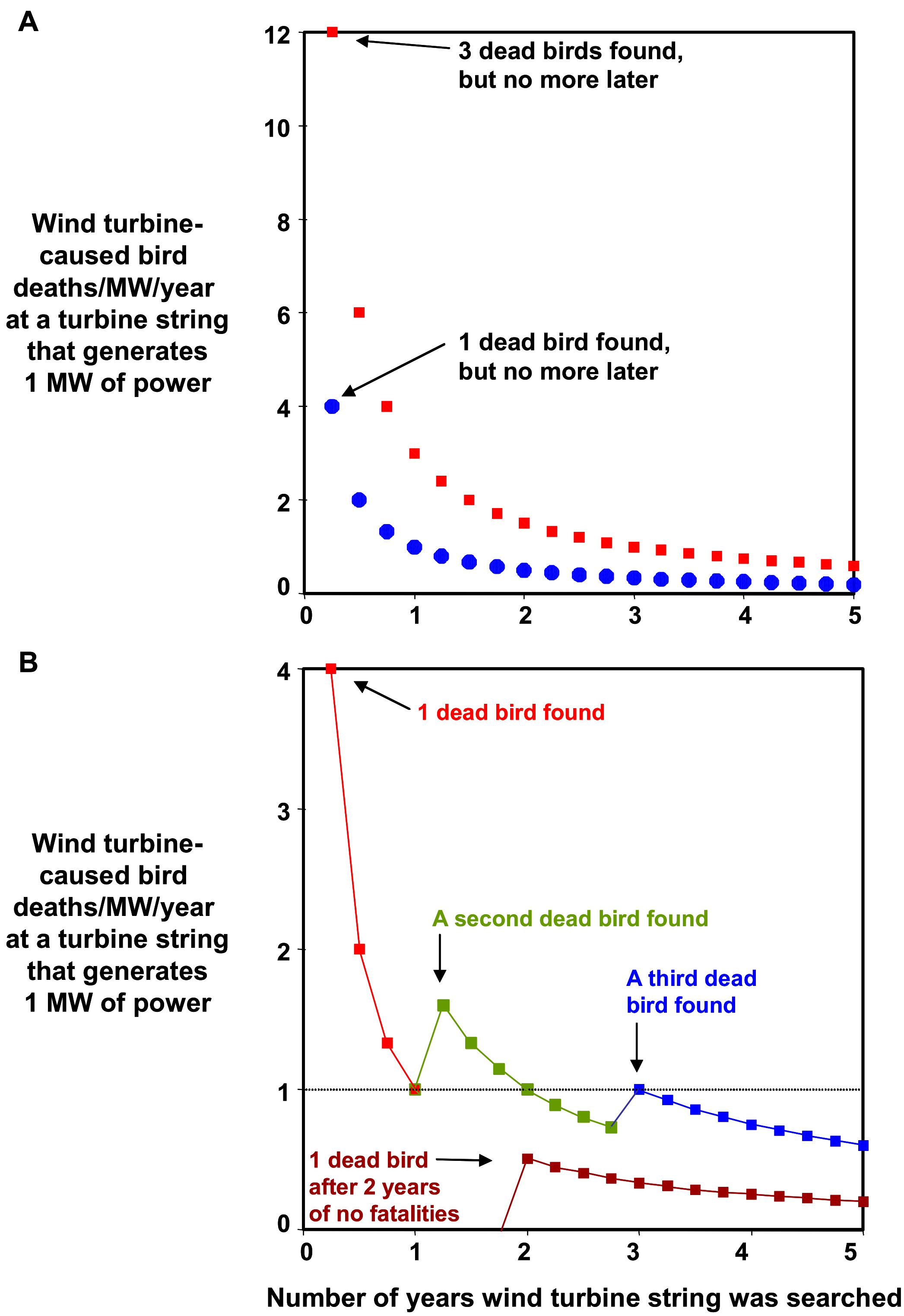

Figure A4. Mortality will relate as an inverse power function to the number of years used to generate the mortality estimate (A). This relationship will be modified by newly discovered fatalities (B).

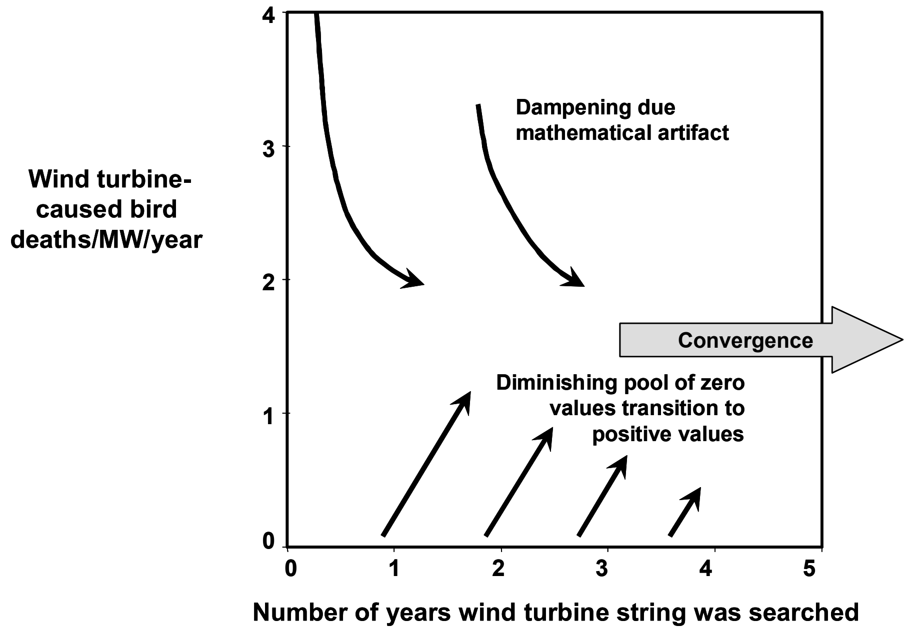

Figure A5. As monitoring continues, the inverse power function between mortality and monitoring period will dampen mortality estimates, while portions of the sample of wind turbines will transfer from the zero to non-zero mortality categories.

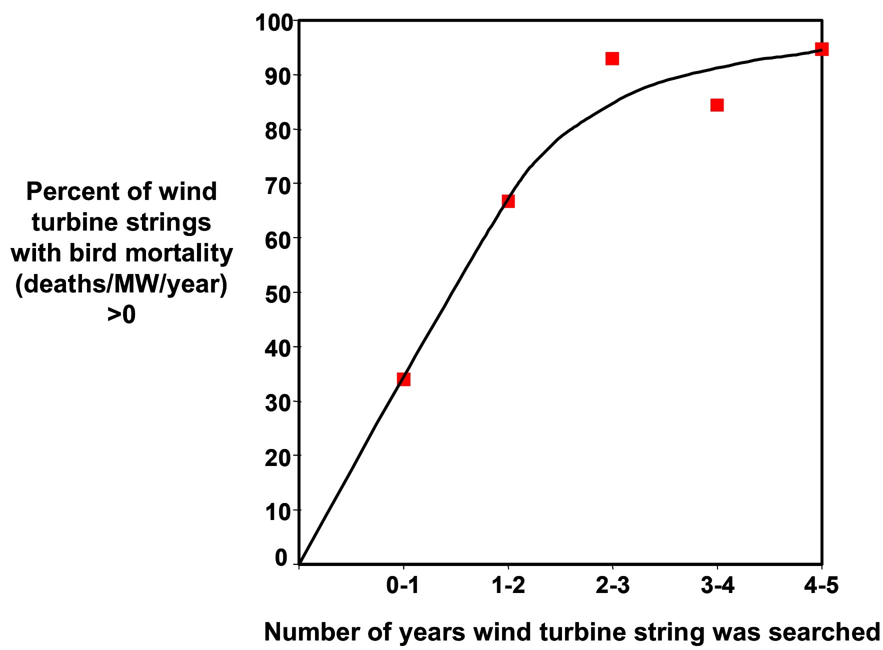

Figure A6. Data from the APWRA indicate that at least three years of carcasses searches are needed before the percentage of wind turbines with > 0 mortality estimates stabilizes.

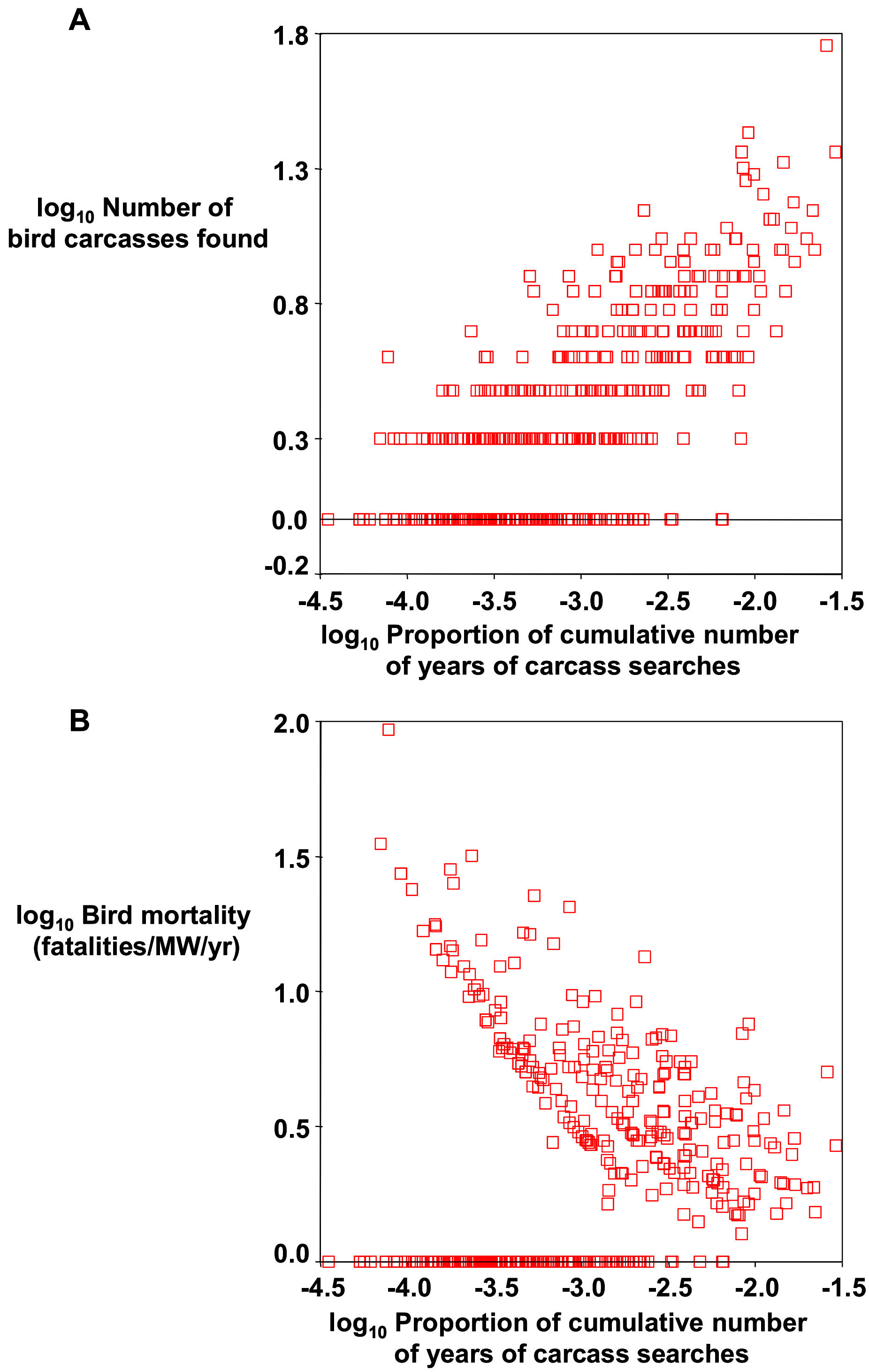

Figure A7. In the APWRA, the number of fatalities at wind turbine strings increases with search effort. Most of our sample of wind turbines had not been searched long enough to reach the asymptote shown in Figure A6 (A). Furthermore, mortality estimates converge from high and zero values to a narrower range of values as sampling effort increases (B).

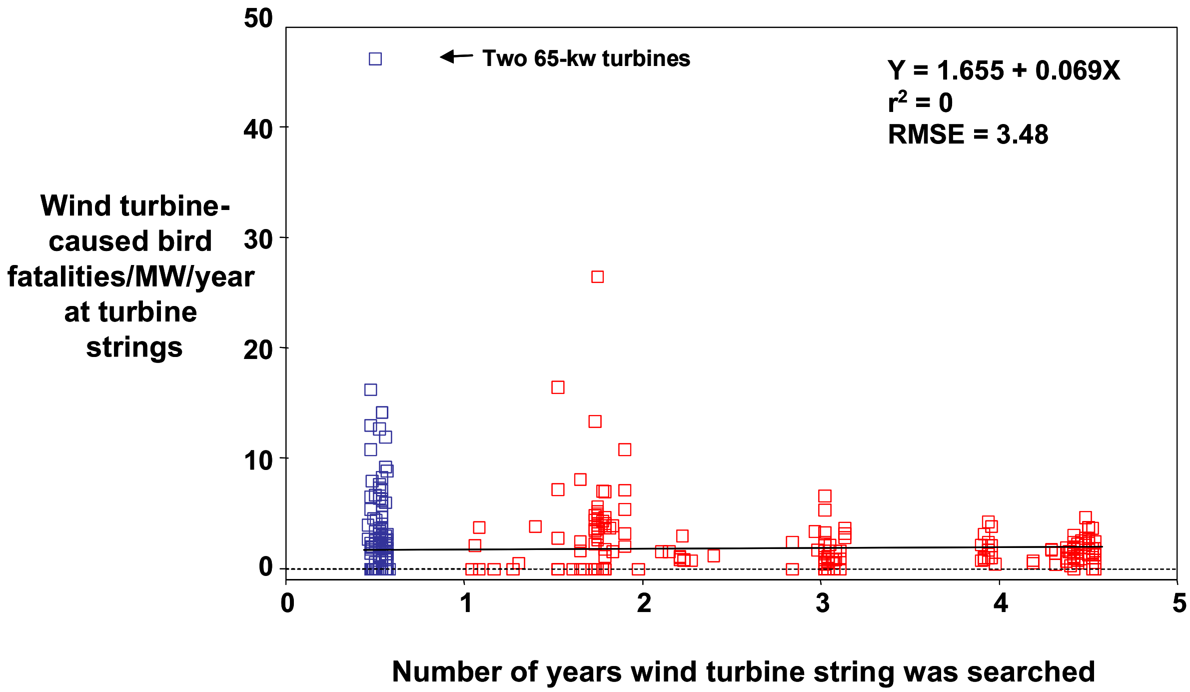

Figure A8. Bird mortality is a function of the duration used to generate the mortality estimate. During the first year of fatality searches, mortality is highly variable and declines through time. After one year of searches, mortality estimates stabilize and their precision increases.

4.0 DISCUSSION

At first glance it might appear that bird mortality can be nearly as efficiently measured per wind turbine as per megawatt, but there are additional considerations that lead us to conclude that the number of fatalities per megawatt per year is the more efficient (preferable) metric to use when reporting bird mortality caused by wind energy generating facilities. This is particularly important given the variability in turbines being installed between wind energy generating facilities.

The types and configurations of the wind turbines included in our analysis ranged in output capacity from 40 to 400 kW; whereas, many of the newer wind turbines being installed range in output capacity from 600 kW to 2 MW. Some newer models are capable of generating > 4 MW of electrical energy. These much larger wind turbines are fewer in number relative to the MW generated, but they have a larger RSA. By sweeping a larger area of sky, each of the larger wind turbines poses a greater likelihood of killing more birds per turbine, but not necessarily more per megawatt. Offsetting these likelihoods might be the greater height domain of the rotor blades on these larger wind turbines, but there is no reason to expect *a priori* that a greater height domain will kill fewer birds, all other factors being equal. In fact, a greater height domain may kill *more* birds if more birds are flying at higher altitudes, which may be true for some species.

We believe that measuring mortality as the number of fatalities/wind turbine/year has become outmoded, because wind turbines now vary too greatly in size and output to warrant this metric as the standard. The advent of fewer, larger wind turbines will likely cause the reporting of an artificial increase in mortality measured as the number of fatalities/turbine/year. Moving to mortality measured as the number of fatalities/MW/year will likely not yield the false appearance that there has been on increase in mortality with changes in turbine design.

Another reason to change to a new standard metric for reporting mortality is public perception. Many non-biologists will likely have a poor understanding of what bird mortality means when it is expressed as the number of fatalities/turbine/year. It is easier to comprehend bird mortality when it is expressed in terms of the number of MWs of energy generated. Furthermore, expressing mortality in terms of MW enables direct comparisons between wind turbine-caused mortality and the mortality caused by other forms of energy generation, which can also be expressed in terms of MW. The number of households, or persons, supported per MW of generated energy can more easily be incorporated into the measure of mortality so that other human activities not associated with energy generation can be compared in their impacts to birds.

Yet another consideration is an analytical one. Expressing mortality in terms of MW allows for the number of wind turbines to be used as a predictor variable in integrative analysis. We might, for example, be able to conclude whether a larger number of wind turbines with shorter heights is more or less dangerous to birds than a fewer number of taller wind turbines. This hypothesis test would be somewhat less confounded by relating mortality expressed as per-MW, rather than per-turbine, when comparing mortality to the number of wind turbines composing the sample.

We also found that the variation in mortality estimates is a function of the monitoring period during which carcass searches were performed. Dividing a relatively constant value by a continuous variable will relate to the continuous variable as an inverse power function. This relationship determines, to some extent, differences in mortality that are observed between wind energy generating facilities or at the same wind farm at different time periods. In the relative short term, the standardized measure of mortality (Anderson et al. 1999) is standardized in its terms and calculation, but not in its measure of impact. At least three years of carcass searches are needed before the sample of wind turbines sufficiently stabilizes in the percentage of non-zero mortality values. Any monitoring duration less than three years is likely to yield unreliable estimates of mortality.