Review

Meta-Analysis of the Effectiveness of Marked Wire in Reducing Avian Collisions with Power Lines

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Abstract: *Collisions of birds with power transmission and distribution lines have been documented for many species, and cause millions of casualties worldwide. Attempts to reduce mortality from such collisions include placing bird flight diverters (i.e., wire markers in the form of, e.g., spirals, swivels, plates, or spheres) on static and some electrified wires to increase their visibility. Although studies of the effectiveness of such devices have yielded contradictory results, the implementation of flight diverters is increasing rapidly. We reviewed the results of studies in which transmission or distribution wires were marked and conducted a meta-analysis to examine the effectiveness of flight diverters in reducing bird mortality. We included in our meta-analysis all studies in which researchers searched for carcasses of birds killed by a collision with wires. In those studies that also included data on flight frequency, we examined 8 covariates of effectiveness: source of data, study design, alternate design (if marked and unmarked spans were alternated in the same line), periodicity of searches for carcasses, width of the search transect, and number of species, lines, and stretches of wire searched. The presence of flight diverters was associated with a decrease in bird collisions. At unmarked lines, there were 0.21 deaths/1000 birds (*n *= 339,830) that flew among lines or over lines. At marked lines, the mortality rate was 78% lower (*n *= 1,060,746). Only the number of species studied had a significant influence on effect size; this was larger in studies that addressed more species. When comparing mortality at marked and unmarked lines, we recommend use of the same time intervals and habitats and standardizing the periodicity of carcass searches.*

Keywords: bird collision, bird flight diverter, flight frequency, ground-wire marking, power line

Meta-Análisis sobre la Eficacia de la Señalización de los Cables para Reducir las Colisiones de Aves contra Tendidos Eléctricos

Resumen: *La colisión de aves con tendidos eléctricos tanto de transmisión como de distribución ha sido documentada en numerosas especies y causa millones de muertes en todo el mundo. Los intentos para reducir la mortalidad causada por dichas colisiones incluyen la colocación de dispositivos anticolisión (i. e., marcadores en cables con forma de espiral, dispositivos giratorios, platillos o esferas) en los cables de tierra, así como, a veces, en los conductores, para aumentar su visibilidad. Aunque los estudios llevados a cabo sobre la efectividad de tales medidas han llegado a conclusiones contradictorias, la instalación de dispositivos anticolisión está aumentando rápidamente. Revisamos los resultados de los estudios en los que se señalizaron cables de transmisión o de distribución y llevamos a cabo un metanálisis para examinar la eficacia de los dispositivos anticolisión a la hora de reducir la mortalidad. Incluimos en nuestro metanálisis todos los trabajos en los que los investigadores realizaron una búsqueda de aves muertas tras colisionar con los cables. En aquellos estudios que además incluyeron frecuencias de vuelo, examinamos 8 covariables de la efectividad: origen de los datos, diseño del estudio, diseño alternado (si los vanos señalizados y no señalizados se alternaban en el mismo tendido), periodicidad en la búsqueda de cadáveres, ancho de la banda de búsqueda, y número de especies, tendidos y tramos muestreados. La instalación de dispositivos anticolisión estuvo ligada a un descenso en el número de aves colisionadas. En los tendidos sin señalizar,*

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Paper submitted November 3, 2010; revised manuscript accepted February 21, 2011.

Conservation Biology, Volume 25, No. 5, 893–903

DOI: 10.1111/j.1523-1739.2011.01699.x

*hubo 0.21 muertes/1,000 aves (*n = *339,830) que cruzaron los cables. En los tendidos marcados, la mortalidad fue un 78% inferior (*n = *1,060,746). Sólo el número de especies estudiadas tuvo una influencia significativa en el tamaño del efecto; éste fue mayor en aquellos trabajos que estudiaron más especies. Cuando se compare la mortalidad en tendidos señalizados y sin señalizar, recomendamos que se usen los mismos intervalos de tiempo y hábitats y que se estandarice la periodicidad de la búsqueda de cadáveres.*

Palabras Clave: colisión de aves, dispositivo anticolisión, frecuencia de vuelo, señalización del cable de tierra, tendido eléctrico

Introduction

Avian collisions with and electrocution by power lines have been documented since the early 1900s, but it was not until the 1970s that biologists and engineers began to realize the extent of these events and to study mitigation measures (e.g., Bevanger 1998; APLIC 2006; Lehman et al. 2007). The number of power lines is increasing worldwide at 5% per year (Jenkins et al. 2010). This percentage applies to both power distribution (generally 2.4 kV to 60 kV) and transmission lines, which carry >69 kV of electricity (APLIC 2006).

Bird mortality from collisions with power lines and other electric-utility structures has been documented for nearly 350 species of birds (Manville 1999). Some crude estimates of the number of individuals that die are also available. For instance, bird collisions with power lines may cause 1 million deaths/year in the Netherlands (Koops 1994), and in the United States estimates show power lines kill from hundreds to thousands to >175 million birds per year (Manville 2005, 2009). Worldwide it is estimated that bird collisions with power structures, including transmission and distribution lines, that result in fatalities could approach 1 billion annually (Hunting 2002).

Until an assessment of the cumulative effects of bird mortality from power lines is conducted, the magnitude of such mortalities will remain uncertain (Manville 2009). Although collisions with power lines are the most important mortality source for some endangered species of birds (Manville 2009), few detailed analyses of how these losses affect trends in population size have been conducted. Collision-related losses may be equivalent to 9–90%, depending on the species, of the annual number of individual tetraonids (grouse) harvested by hunting in Norway (Bevanger 1995). Whereas estimated hunting harvest of Capercaillies (*Tetrao urogallus*) was 22,200, estimated mortality from collisions with power lines was 19,900. In Switzerland ring-recovery data show 25% of juvenile and 6% of adult White Storks (*Ciconia ciconia*) die annually due to collision with and electrocution by power lines (Schaub & Pradel 2004). Shaw (2009) estimated that in South Africa 30% of Denham's Bustard (*Neotis denhami*) are killed annually by collisions with power lines. Birds with low maneuverability, that is, those with high wing loading and low aspect (e.g., bustards, cranes, storks, pelicans, waterfowl, some grouses), are among the species most likely to collide with power lines (Bevanger 1998; Janss 2000). Species with narrow visual fields also have a high probability of colliding with power lines (Martin & Shaw 2010).

Although efforts to reduce bird collisions are increasing rapidly worldwide, the effectiveness of such measures has not yet been tested adequately. Results from examinations of the effectiveness of anticollision systems are diverse, varying from no reduction of collisions (e.g., Scott et al. 1972; Janss et al. 1999; Anderson 2002) to a reduction in collisions (e.g., Alonso et al. 1994; Bevanger & Brøseth 2001). This heterogeneity may be due to differences in behavior and morphology of species, habitat variability, weather, type and number of marking devices used per length of line, and approaches used to test for an effect.

The mitigation measures used include placement of raptor decoys on posts (Janss et al. 1999), marking static wire to make it more visible, and replacement of static wire with lighting arrestors at transmission towers (Beaulaurier 1981; Bevanger & Brøseth 2001). Where collisions of birds with energized transmission lines are a problem, lines are sometimes marked with clamp-on devices. However, these devices, which surround the wire where they are attached, can cause power reductions and line damage and thus may not be feasible for high-voltage wires (APLIC 2006). Removing the static wire would reduce bird mortality, but the wires are needed to protect conductors from lightning (Beaulaurier 1981). Because lightning strikes can result in power outages and line damage and fires, the most common mitigation measure has been the attachment of spirals, plates, swivels, or spheres to static wire to increase wire visibility. Collectively, these devices are called bird flight diverters (e.g., APLIC 1994; Hebert & Reese 1995; Jenkins et al. 2010). Despite the general belief that bird flight diverters reduce bird mortality, results of several studies show they do not (e.g., Scott et al. 1972; Anderson 2002). However, several of these studies had small sample sizes or did not include statistical tests. Placement of bird flight diverters is expensive (e.g., US$1100–2600/km of marking in South Africa [Kruger 2001] and €6000 in Spain [Alonso et al. 2005]), so evidence of their effectiveness is needed.

Narrative reviews of the effectiveness of wire marking to reduce avian collisions with power lines have been conducted (APLIC 1994; Bevanger 1994; Jenkins et al. 2010), mainly through counts of the number of studies indicating markers do or do not reduce collisions. These qualitative reviews do not control for sample size or variance across studies. They give equal value to publications with anecdotal data and to those with detailed experimental designs and large sample sizes and small variances. Not controlling for sample size can lead to type II errors (Arnqvist & Wooster 1995), that is underestimation of the effects of collisions on population sizes of birds (Fernández-Duque & Valeggia 1994).

We conducted a meta-analysis of the published literature and unpublished reports (primarily reports of private companies) to evaluate whether wire marking reduces the number of bird collisions with power lines. A meta-analysis is quantitative and allows for comparison of results among studies. Meta-analysis weights the value of different studies on the basis of their sample sizes and variances and provides a balanced effect for the studied topic (Arnqvist & Wooster 1995; Gurevitch & Hedges 2001; Stewart 2010). Meta-analyses have been used widely in research domains in which available empirical data provide no clear consensus (Stewart et al. 2005, 2007; Benítez-López et al. 2010). Meta-analyses are especially valuable when there is a high probability of incurring type II errors (Arnqvist & Wooster 1995).

Methods

Data

Our meta-analyses included studies that reported on counts of carcasses associated with marked and unmarked power lines. We did not include studies that provided only data on the behavior of birds when approaching the power lines or only data from marked or unmarked sections of power lines in space or time. We did not use data on mortality that was estimated after correcting for potential biases (e.g., scavenger removal, estimates of injury, habitat, or observers) because not all studies correct for such biases. Furthermore, calculation of mortality after correcting for biases was beyond the scope of our analyses. Instead, we used the raw data from carcass counts.

We conducted 2 meta-analyses, the first with data from all studies that reported carcass counts and the second with studies that also included counts of birds flying across the line that were used to calculate collision rates. In the second meta-analysis, we evaluated the sensitivity of the results from the first by using data on flight frequency (Stewart et al. [2007]; Benítez-López et al. [2010]).

We searched ISI Web of Science, Scirus, Zoological Record, and JSTOR for wire-marking studies. We identified additional studies in the reference lists of pertinent papers we found in the databases. The number of published papers listed on the 4 databases was relatively low, which may reflect the small sample sizes typical of such studies. Thus, we searched Google for additional studies not published in peer-reviewed journals.

For all searches, our search terms were combinations of the following words or phrases: bird, crane, swan, raptor, waterfowl, aviation ball, flight diverter, swan diverter, ground wire, static wire, marker, power line, spiral, wire, collision, effectiveness, impact, power-line marking, and wire marking. We searched for publications in English, Spanish, German, and French. We contacted most authors who have worked on this topic over the last 30 years. These authors were our most fruitful source of data because they provided use with other contacts and with several unpublished studies that would otherwise have been inaccessible. We also contacted environmental departments of electrical companies, managers of state and federal wildlife agencies, and nongovernmental conservation organizations worldwide to obtain unpublished documents, such as PhD dissertations and public and internal reports, to increase the number of studies we could use (Fernández-Duque & Valeggia 1994).

We expected this variety of sources would reduce the probability of biasing the meta-analysis toward studies reporting statistically significant results, which are believed to be published more frequently than those with results that are not statistically significant (Arnqvist & Wooster 1995; Stewart 2010). We reveal our sources here so as to avoid the hidden-publication bias that may be present in other nonsystematic syntheses (Stewart 2010). However, we also formally tested potential publication biases.

If more than one publication presented results from the same study area and period (e.g., Crowder [2000], Crowder & Rhodes [2001], Shaw [2009], and Shaw et al. [2010]), we relied on data from the most complete study. We extracted the raw data from each study in our meta-analyses. Thus, if the same results were published in an abbreviated form (typically, a paper) and in a more detailed form (for instance, in a report or dissertation), we used the latter because we could obtain the raw data more easily. When a publication included more than one study, for instance if it assessed the number of collisions associated with more than one marker in different line segments or lines (e.g., Anderson 2002) or the same marker at different intervals in different line segments or lines (e.g., Koops & de Jong 1982), we treated the experiments as independent (Benítez-López et al. 2010; Gilbert-Norton et al. 2010). We also treated as independent studies that tested marker effectiveness with a before-after-control-impact (BACI) design and with a parallel design (i.e., marked and unmarked lines studied during the same time interval). We excluded studies that simultaneously tested more than one marker (e.g., bird flight diverters and strips in the same wire) because their effects could be cumulative and could have stronger effects than those experiments in which only a single device was used.

Studies of Carcasses

Because our primary data were the means of 2 groups, we calculated the ratio of the means to obtain the "response ratio" (hereafter R) as the effect size (Borenstein et al. 2009). Following Bevanger (1999), we controlled the number of avian deaths per power line length and period of time as

$$R = \text{MML/MUML} = [\text{cML}/(\text{kmML} \times \text{tML})] / [\text{cUML}/(\text{kmUML} \times \text{tUML})], \quad (1)$$

where MML is the mortality associated with the marked line, MUML is the mortality associated with the unmarked line, cML is the number of carcasses found under the marked line, kmML is the length in kilometers of the marked line, tML is the number of months during which carcasses were counted under the marked line, and cUML, kmUML, and tUML are the respective values for the unmarked line. We analyzed R after log transformation to maintain symmetry in the analysis (Hedges et al. 1999; Borenstein et al. 2009). Negative ln$R$ values (i.e., $\ln R < 0$) indicated a decrease in mortality, and positive values indicated an increase. The response ratio is a common metric in meta-analyses of ecological studies (Hedges et al. 1999). However, because authors of the studies we analyzed reported only the total number of dead birds per kilometer and month, the sample size for every study was 1.0 (J. Gurevitch, personal communication). Thus, we conducted an unweighted analysis (i.e., all the variances were 1.0) (Rosenberg et al. 2000; J. Gurevitch, personal communication). An unweighted analysis does not allow one to investigate the potential structure of the data because the weight from every study is required (Neter et al. 1989).

Carcass Counts and Flight Frequencies

We examined the sensitivity of the results from the first analysis by conducting a second meta-analysis that included only those studies in which both carcasses and flight frequencies were counted (i.e., number of birds flying across studied power lines, or sample size). We assessed the difference between probabilities of collision (i.e., the risk difference [RD]) associated with unmarked and marked lines. The probability of collision associated with either line was mortality divided by the total number of birds crossing the line (Borenstein et al. 2009).

$$RD = (\text{MML/nML}) - (\text{MUML/nUML}), \quad (2)$$

where nML is the number of birds flying across the marked line and nUML is the number of birds crossing the unmarked one.

The sample size we used to calculate the weight for every study was the total number of birds observed flying across the studied power lines. Mortality could have been overestimated in some cases because studies counted bird crossings during periods that were shorter than those in which carcasses were counted. Furthermore, sampling efforts were not always the same in marked and unmarked sections because the sections were not always the same length or sampled during the same time intervals. Thus, we controlled for sampling effort before calculating nML and nUML. We divided the sample size of each study by the sampling effort we assessed, ignoring the reported number of birds crossing marked and unmarked sections (unless sampling effort was equal). In 4 studies (Brown & Drewien 1995; Crowder 2000; Brauneis et al. 2003; Lorenzo & Cabrera 2009) that evaluated more than one device, but did not clearly indicate the sections of marked lines where flying birds were counted, we averaged the numbers of birds crossing for the different markers. We did not use data from studies that assumed the same crossing rates for stretches with and without markers because this assumption is incorrect (Alonso et al. 1994; Calabuig & Ferrer 2009). Negative RD values indicated a decrease in mortality and positive values indicated an increase. We calculated the variance of RD with the following formula (Borenstein et al. 2009):

$$V_{\text{RD}} = (\text{MML} \times \text{AML})/\text{nML}^3 + (\text{MUML} \times \text{AUML})/\text{nUML}^3, \quad (3)$$

where AML and AUML are birds that were alive after crossing marked and unmarked lines, respectively. In applying this sensitivity analysis we had to discard some studies, but we improved statistical power because we could use weighted analyses.

Data Analyses

We loaded effect sizes and variances to carry out all analyses with MetaWin (version 2.0, Sinauer Associates, Sunderland, MA, USA; Rosenberg et al. 2000). We first assessed the effect of wire marking for the entire data set with random-effects modeling, which allows for the possibility that studies differ in sampling error (as fixed-effects models do) and in random variation in effect sizes (Gurevitch & Hedges 2001). Random-effects models are more appropriate for analysis of ecological data because numerous complex interactions are likely to result in heterogeneity among studies (Pullin & Stewart 2006). We calculated 95% confidence intervals (CIs) (bias-corrected bootstrap, 999 iterations) for each effect size (Rosenberg et al. 2000). If the 95% CI did not overlap zero, then effects were significant at $p < 0.05$. We calculated the total heterogeneity, Q_T, to analyze whether the variance among effect sizes was greater than expected due to the sampling error (Rosenberg et al. 2000). This variable was a weighted sum of squares, and we tested it against a χ^2 distribution with n-1 df. A significant Q_T implies that other explanatory variables should be investigated (Rosenberg et al. 2000). We estimated the percentage of variation in effect sizes explained by each predictor as Q_M/Q_T, where Q_M is the variance explained by the model from every predictor (Rosenberg et al. 2000).

In analysis of the subset of studies that included data on flight frequency, we calculated differences in effect sizes for the set of variables with random-effects models. We evaluated the homogeneity of results for the set of variables. We evaluated the "source" of information, that is, the differences between studies from peer-reviewed journals (journal) and other sources (unpublished). We evaluated the variable "design," which differentiated between BACI designs and those in which marked and unmarked lines (or line sectors) were studied in the same time interval. We used the variable "alternate" to test whether studies in which spans were marked in alternating order (i.e., marked-unmarked-marked) affected effect size; birds may have flown into unmarked spans to avoid marked spans (Alonso et al. 1994; Crowder 2000). For categorical data structure, we tested Q_M against a χ^2 distribution with n-1 df. We calculated cumulative effect sizes for every group; effects were significant at $p < 0.05$ when the 95% CI did not overlap zero. A significant Q_M indicated there were differences among cumulative effects for the designated groups, whereas a significant Q_E implied some heterogeneity among effect sizes was not explained by the model (Rosenberg et al. 2000).

We also selected 5 continuous variables: "periodicity," mean number of carcass searches per month; "strip," total width searched on both sides of the line in meters; "species," number of bird species recorded; "lines," number of power lines included in the study; and "stretches," number of marked or unmarked stretches of power line, independent of the number of spans (i.e., the length of line between 2 consecutive posts) contained in every stretch. We determined the relation between effect size and every continuous variable with weighted least-squares regression. A significant Q_M (or regression coefficient) implied the independent variable explained significant variation in the effect sizes, and a significant Q_E implied some heterogeneity among effect sizes was not explained by the model (Rosenberg et al. 2000).

We explored the possibility of publication bias with 3 different approaches: construction of a funnel plot of sample size versus effect size; use of Spearman rank correlation between the standardized effect size and the standardized variance across studies (statistical significance indicates large effect sizes are more likely to be published than small effect sizes); and evaluation of the Rosenthal (1979) fail-safe number, which is the number of nonsignificant, unpublished, or missing studies that would need to add to the meta-analysis to lose the statistical significance of the results. If the fail-safe number is >5 times the sample size plus 10 ([sample size + 10] × 5), it is reasonable to conclude the results are robust regarding publication bias. The 3 methods were used with the meta-analysis that included flight-frequency data. We used the fail-safe number in the meta-analysis of studies in which only carcass counts were used because these studies did not provide sample sizes, an essential parameter for the other 2 methods.

Results

Twenty-one studies, including 52 separate wire-marking experiments, met our selection criteria (Supporting Information). Wire marking reduced bird mortality at $p < 0.05$ (i.e., 95% CI did not overlap zero; −1.42 to −0.47). The test for overall heterogeneity was not significant ($Q_T = 51.00$, df $= 51$, $p = 0.47$).

We selected 11 of the 21 studies, including 15 separate wire-marking experiments because data on flight frequencies were collected (Supporting Information). Of these 15 experiments with flight frequencies, results of 7 were published in peer-reviewed journals and 8 were in unpublished reports, 3 of the experiments had BACI designs, and 11 had parallel designs. Of these 11, 5 had alternate designs and 6 had continuous designs (Fig. 1). Overall collision rates were 0.21/1000 bird crossings at unmarked lines and 0.05/1000 crossings at marked lines (Fig. 1). With the exception of the few studies with BACI designs, wire marking reduced bird mortality by 55–94% (overall 78%; Fig. 1). The test for overall heterogeneity was significant ($Q_T = 69.27$, df $= 14$, $p < 0.001$), which implies other explanatory variables should be investigated. Among the 8 variables, only number of species was significant at $p < 0.05$ (Table 1 & Fig. 2), and the effect size of the studies was larger for those in which more species were present. All variables showed heterogeneity among effect sizes that were not explained by their respective models (Table 1).

The fail-safe number for the meta-analysis of carcass counts was 751, which is >5 times the sample size plus 10 (i.e., 310). The scatter plot derived from the sensitivity analysis did not show publication bias. The plot was funnel shaped with a large opening at the smallest sample sizes. The fail-safe number for sensitive analysis was 393, which is 5 times larger than the sample size plus 10 (i.e., 125). Accordingly, Spearman rank correlation of standardized effect size and the standardized variance was not significant ($R_s = -0.10$, $p = 0.73$).

Discussion

Effectiveness of Wire Marking

Our results suggest that marking static wires reduces the number of bird casualties at power lines. However, collision risk was generally low even at unmarked lines. We did not compare the relative efficiency of various types of markers (color, shape) or evaluate the density of marking devices on the wire. Few studies have been conducted on

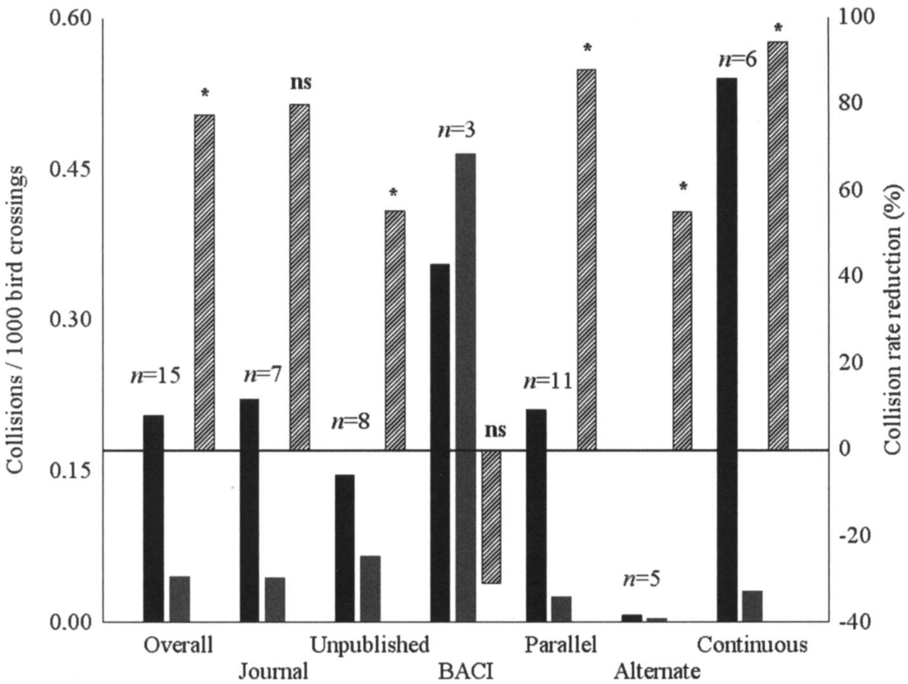

Figure 1. Rate of avian collisions with power lines for the studies included in the meta-analysis (overall) and for 3 categorical variables, including studies reporting carcass counts and flight frequencies (black, unmarked power lines; gray, marked power lines; numbers above bars, number of experiments), and percent reduction in collisions for every category of study (striped, right axis) (, significant at alpha <0.05; ns, alpha ≥0.05; significant values are based on 95% bootstrapped confidence intervals). The categorical variables are (1) source (study published in a journal or unpublished), (2) BACI study design (before-after-control-impact) or study design in which marked and unmarked lines (or line sectors) were monitored simultaneously (parallel), and (3) parallel study designs with spans marked alternately (alternate) or continuously (continuous).*

the effectiveness of different markers for different species or habitats.

That our literature review included unpublished reports, dissertations, and papers published in peer-reviewed journals allowed us to increase the number of studies included in the meta-analysis and to compare results between published and unpublished studies. Assuming positive results are more likely to be published, use of all possible data sources reduces the probability of overestimating positive results (Fernández-Duque & Valeggia 1994).

On the basis of studies reporting only carcass counts, we inferred that marked lines are associated with a reduction in the number of collisions. Fifty-six percent of the studies we examined included estimates of bird density. Of these, we included in our second meta-analysis only those in which flight frequencies in relation to marker effectiveness were analyzed. Bird densities around power lines may not be associated with the magnitude of collision risk because species with large home ranges and species that make daily forays between roosting and feeding habitats often cross power lines more frequently than species with small home ranges (e.g., most sedentary passerines), which makes them more likely to collide with wires.

When marked and unmarked spans are alternated, birds could fly into unmarked spans more often, presumably to avoid marked ones (Alonso et al. 1994; Crowder 2000). However, we found no evidence of this. The absence of an effect of alternate marking could be due to the fact that the most common reaction of birds when approaching marked spans adjacent to unmarked spans is to fly higher rather than to change direction (Morkill & Anderson 1991; Savereno et al. 1996). The effect size was smaller in studies with one or only a few species, probably because these (e.g., Morkill & Anderson 1991; Sudman 2000) studies focused on species that rarely respond to marking and thus are most likely to collide with wires (i.e., cranes and waterfowl) (Bevanger 1998; Janss 2000). All continuous variables had significant residual error variances, which implies that not all heterogeneity among effect sizes was explained by their respective models (Rosenberg et al. 2000).

Testing Differences among Marker Traits

Some researchers have statistically tested differences among marker characteristics. Scott et al. (1972) found no evidence that 2 types of devices, clipped strips and tapes, reduce bird casualties. Brown and Drewien

Table 1. Summary of results of random models used to analyze differences in effectiveness of markers to prevent bird collisions with power lines.

Variable[a]	*df*	Q_M[b] (*p*)	Q_E[c] (*p*)	Q_M/Q_T[d]
Source	1, 13	0.12 (0.72)	63.70 (<0.00)	0.00
Design	1, 12	0.04 (0.85)	62.20 (<0.00)	0.00
Alternate	1, 9	0.49 (0.48)	27.85 (<0.00)	0.02
Periodicity	1, 13	1.79 (0.18)	66.27 (<0.00)	0.03
Strip	1, 12	2.62 (0.11)	64.71 (<0.00)	0.04
Number of species	1, 12	6.85 (<0.01)	70.63 (<0.00)	0.09
Number of lines	1, 13	1.45 (0.23)	64.43 (<0.00)	0.02
Number of stretches	1, 13	0.80 (0.37)	62.54 (<0.00)	0.01

[a]*Key: source, peer-reviewed journal or unpublished; design, BACI (before-after-control-impact) design or marked and unmarked lines (or line sectors) studied simultaneously; alternate, stretches of wire marked in alternating order or in a continuous form; periodicity, mean number of carcass searches per month; strip, total width of search strip; number of species, total recorded per study; number of lines, power lines included in the study; number of stretches, total marked and unmarked stretches of power line studied.*
[b]*Heterogeneity explained by the model or between-group heterogeneity.*
[c]*Residual error variance or within-group heterogeneity.*
[d]*Fraction of the total heterogeneity explained by the model.*

(1995) found slightly fewer mortalities associated with damper devices compared with plates, although reduction in mortality of segments marked with these devices compared with unmarked segments was significant for both dampers and plates. Janss and Ferrer (1998) found that white spirals and flapper flight diverters significantly reduce mortality, whereas black stripes do not. However, habitat differences (crops vs. wetlands) may have influenced their results. Anderson (2002) found that flappers are more effective than flight diverters. Stake (2009) found that small flight diverters and large diverters both reduce the number of bird collisions, but that large diverters are ineffective at some sites. Calabuig and Ferrer (2009) found that cross-shaped markers are more effective than spirals of different colors. Calabuig and Ferrer (2009) found that spirals of different colors (white, orange, and yellow) similarly reduce mortality relative to unmarked spans. Spirals appear to be more durable than flapper flight diverters (Calabuig & Ferrer 2009). However, all these studies have low statistical power, which could lead to type II errors (Arnqvist & Wooster 1995). Some researchers have evaluated the effects of marking at different intervals, but did not statistically analyze their results (Koops & de Jong 1982; Anderson 2002). Other researchers have examined the effectiveness of markers of different sizes, but did not make statistical comparisons among treatments (Koops & de Jong 1982).

Wire marking with standard flight diverters may not reduce the number of collisions of crepuscular or nocturnal birds. Waterfowl and nocturnal migrants are among the birds most prone to collisions with wires (reviewed in Drewitt & Langston 2008). Only a few studies of the effectiveness of new types of flight diverters (e.g., FireFly diverters) have been conducted (Pilo et al. 1994; Yee 2007; Murphy et al. 2009). Furthermore, many collisions may occur during the day, when visibility is high (Drewitt & Langston 2008). Martin and Shaw (2010) suggest that wire marking may have limited success for bird species with narrow visual fields, such as bustards, storks, and cranes. Thus, it is possible that no single type of marker will be equally effective with all bird species or in all situations, which suggests investigations of nonvisual devices are needed.

Guidelines for Marking-Efficiency Experiments

The large differences in wire-marking techniques constrained our ability to infer whether this method reduces bird collisions. We expect that the number of studies on this topic may increase substantially over time given the increasing demand for fewer and smaller effects of human actions on the environment and increasing use of marking devices on power lines worldwide (APLIC 1994, 2006; Manville 2009).

Four improvements in the design of studies of wire-marking effectiveness may help determine which marking techniques are the most effective. First, we recommend collecting data on carcass counts and flight frequency for the same length of time and at the same time of year at marked and unmarked wire segments. For instance, some studies with BACI designs monitored marked and unmarked lines for different lengths of time (e.g., Anderson 2002; de la Zerda & Rosselli 2003). This could produce biases in the data because flight frequencies are not constant throughout the year; frequencies differ among and within seasons (e.g., spring migration). Even when data are collected at the same time of year, flight frequencies can vary. For example, Alonso et al. (1994) recorded 2.9 times more flights in December–April before wires were marked compared with December–April after wires were marked. Consequently, we recommend recording flight frequencies and number of carcasses simultaneously.

Second, we suggest studying marked and unmarked lines in areas with similar vegetation and topography, the use of similar lengths of time spent searching for carcasses, and searching transects of equal lengths and widths (Bevanger 1999). For instance, bird collisions with power lines are more frequent for lines that cross wetlands and where lines are between feeding and roosting areas (Scott el al. 1972; McNeil et al. 1985; Ferrer & Janss 1999). Monitoring of different lengths of lines in different land-cover types or bird habitats could drive differences between marked and unmarked lines or among different

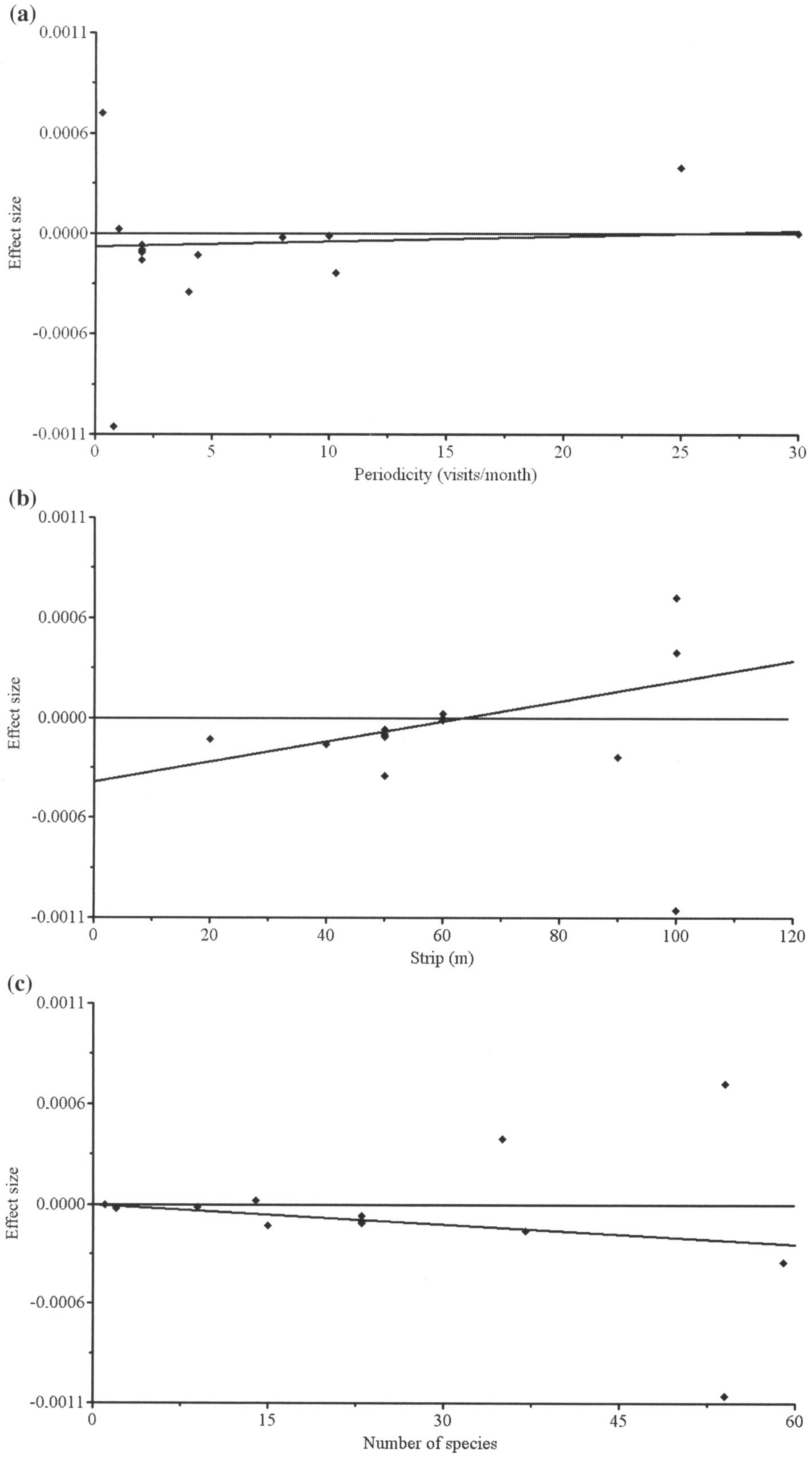

Figure 2. In a meta-analysis of studies of effectiveness of wire marking in reducing bird collisions with power lines, relation between effect size and (a) mean number of carcass searches per month (periodicity), (b) total width of transect searched on both sides of the power line (strip), (c) number of species recorded per study, (d) number of power lines examined per study, and (e) number of marked and unmarked stretches of power line monitored per study (stretches). Each point represents an experimental case.

markers (e.g., Janss & Ferrer 1998) because different bird species have different habitats and not all species have the same probability of collision (Bevanger 1998; Janss 2000; Martin & Shaw 2010).

Third, we recommend standardizing the periodicity of carcass searches and the search strip width, at least within every study. Although both variables must be constant to support detailed comparisons among studies

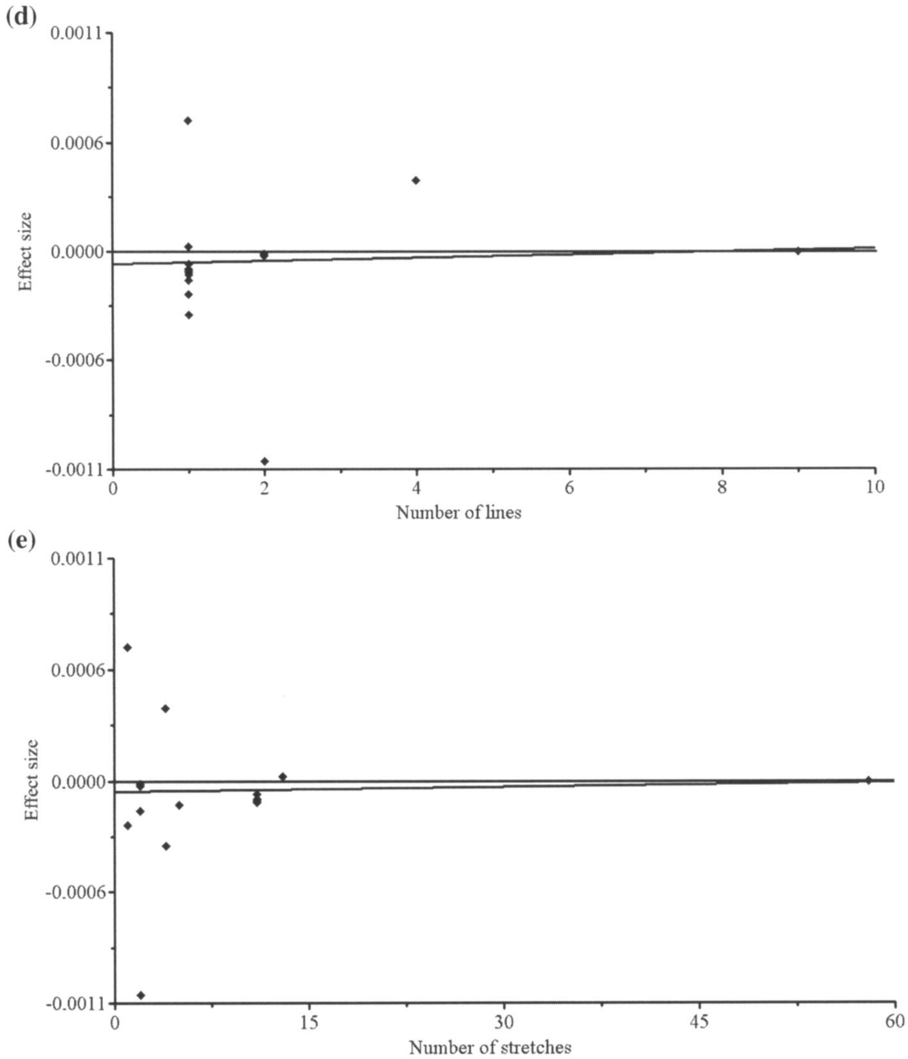

Figure 2. (continued)

(Bevanger 1999), periodicity in the studies we examined was sometimes fairly different even between marked and unmarked lines within a study (e.g., Koops & de Jong 1982). In general, we think the frequency of carcass searches should be determined on the basis of the species' body size because body size is correlated with the removal rate of carcasses by scavengers. Larger carcasses generally remain in the field longer than smaller ones and are more easily located (Ponce et al. 2010). Moreover, the carcass removal rate varies among habitats and density and type of scavengers (Bevanger 1994), so the periodicity of carcass searches and the length and width search strip should be defined according to the target species. Few researchers analyzed the distance from the power line at which carcasses were found (but see Frost 2008; Shaw et al. 2010). Ideally, carcass-disappearance studies in which similar protocols are applied should be carried out in each study area prior to studies of marking efficiency (e.g., Pelayo & Sampietro 1994; Onrubia et al. 1996).

Fourth, we recommend researchers compare the effectiveness of currently available commercial markers used to reduce bird collision. Due to the heterogeneity of markers used in the studies in our meta-analysis, we could not compare effectiveness of different types of devices (e.g., flight diverters, aviation balls, flappers) or device color, differences between categorical or continuous measures of device size, or differences among spacing of devices (e.g., every 5, 10, 20 m). Few conclusions about effectiveness can be drawn from experiments in which the life expectancy or color fading of different commercial devices was examined (Hunting 2002). The optimal density of markers or the effectiveness of using specific colors over others has not been explored (Hunting 2002).

Acknowledgments

R. Harness, B. Parshalle, M. Rogen, A.M. Manville, J.A. Lorenzo, L. Spiegel, J. Kreuziger, D. Frost, M. de Lucas,

M. Ferrer, J. Smallie, M. Stake, T. Lislevand, J.J. Ramos, S. Smallwood, J. Shaw, F.J. Purroy, and J.M. Álvarez provided valuable information for this review. J. Gurevitch kindly resolved several doubts on meta-analysis design, J.D. Ibáñez helped us with MetaWin use, L. de Neve provided translations of papers in Dutch, and S. Young reviewed the English. J. Faaborg, M. McCarthy, E. Fleishman, A.M. Manville, and an anonymous reviewer improved a first draft. Financial support for this study was provided by project CGL2008-02567 of the Dirección General de Investigación, Spanish Ministry of Science and Innovation.

Supporting Information

Raw data and effect sizes calculated from studies used in the meta-analysis are available online (Appendixes S1 & S2). The authors are responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Literature Cited

Alonso, J. C., J. A. Alonso, and R. Muñoz-Pulido. 1994. Mitigation of bird collisions with transmission lines through groundwire marking. Biological Conservation **67**:129-134.

Alonso, J. C., C. A. Martín, and C. Palacín, coordinators. 2005. Proyecto de medidas preventivas, correctoras y compensatorias de la afección de la M-50 y de la Autopista de Peaje R-2 a la población de avutardas y otras aves esteparias de la IBA Talamanca-Camarma, y al LIC Cuenca de los ríos Jarama y Henares. Museo Nacional de Ciencias Naturales (CSIC), Madrid.

Anderson, M. D. 2002. The effectiveness of two different marking devices to reduce large terrestrial bird collisions with overhead electricity cables in the eastern Karoo, South Africa. Report 1. Karoo Large Terrestrial Bird Powerline Project, Eskom, Johannesburg.

APLIC (Avian Power Line Interaction Committee). 1994. Mitigating bird collisions with power lines: the state of the art in 1994. Edison Electric Institute, Washington, D.C.

APLIC (Avian Power Line Interaction Committee). 2006. Suggested practices for avian protection on power lines: state of the art in 2006. Edison Electric Institute, Washington, D.C., and the California Energy Commission, Sacramento, California.

Arnqvist, G., and D. Wooster. 1995. Meta-analysis: synthesizing research findings in ecology and evolution. Trends in Ecology Evolution **10**:236-240.

Beaulaurier, D. L. 1981. Mitigation of bird collisions with transmission lines. Bonneville Power Administration, Portland, Oregon.

Benítez-López, A., R. Alkemade, and P. A. Verweij. 2010. The impacts of roads and other infrastructure on mammal and bird populations: a meta-analysis. Biological Conservation **143**:1307-1316.

Bevanger, K. 1994. Bird interactions with utility structures: collision and electrocution, causes and mitigating measures. Ibis **136**:412-425.

Bevanger, K. 1995. Estimates and population consequences of tetraonid mortality caused by collisions with high tension power lines in Norway. Journal of Applied Ecology **32**:745-753.

Bevanger, K. 1998. Biological and conservation aspects of bird mortality caused by electric power lines. Biological Conservation **86**:67-76.

Bevanger, K. 1999. Estimating bird mortality caused by collision and electrocution with power lines: a review of methodology. Pages 29-56 in M. Ferrer and G. F. E. Janss, editors. Birds and power lines: collision, electrocution and breeding. Quercus, Madrid.

Bevanger, K., and H. Brøseth. 2001. Bird collisions with power lines: an experiment with ptarmigan (*Lagopus* spp.). Biological Conservation **99**:341-346.

Borenstein, M., L. V. Hedges, J. P. T. Higgins, and H. R. Rothstein. 2009. Introduction to meta-analysis. Wiley, West Sussex, United Kingdom.

Brauneis, W., W. Watzlaw, and L. Horn. 2003. Das Verhalten von Vögeln im Bereich eines ausgewählten Trassenabschnittes der 110 kV-Leitung Bernburg-Susigke (Bundesland Sachsen-Anhalt). Flugreaktionen, Drahtanflüge, Brutvorkommen. Ökologie der Vögel **25**:69-115.

Brown, W. M., and R. C. Drewien. 1995. Evaluation of two power line markers to reduce crane and waterfowl collision mortality. Wildlife Society Bulletin **23**:217-227.

Calabuig, C. P., and M. Ferrer. 2009. Análisis de la eficacia y la vida útil de la señalización anticolisión "salvapájaros" en líneas de transporte de energía eléctrica. Red Eléctrica de España, Sociedad Anónima Unipersonal, and Consejo Superior de Investigaciones Científicas, Seville.

Crowder, M. R. 2000. Assessment of devices designed to lower the incidence of avian power line strikes. PhD thesis. Purdue University, West Lafayette, Indiana.

Crowder, M. R., and O. E. Rhodes. 2001. Avian collisions with power lines: a review. Pages 139-168 in R. G. Carlton, editor. Avian interactions with utility and communication structures. Workshop Proceedings. Electric Power Research Institute, Palo Alto, California.

De la Zerda, S., and L. Rosselli. 2003. Mitigación de colisión de aves contra líneas de transmisión eléctrica con marcaje del cable de guarda. Ornitología Colombiana **1**:42-62.

Drewitt, A. L., and R. H. W Langston. 2008. Collision effects of wind-power generators and other obstacles on birds. Annals of the New York Academy of Sciences **1134**:233-266.

Fernández-Duque, E., and C. Valeggia. 1994. Meta-analysis: a valuable tool in conservation research. Conservation Biology **8**:555-561.

Ferrer, M., G. F. E. Janss, editors. 1999. Birds and power lines. Collision, electrocution and breeding. Quercus, Madrid.

Frost, D. 2008. The use of 'flight diverters' reduces mute swan *Cygnus olor* collision with power lines at Abberton Reservoir, Essex, England. Conservation Evidence **5**:83-91.

Gilbert-Norton, L., R. Wilson, J. R. Stevens, and K. H. Beard. 2010. A meta-analytic review of corridor effectiveness. Conservation Biology **24**:660-668.

Gurevitch, J., and L. V. Hedges. 2001. Meta-analysis: combining the results of independent experiments. Pages 347-369 in S. M. Scheiner and J. Gurevitch, editors. Design and analysis of ecological experiments. Oxford University Press, New York.

Hedges, L. V., J. Gurevitch, and P. S. Curtis. 1999. The meta-analysis of response ratios in experimental ecology. Ecology **80**:1150-1156.

Hebert, E., and E. Reese (editors). 1995. Avian collision and electrocution: an annotated bibliography. Publication P700-95-001. California Energy Commission, Sacramento.

Hunting, K. 2002. A roadmap for PIER research on avian collisions with power lines in California. Technical report P500-02-071F. California Energy Commission, Public Interest Energy Research (PIER) Program, Sacramento.

Janss, G. F. E. 2000. Avian mortality from power lines: a morphologic approach of a species-specific mortality. Biological Conservation **95**:353-359.

Janss, G. F. E., and M. Ferrer. 1998. Rate of bird collision with power lines: effects of conductor-marking and static wire-marking. Journal of Field Ornithology **69**:8-17.

Janss, G. F. E., A. Lazo, and M. Ferrer. 1999. Use of raptor models to reduce avian collisions with powerlines. Journal of Raptor Research **33**:154-159.

Jenkins, A. R., J. J. Smallie, and M. Diamond. 2010. Avian collisions with power lines: a global review of causes and mitigation with a South African perspective. Bird Conservation International **20:**263–278.

Koops, F. B. J. 1994. Collision victims of high-tension lines in The Netherlands and effects of marking. Pages 51–57 in First technical sessions on power lines and the environment. Red Eléctrica de España, Madrid.

Koops, F. B. J., and J. de Jong. 1982. Vermindering van draadslachtoffers door markering van hoogspanningsleiden in de omgeving van Heerenveen. Elektrotechniek **60:**641–646.

Kruger, R. 2001. A risk based approach to the cost of implementing raptor mitigation measures on Eskom distribution networks in South Africa. Pages 229–246 in R. G. Carlton, editor. Avian interactions with utility and communication structures. Workshop proceedings. Electric Power Research Institute, Palo Alto, California.

Lehman, R. N., P. L. Kennedy, and J. A. Savidge. 2007. The state of the art in raptor electrocution research: a global review. Biological Conservation **135:**459–474.

Lorenzo, J. A., and M. Cabrera. 2009. Estudio de la mortalidad de aves por los tendidos eléctricos en los ambientes no esteparios de Lanzarote y Fuerteventura, y valoración de las medidas correctoras instaladas en Fuerteventura. Memoria final. Sociedad Española de Ornitología, BirdLife, and Empresa Nacional de Electricidad, Sociedad Anónima, Tenerife, Spain.

Manville, A. M., II. 1999. The ABC's of avoiding bird collisions at communication towers: the next steps. Pages 85–104 in R. G. Carlton, editor. Avian interactions with utility and communication structures. Workshop proceedings. Electric Power Research Institute, Palo Alto, California.

Manville, A. M., II. 2005. Bird strikes and electrocutions at power lines, communication towers, and wind turbines: state of the art and state of the science - next steps toward mitigation. Bird conservation implementation in the Americas. Pages 1051–1064 in C. J. Ralph and T. D. Rich, editors. Proceedings 3rd international Partners in Flight conference 2002. General technical report PSW-GTR-191. U.S. Department of Agriculture Forest Service, Pacific Southwest Research Station, Albany, California.

Manville, A. M., II. 2009. Towers, turbines, power lines, and buildings: steps being taken by the U.S. Fish and Wildlife Service to avoid or minimize take of migratory birds at these structures. Pages 262–272 in T.D. Rich, C. Arizmendi, D. Demarest, and C. Thompson, editors. Tundra to tropics: connecting birds, habitats, and people. Proceedings 4th international Partners in Flight conference. Partners in Flight.

Martin, G. R., and J. M. Shaw. 2010. Bird collisions with power lines: failing to see the way ahead? Biological Conservation **143:**2695–2702.

McNeil, R., J. R. Rodríguez, and H. Ouellet. 1985. Bird mortality at a power transmission line in North Eastern Venezuela. Biological Conservation **31:**153–165.

Morkill, A. E, and S. H. Anderson. 1991. Effectiveness of marking powerlines to reduce sandhill crane collisions. Wildlife Society Bulletin **19:**442–449.

Murphy, R. K., S. M. McPherron, G. D. Wright, and K. L. Serbousek. 2009. Effectiveness of avian collision averters in preventing migratory bird mortality from powerline strikes in the central Platte River, Nebraska. Nebraska Game and Parks Commission, U.S. Fish and Wildlife Service, and University of Nebraska, Kearney.

Neter, J., W. Wasserman, and M. H. Kutner. 1989. Applied linear regression models. 2nd edition. Irwin, Homewood, Illinois.

Onrubia, A., F. J. Purroy, and A. Ubeda. 1996. La eficacia de las señales de visualización sobre colisión y electrocución de aves en tendidos eléctricos de Madrigal de las Altas Torres (Ávila). Pages 265–271 in J. Fernández Gutiérrez and J. Sánz-Zuasti, editors. Conservación de las aves esteparias y su hábitat. Junta de Castilla y León, Valladolid, Spain.

Pelayo, E, and F. J. Sampietro. 1994. Estudio del impacto sobre las aves del tendido eléctrico de alta tensión La Sierna-Peñaflor. Valoración de la eficacia de la señalización con espirales, y aproximación a la incidencia de mortalidad real sobre aves. Sociedad Española de Ornitología/BirdLife and Red Eléctrica de España, Madrid.

Pilo, B., A. Kumar, S. Oommen, and K. R. Vinod. 1994. Anti-bird collision strobe lights: field experiments on Indian birds. 22/WP 8. Bird Strike Committee Europe, Vienna.

Ponce, C., J. C. Alonso, G. Argandoña, A. G. Fernández, and M. Carrasco. 2010. Carcass removal by scavengers and search accuracy affect bird mortality estimates at power lines. Animal Conservation **13:**603–613.

Pullin, A. S., and G. B. Stewart. 2006. Guidelines for systematic review in conservation and environmental management. Conservation Biology **20:**1647–1656.

Rosenberg, M. S., D. C. Adams, and J. Gurevitch. 2000. MetaWin: statistical software for meta-analysis Version 2. Sinauer Associates, Sunderland, Massachusetts.

Rosenthal, R. 1979. The "file drawer problem" and tolerance for null results. Psychological Bulletin **86:**638–641.

Savereno, A. J., L. A. Savereno, R. Boettcher, and S. M. Haig. 1996. Avian behavior and mortality at power lines in coastal South Carolina. Wildlife Society Bulletin **24:**636–648.

Schaub, M., and R. Pradel. 2004. Assessing the relative importance of different sources of mortality from recoveries of marked animals. Ecology **85:**930–938.

Scott R. E., L. J. Roberts, and C. J. Cadbury. 1972. Bird deaths from power lines at Dungeness. British Birds **65:**273–286.

Shaw, J. M. 2009. The end of the line for South Africa's national bird? Modelling power line collision risk for the Blue Crane. MS thesis. University of Cape Town, Cape Town.

Shaw, J. M., A. R. Jenkins, J. J. Smallie, P. G. Ryan. 2010. Modelling power-line collision risk for the Blue Crane *Anthropoides paradiseus* in South Africa. Ibis **152:**590–599

Stake, M. M. 2009. Evaluating diverter effectiveness in reducing avian collisions with distribution lines at San Luis National Wildlife Refuge Complex, Merced County, California. CEC-500-2009-078. Public Interest Energy Research (PIER) Program, Ventana Wildlife Society, and California Energy Commission, Sacramento, California.

Stewart, G. B., C. F. Coles, and A. S Pullin. 2005. Applying evidence-based practice in conservation management: lessons from the first systematic review and dissemination projects. Biological Conservation **126:**270–278.

Stewart, G. B., A. S. Pullin, and C. F. Coles. 2007. Poor evidence-base for assessment of windfarm impacts on birds. Environmental Conservation **34:**1–11.

Stewart, G. 2010. Meta-analysis in applied ecology. Biology Letters **6:**78–81.

Sudman, S. R., coordinator. 2000. Das Anflugverhalten von überwinternden, arktischen Wildgänsen im Bereich von markierten und unmarkierten Hochspannungsfreileitungen am Niederrhein. Naturschutzzentrum im Kreis Kleve e.V. Kranenburg-Nütterden. Sterna, Kranenburg-Nütterden, Germany.

Yee, M. L. 2007. Testing the effectiveness of an avian flight diverter for reducing avian collisions with distribution power lines in the Sacramento Valley, California. CEC-500-2007-122. Public Energy Related Environmental Research Program, California Energy Commission, Sacramento.