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Review

The state of the art in raptor electrocution research: A global review

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ABSTRACT

We systematically reviewed the raptor electrocution literature to evaluate study designs and methods used in raptor electrocution research, mitigation, and monitoring, emphasizing original research published in English. Specifically, we wondered if three decades of effort to reduce raptor electrocutions has had positive effects. The majority of literature examined came from North America, western Europe, and South Africa. In spite of intensive and often sustained effort by industry and governments across three continents for 30 years, reductions in the incidence of electrocution have been demonstrated in only a few studies. Reliable rate estimates of electrocution mortality generally are unavailable, with some exceptions. Nearly half of 110 studies we analyzed in detail were retrospective reviews of historical mortality records, banding data, or results of necropsies on dead birds received at pathology and veterinary facilities. Among prospective studies, less than half used unbiased approaches to sampling and many did not provide enough detail to assess the sampling design used. At this time, few researchers can demonstrate the reliability of standardized retrofitting procedures or the effectiveness of monitoring techniques. Future progress in reducing raptor mortalities on power lines will benefit from properly designed studies that generate rate estimates of mortality, address biasing factors, and include predictions concerning risk and techniques to reduce risk that can be tested in the field or laboratory.

Contents

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1. Introduction

Raptor electrocution on power lines has been the focus of extensive research, product testing, design standards development, and mitigation in the United States since the early 1970s (Boeker and Nickerson, 1975; Nelson and Nelson, 1976; Olendorff et al., 1981). In spite of these efforts, thousands of power line mortalities continue to occur in the U.S. each year (Franson et al., 1995; Melcher and Suazo, 1999; Harness and Wilson, 2001). Electrocution problems cost U.S. energy suppliers billions of dollars annually in power interruptions, lost revenues, repairs to equipment, and statutory compliance (Hunting, 2002). Since 1999, electrocution problems have resulted in negative media attention, increased scrutiny by regulatory agencies, and a landmark court conviction (Melcher and Suazo, 1999; Williams, 2000; Suazo, 2000). Lehman (2001) reviewed agency and industry responses to the problem over a 30-year period, and argued that optimistic projections from the 1970s to the 1990s that elimination of raptor electrocutions was within reach (Nelson and Nelson, 1976; Wildlife Management Institute, 1982; Phillips, 1986; Gauthereaux, (1993) were not credible, and led to misinterpretation of the problem's actual magnitude. Raptor mortalities have persisted because of the sheer number of potentially lethal distribution poles currently in use, and because mitigation programs since the 1980s have tended to be reactive rather than proactive (Avian Power Line Interaction Committee [APLIC], 1996]). Over 185 million wood distribution poles are currently operating in North America (American Iron and Steel Institute, 2005), and all pose some level of risk to raptors (Lehman, 2001). Yet, most utilities have taken an ad hoc approach to mitigation, i.e., retrofitting of poles after they cause mortalities. Treatment of electrocution hazards at landscape or system-wide scales has been the exception, not the rule. Lehman (2001) also emphasized the need for credible estimates of electrocution mortality, retrofitting at increased scales, and for improved sampling methods and greater scientific rigor in assessing and mitigating power line issues. We now return to the latter topic in greater depth, and expand our focus to assess raptor electrocution issues worldwide.

2. Objectives

Recent evidence of large-scale mortality and questions about the reliability of electrocution data in the U.S. led us to wonder what we know about the causes, consequences, and prevention of raptor electrocutions with reasonable certainty. We wondered specifically to what extent rigorous scientific standards have been applied in studies of raptor electrocution inside and outside the U.S., and what evidence may exist to suggest that global efforts to reduce raptor/power line mortality are having positive effects. Thus, in 2004, we began a state-of-the-art review of the raptor electrocution literature worldwide. Our objectives were:

1. Assess what we know about raptor electrocutions, based on corroborated evidence (i.e., establish a scientific baseline).
2. Describe research designs, sampling strategies, and methods of data collection and analysis used in recent and past studies of raptor electrocution.
3. Evaluate the relevance, quality, and scientific rigor of electrocution research and discuss information needs.

3. Methods

3.1. *Search strategy*

We conducted a systematic review of raptor electrocution research following procedures outlined by the Center for Evidence-Based Conservation (Pullin and Stewart, 2006). We began by developing a 4-step a priori review protocol that identified the review's objectives (presented above), search strategies, selection criteria (for capturing relevant studies), and evaluation factors (for assessing research quality). Our strategy was to conduct an exhaustive search of the avian and raptor literature for studies involving the raptor electrocution problem, targeting those that presented mortality data. We searched all citations from an annotated bibliography on raptor power line interactions (Hebert et al., 1995), a recent review of the electrocution literature (Hunting, 2002), and 3 editions of *Suggested Practices for Raptor Protection on Power Lines*, the standard industry manual in the U.S. for lowering electrocution risks (Miller et al., 1975; Olendorff et al., 1981; APLIC, 1996). Initially, we filtered articles by title, source, or annotation (when present), excluding articles from the popular media, anecdotal accounts of one or a few electrocution incidents, papers without data, papers that evaluated impacts of proposed power lines, or that emphasized raptor/power line collisions. We placed retained items in a scan file for future processing.

We also identified relevant studies through internet searches of appropriate data bases, including Web of Science, Current Contents, BIOS Previews, Zoological Record, SCOPUS, BiblioLine, Cambridge Scientific Abstracts, and the Raptor Information System (http://ris.wr.usgs.gov), using the following search terms: raptor electrocution, avian electrocution, raptor mortality, power line mortality, and raptor rehabilitation. We did not conduct foreign language searches in this review; however, we identified studies on a global scale, and included all apparently suitable studies, irrespective of geographic location.

3.2. *Evaluation of studies*

From January 2004 to October 2005, we scanned the contents of articles in the scan file and placed them in an evaluation file if (1) electrocution mortalities of raptors and common ravens (*Corvus corax*) were reported as original data (i.e., were not cited as the work of other researchers); (2) on-the-ground searches for electrocuted birds were conducted (even if none were found); or (3) results of power line nesting and perching studies were used to assess electrocution risk.

To assess the scientific quality of electrocution research, we evaluated and attempted to classify each study that reported electrocution mortalities on the basis of three study design factors: study type (prospective vs. retrospective); sampling design; and sampling method (Tables 1 and 2). If a factor was not specified, and we could not obtain the information from the text of the paper, we classified the factor as unknown. We also evaluated each paper for 10 methods-based factors that have practical importance for assessing mortality, predicting risk, or designing protection strategies when used or applied: (1) clinical necropsies; (2) scavenger removal trials; (3) estimates of mortality rates; (4) large-scale mortality estimates; (5) population abundance or density estimates; (6) documentation of pole use or perch behavior; (7) use of predictive risk models; (8) use of information-theoretic model selection; (9) post-retrofit monitoring; and (10) rate comparisons before and after retrofitting. Proper application or use of these study features may increase accuracy and precision of mortality estimates, improve risk assessments, streamline protection efforts, and generally assure relevant and credible results.

Table 1 – Research design factors used to describe and evaluate studies of raptor electrocution

Factor	Category	Definition	Source
Study type	Prospective	SUs[a] selected before mortalities occur	Schork and Remington (2000)
	Retrospective	SUs selected after mortalities occur	Schork and Remington (2000)
Sampling design[b]	Random	Probability sample; all SUs equally likely to be selected	Morrison et al. (2001)
	Convenience[c]	SUs chosen where likely to occur, where accessible, or when opportunities arise	Anderson (2001)
	Encounter[c,d]	Sampling frame undefined	Thompson et al. (1998)
	Poll[c]	Responses to questionnaire or information request; SUs self-selected	
	Census	All SUs enumerated	Morrison et al. (2001)
	Unknown	Not enough information to assess sampling design	

a SU = sampling unit, defined for this review as a dead bird, a report about a dead bird, or a sampling plot (typically around a power pole but in some studies a nest site).
b Defined as the protocol for obtaining estimates of a parameter of interest for a sampled population (Thompson et al., 1998).
c Nonrandom designs (SU selection probabilities unknown).
d In encounter sampling, the sampling frame (list of available sampling units) is undefined.
For example, in a banding study any bird that enters a trap is banded, but there is no formal selection of sampling units and the number of birds available for trapping is unknown.

Table 2 – Sampling methods and corresponding sampling units from 110 studies on raptor electrocution

Sampling method[a]	Sampling unit	Definition[b]
Mortality search (34)	Sampling plot	Part of established sampling plan. Dead recoveries are a sub-sample (R, CO, CE)
Records review (8)	Mortality report	Review of historical mortality records (R, CO)
Retrospective banding (5)	Band recovery	Review of band recoveries of birds banded by others (E)
Prospective banding (7)	Band recovery	Review of own band recoveries (E)
Pathology survey (19)	Dead recovery	Results of necropsies by pathologists. Birds often from multiple sources (CO, E)
Rehab/reintroduction releases (7)	Dead recovery	Recoveries of rehabilitated or re-introduced birds after release (R, CO, CE)
Falconer survey (3)	Mortality report	Lost falconers' birds. Data often from questionnaires (P)
Veterinary survey (4)	Live recovery	Birds found shocked but alive under power poles (R, CO, CE)
Radio telemetry (8)	Dead recovery	Birds with radio transmitters found dead (R, CO, CE)
Fault monitoring (6)	Line fault	Any service disruption or outage (CO, E)
Incidental encounter (17)	Dead recovery	Recoveries from unrelated chance encounters (CO, CE)

a Numbers of studies that used each method are shown in parentheses. The total is greater than 110 because some studies used more than one method.
b Capital letters in parentheses refer to sampling designs used with corresponding sampling methods: R = random; CE = census; CO = convenience; E = encounter; P = poll.

3.3. *Baseline assessments*

To assess what we know about the causes, consequences, and prevention of raptor electrocutions, we asked three questions posed by Bevanger (1994a): (1) What species are involved? (2) What biological and ecological factors contribute to risk? (3) How does the additional mortality affect populations? Although quantitative data were unavailable for many aspects of the electrocution problem in 1994, Bevanger argued that knowledge of electrocution issues at that time was sufficient to draw conclusions within a "management and public policy context", i.e., to proceed with decision-making and management action. In this review, we looked for conclusions in the literature that were accompanied by supporting data (not merely expressed as opinion or cited from another source), and considered conclusions regarding the 3 questions to be valid only if data from at least one additional, independent source could be found.

4. Results of literature searches

Searches of existing literature reviews, bibliographies, and citations from electronic sources produced >2500 citations on electrocution mortality and avian/power line interactions. Many citations appeared on more than one reference list or addressed topics other than electrocution. These citations were not considered further, leaving approximately 425 articles in the scan file. Of these, most addressed power line topics other than electrocution discussed electrocution issues generally without presenting mortality data, or mentioned our topic only in passing. Ultimately, we retained 110 papers for evaluation of research designs and sampling methods (Appendix A). Of these, 59 articles were from North America, 37 were from Eurasia, 12 were from Africa, 1 was from the Middle East, and 1 was from Australia (Table 3). We found no material from large parts of the world where electrocutions are likely occurring, including Asia, Central America, and South America. The electrocution literature from western Europe was large (>200 titles), but most of it was not published in English. A large body of research from Spain (16 studies), was found in English-language journals, and a considerable volume of work on avian electrocution issues (11 studies) has occurred in South Africa. Nearly half (49) of the studies we examined were from the U.S.; thus, 3 countries accounted for nearly 70% of the literature we evaluated.

5. The scientific baseline: what we know

The raptor electrocution literature points to numerous ecological, physical, and landscape factors that may influence electrocution hazards. Each may operate to varying degrees depending on the species, time, location, or environmental conditions, and the relative importance of each is not always certain.

5.1. *What species are involved?*

Species differences are extremely important in understanding the dynamics of raptor electrocutions. Some species are prone to electrocution because they are large, and can easily span distances between energized or grounded components of power poles, and others are susceptible because they live in areas lacking natural perches (Olendorff et al., 1981; Janss and Ferrer, 1999a). Forest-dwelling raptors (e.g., accipiters) are rarely found in electrocution records because natural perches are abundant in forests (Switzer, 1977; O'Neil, 1988; Harness and Wilson, 2001). Ground-nesting species (harriers and some owls) appear infrequently because they typically hunt while in flight and perch on or near the ground (Pendleton, 1978; Benson, 1981). Kites and the smallest owls generally cannot span the distance between electric conductors, even with outstretched wings (APLIC, 1996).

Thirty-one species of diurnal raptors and 19 owl species regularly breed in North America (Johnsgard, 1988, 1990). Of these, 26 (52%) have been reported as electrocution victims. In the U.S., golden eagles (*Aquila chrysaetos*) are electrocuted more than any other species, accounting for 50–93% of all reported mortalities in some studies (Smith and Murphy, 1972;

Table 3 – Source and study type of 110 studies that presented original research on raptor electrocution

Continent/country	No. of papers[a]		Totals	Years
	Prospective	Retrospective		
North America				
United States	19	30	49	1969–2004
Canada	5	3	8	1978–2005
Mexico	2		2	2000–2003
South Africa	9	2	11	1972–2004
Eurasia				
Spain	14[b]	2	16[b]	1991–2001
United Kingdom	3	1	4	1981–2003
Italy	4	1	5	1994–2005
France	1		1	2004
Germany	1	2	3	1985–2003
Norway	1	1	2	1997–1998
Hungary		1	1	2004
Slovakia		1	1	2004
Bulgaria		1	1	2004
Russia	2		2	2005
Kazakhstan	1		1	2005
Other Countries				
Australia	1		1	1996
Israel		1	1	1984
Sudan		1	1	1985
Totals	63	47	110	

a The number of papers from each source and study type is shown along with the year or range of years papers were published. The 110 papers included 51 from peer-reviewed journals, 5 from regional journals (not peer-reviewed), 6 from conservation organization newsletters, 1 from an industry trade journal, 28 from symposia proceedings, 1 Ph.D. dissertation, 4 Master's theses, 5 book chapters, and 9 unpublished government, industry, and academic reports.
b Includes 1 study from the Canary Islands.

Ansell and Smith, 1980; O'Neil, 1988; Harness and Wilson, 2001).

In South Africa, at least 14 diurnal raptor species and five owl species have been electrocuted on power facilities. Two species – the Cape griffon (*Gyps coprotheres*) and African white-backed vulture (*Gyps africanus*) – have appeared in electrocution records in large numbers since studies began in the early 1970s (Markus, 1972; Ledger and Annegarn, 1981; Krüger, 1999). In Europe, many non-raptorial birds appear in mortality data, and raptors often represent <10% of total mortality (Bayle, 1999). However, proportions exceeding 50% have been reported (Janss and Ferrer, 1999a). At least 30 of 37 raptor and owl species (81%) that breed or winter on the continent have been electrocuted on power lines or killed in wire (conductor) strikes (Bayle, 1999). Raptors most often found below power poles in Europe include the common buzzard (*Buteo buteo*), black kite (*Milvus migrans*), red kite (*Milvus milvus*), and Eurasian kestrel (*Falco tinnunculus*).

5.2. *What factors contribute to electrocution risk?*

Electrocution risk is influenced by multiple factors within a bird's environment that operate at multiple scales (Table 4). At the largest scale are landscape factors that attract raptors or concentrate birds in the vicinity of power lines (Hunting, 2002). These may include vegetation structure and composition, prey density, and perch availability. At the scale of an individual pole are factors that affect its suitability as a perch, e.g., topography and relative pole height. At the smallest scale (the perch itself) are factors that work in concert to cause electrocutions, including pole-top configuration, clearances among electrical components, physical dimensions of raptors, and raptor behavior.

5.2.1. *Morphology*

Size is the most crucial factor affecting electrocution risk in North America and South Africa (Olendorff et al., 1981; APLIC, 1996; Krüger, 1999). Large birds are more vulnerable because the likelihood of spanning electrical components with outstretched wings or other body parts is higher than for small birds. In the U.S., large eagles dominate electrocution records (Boeker and Nickerson, 1975; Benson, 1981; Harness and Wilson, 2001), and in South Africa vultures are common victims (Ledger and Annegarn, 1981; Ledger, 1984; Krüger, 1999). In Europe, size is less important because most poles are constructed of steel or steel-reinforced concrete (Bayle, 1999; Negro, 1999); thus, all birds that use distribution line structures – including families of small birds – are at risk (see next section).

Large size alone, however, cannot account for the high incidence of electrocution in some species. In the U.S., golden eagles reach their highest densities in the shrubsteppe regions of the Intermountain West where natural perches are rare (Harlow and Bloom, 1989). In contrast, the bald eagle (*Haliaeetus leucocephalus*) is similar in size but inherently at lower risk because it is adapted to forested habitats and shorelines where perches often are abundant (Stalmaster, 1987). Like golden eagles in the U.S., the vultures of South

Table 4 – Factors that contribute to electrocution risk in raptors and selected studies that provide supporting data

Source	Pole design	Topography	Habitat	Prey	Season	Weather	Age	Gender	Size	Human dist.[a]	Behavior[b]
Benson (1981)	×	×	×	×	×	×	×		×	×	s, w
Ledger and Annegarn (1981)	×	×	×			×			×		r
Ledger (1984)	×						×		×		r
O'Neil (1988)	×	×	×								
Ferrer et al. (1991)	×		×		×	×					
Ferrer and Hiraldo (1992)							×	×	×		p
Garrett (1993)	×			×							s
Lawson and Wyndham (1993)	×										s
Dawson and Mannan (1994)					×		×	×		×	s
Bevanger and Overskaug (1998)					×		×	×	×		
Janss and Ferrer (1999a)	×		×				×	×	×		
van Rooyen and Ledger (1999)	×										r, p
Janss (2000)									×		p
Harness and Wilson (2001)	×			×	×		×		×		
Janss and Ferrer (2001)	×		×				×				
Mañosa (2001)	×	×	×								
Real et al. (2001)			×						×		
Rubolini et al. (2001)				×			×		×	×	
Marchesi et al. (2002)										×	
Olson (2002)	×						×		×		
Schomburg (2003)	×	×	×				×	×	×		s
Krüger et al. (2004)	×										s, r, p, w
Sergio et al. (2004)	×	×	×		×		×		×	×	
Cartron et al. (2005)	×			×	×				×	×	r

a Human disturbance.
b Behaviors that contribute to electrocution risk: perching (p) and roosting (r) on electric power structures, s = social interactions, and w = wingspreading (to dry wet feathers).

Africa often occur in open habitats lacking natural perches. Thus, vultures routinely perch and roost on power line structures. Cape and African white-backed vultures are also highly gregarious, often gathering on power line structures in large numbers. In these settings, crowding and competition for perches can lead to numerous electrocutions.

5.2.2. *Pole type and configuration*

The most obvious factors contributing to electrocution risk are power line type and configuration of electrical hardware on support structures. In the U.S., nearly all electrocutions occur on comparatively low-voltage distribution lines (<69 kV) supplying residences and other individual users – as opposed to transmission lines which transmit electricity at higher loads (Olendorff et al., 1981; APLIC, 1996). Before 1971, these lines typically were designed with narrow clearances between energized components, and few if any of the components were insulated. In addition, most U.S. distribution poles and crossarms are made of wood, a nonconductive material. On these structures, two points of contact with energized or grounded hardware are needed for electrocution to occur. Poles with transformers or other auxiliary equipment (fused cutouts, capacitors, reclosers, jumper wires) are more hazardous than the simplest structures because the additional hardware increases the number of energized components and reduces their spatial separation (Olendorff et al., 1981; APLIC, 1996; Harness and Wilson, 2001).

Most electrocutions in South Africa (up to 95%) occur on 4 types of power line structures: 22-kV wooden T-structures, 88-kV steel kite transmission towers, terminal H-frame wood structures, and Delta suspension structures (Krüger, 1999). T-structures and terminal H-Frames kill a broad array of taxa, including *Gyps*, *Polemaetus*, *Aquila*, *Buteo*, *Circaetus*, *Falco*, and *Bubo* spp. The kite and Delta suspension structures kill mostly very large species – Cape griffons, African white-backed vultures, and martial eagles (*Polemaetus bellicosis*).

In Europe, nearly all utility structures, including crossarms, are constructed of steel or steel-reinforced concrete and are conductive and grounded by design (Bayle, 1999; Janss, 2000). A bird perched on a crossarm can be killed by making just one contact with a conductor (Janss and Ferrer, 1999b); consequently, mortality levels can be extremely high. Adamec (2004) reported annual mortalities exceeding 10,000 birds in the Slovak Republic. Given such losses, Bayle (1999) suggested the only reliable solution is to place virtually all medium-voltage power lines on the continent underground. The idea has been taken seriously, and Belgium, the United Kingdom, and Germany, are working toward that goal. In the Netherlands, the process has been completed.

5.2.3. *Topography*

Raptors use power poles as hunting perches, a key factor in analyzing electrocution problems (Benson, 1981; APLIC, 1996). During the 1970s, researchers in the United States noted that raptors often perched on poles that were more elevated above the surrounding terrain and provided a wider field of view than adjacent poles (Boeker and Nickerson, 1975; Nelson and Nelson, 1976). Benson (1981) confirmed that poles providing the greatest height advantage above the terrain, i.e., those on bluffs and knolls, had the highest rates of electrocution. Multiple electrocutions can occur on these "preferred" poles – up to 8 have been recorded at single structures (Benton and Dickinson, 1966; Nelson and Nelson, 1976).

5.2.4. *Season and weather*

Some studies have reported seasonal variation in electrocutions and attributed increased mortality during certain periods to weather, nesting activity, and other similar factors. Benson (1981) estimated that 80% of golden eagle mortalities in 6 western states were winter losses. In contrast, 75% of non-eagle mortalities occurred during the nesting period. Harness and Wilson (2001) reported similar results in a study of industry mortality records from the western U.S. during a 10-year period (1986–1996).

Feather wetting during inclement weather (rain, snow) is extremely important to electrocution risk. Nelson (1979, 1980) conducted non-lethal conductivity studies with a live golden eagle and concluded that contacts between wet feathers and conductors were 10 times more likely to cause an electrocution than contacts involving dry feathers. However, skin-to-skin contacts (e.g., at the wrists, the leading edge of ventral wing surfaces) were even more dangerous than contacts involving wet feathers.

Direction of the prevailing wind relative to the crossarm also may contribute to raptor electrocutions. Nelson and Nelson (1976) suspected that poles with crossarms perpendicular to the prevailing winds produced fewer eagle mortalities than those with crossarms diagonal or parallel to the wind, because of difficulties associated with crosswind take-offs and landings. Subsequently, Benson (1981) found about half as many birds below poles with perpendicular crossarms compared to those with parallel crossarms.

Late summer increases in hawk electrocutions may result from seasonal population increases during fledging and post-fledging periods of reproduction (Harness and Wilson, 2001); however, higher risk during the nesting period may also be related to behaviors that acutely increase hazards. Raptors often link talon-to-talon during courtship and nest defense, greatly increasing their effective wingspans – and the danger – near power lines (Dickerman, 2003). Mortalities have also been reported for adults returning to the nest, when prey or nesting material dangling from the feet spanned gaps between conductors, and for nestlings, when nesting material lying across conductors caught fire and killed young that could not escape (Hardy, 1970; Gillard, 1977; Switzer, 1977; Vanderburgh, 1993).

5.2.5. *Age and gender*

Most golden eagles electrocuted on power lines in North America (>90% in some studies) are immature or subadult birds (Boeker and Nickerson, 1975; Benson, 1981). Susceptibility of immature golden eagles to electrocution involves several factors, but none is more important than flying and hunting experience. Inexperienced birds are less adept at landings and take-offs, and thus are at greater risk. Elevated risk for young birds was also discussed by Dawson and Mannan (1994) for Harris' hawks (*Parabuteo unicinctus*), and by Fitzner (1978) for Swainson's hawks (*Buteo swainsoni*). Ferrer and Hiraldo (1992) observed age and gender influences in the Spanish imperial eagle (*Aquila adalberti*): 88% of all deaths were immature birds and 78% were females. The high mortality rate in females was attributed to their larger size.

5.3. *What are the effects on populations?*

For most raptor species there is no scientific documentation that electrocution mortality has contributed to population declines. The demographic data needed for advanced risk analysis, as outlined by Akcakaya (1993), or to assess if electrocution mortality is additive or compensatory, is unavailable for nearly all species. Generally, avian power line mortality is not high enough to affect long-term population size (Bevanger, 1994a, 1998). However, shooting, poisoning, trapping, collision with human-made objects, exposure to environmental contaminants, and electrocution all take their toll. At some point, a population may begin to decline because human-caused mortality has become additive and more than the population can sustain. A conservative approach to these problems is to reduce human-caused mortality whenever possible, particularly in those species known or suspected to be threatened.

Some studies have pointed to electrocution as the primary cause of raptor population declines. In South Africa, the Cape griffon is electrocuted more than any other raptor species and is considered threatened (Ledger, 1980; Krüger, 1999). Nikolaus (1984) suggested that electrocutions were responsible for Egyptian vulture (*Neophron pernopterus*) declines near Khartoum, in the Sudan, and griffon vultures (*Gyps fulvus*) in Israel have declined possibly due to electrocution and other human-caused factors (Lesham, 1985). Electrocution is probably the main cause of declines in Bonelli's eagle (*Hieraaetus fasciatus*) in Spain and France (Real et al., 1996; Real and Mañosa, 1997), and in the Eurasian eagle owl (*Bubo bubo*) in France (Bayle, 1999) and Italy (Rubolini et al., 2001). According to the European Union's action plan for Bonelli's eagle, reduction of electrocution mortality is likely to be critical to the survival of the species (Arroyo and Ferreiro, 1999). Resolving electrocution issues has been critical to the survival of the Spanish imperial eagle, one of the most endangered raptors in the world (Janss and Ferrer, 1999a).

6. Information needs: what we do not know

Other basic questions about raptor electrocutions, including some that are essential to mitigation efforts, remain open to debate because the data needed to address them are limited, not available, or do not exist. How many birds are electrocuted? What proportion of electrocution mortality is actually detected? What monitoring techniques are best for estimating electrocution rates? Can electrocution risk be predicted? How many poles are actually killing birds? Are current retrofitting practices reducing electrocution mortality? The technical issues that have prevented a fuller response to these questions can be categorized into three areas: (1) inadequate data collection and analysis; (2) lack of tested models to guide risk assessment and reduction; and (3) failure to publish results.

6.1. *Lack of systematic data collection and analysis*

Bevanger (1999) stressed the need for sound scientific methods in assessing avian/power line mortalities and the importance of study design in linking the objectives of a study with appropriate methods. Below we summarize study designs and methods used in raptor studies throughout the world, and assess the overall quality and relevance of electrocution research.

6.1.1. *Study type and sampling design*

The methods used to select a sample of the population for observation and to collect data from the sample are important (Thompson et al., 1998). For our purposes, we recognized two basic types of studies: prospective and retrospective; and five sampling designs – random, convenience, and encounter sampling; polls; and censuses (Table 1).

A prospective study is one in which birds or other sampling units are selected for study before mortalities occur (Schork and Remington, 2000). In contrast, birds used in retrospective studies are included because they are dead. When biologists search for dead birds below pre-selected power poles, or conduct radio telemetry or marking studies to assess survival and mortality of individuals, the studies are prospective. A researcher evaluating mortality records provided by industry or government sources, or evaluating banding data for a given time period or species, is doing retrospective work. Advantages of prospective studies are (1) cause of death can be determined by direct observation, e.g., by tracking a radio signal to a dead bird; and (2) the researcher can control potential biases by imposing rigorous protocols during data collection (e.g., by stratifying among factors that vary in distinct ways). In retrospective studies, there is little possibility of corroborating information provided about an event that occurred perhaps months or years before the study, and nothing can be done to eliminate bias introduced at the time data were collected.

In spite of the advantages of prospective work, in the United States retrospective studies have dominated research on raptor mortality (Table 3). Fourteen of 49 U.S. studies from 1969 to 2004 were retrospective surveys of dead birds provided to wildlife pathologists (e.g., Franson and Little, 1996; Deem et al., 1998), and 16 were retrospective reviews of banding data or mortality reports from utility companies and regulatory agencies (e.g., Boeker and Nickerson, 1975; O'Neil, 1988; Suazo, 2000). Thus, only 19 (39%) of 49 electrocution studies in the U.S. since 1969 were prospective. In contrast, 9 of 11 studies in South Africa and 14 of 16 studies in Spain were prospective.

Many studies on raptor electrocution (retrospective and prospective) have relied on opportunistic or chance encounters with dead birds (e.g., by utility crews or consumers) as the primary approach to sampling, or on mortality searches conducted only along roads or only where mortality was known to be high (e.g., Boeker and Nickerson, 1975; Nikolaus, 1984; O'Neil, 1988). Anderson (2001) referred to these approaches as "convenience sampling" and discussed the flaws associated with their use. First, convenience sampling does not allow formal inductive inference from sample to population because the assumption that the sample is representative of the population is not tested. Second, convenience sampling provides no valid basis for estimating precision in the parameters measured (e.g., using standard errors and confidence intervals).

Table 5 – Sampling designs used in 110 studies on raptor electrocution

Sampling design	United States	South Africa	Spain	Other countries	Totals
Convenience	13	6	1	10	30
Encounter	20	0	4	12	36
Poll	3	1	2	2	8
Random	3	0	0	2	5
Census	9	4	4	7	24
Not specified[a]	1	1	8	2	12
Totals	49	12	19	35	115[b]

a Sampling design not specified by the researchers and not enough information provided to make a determination.
b Total >110 because several studies used more than one sampling design.

Recommended approaches to sampling usually involve selection of sampling units in a probabilistic manner – i.e., randomly – so that each unit in the population has an equal probability of being selected (Morrison et al., 2001). In the case of raptor electrocutions, randomization assures accuracy in estimates of mortality (e.g., numbers of birds killed, numbers of poles involved in electrocutions), and permits inferences to be made about sampling units that were not selected for study. If a census is conducted – i.e., all sampling units are selected – concerns about biased samples are not relevant (because there is no sample) and no inference is necessary (because nothing is being estimated). Yet, only 24 studies worldwide indicated that a census (typically a census of poles) was done, and only 5 studies specifically identified the sampling design as random (Benson, 1981; Csermely and Corona, 1994; Millsap et al., 2004; Dwyer, 2004; Platt, 2005). Thus, only one-quarter of the studies we examined (and less than half of prospective studies) employed unbiased survey methods (Table 5).

6.1.2. *Sampling methods*

We identified 11 distinct methods used to find dead birds or obtain information about electrocution victims (Table 2). Searches for dead birds below poles were done in 34 studies, in many cases at a pre-selected set of poles (timing, frequency of searches, search modes, and plot size varied among studies, however). Seventeen studies relied on data from incidental encounters with dead birds (i.e., were not based on pre-selected pole samples), and necropsies by wildlife pathologists were the basis for 19 mortality studies. Radio telemetry was used in 8 studies to track and assess survival of small numbers of live birds caught as free-flying adults or instrumented as nestlings. Sampling methods described in the literature also included banding studies (retrospective and prospective), review of historical mortality records from industry or government files, and tracking of live birds after their release from rehabilitation or captive breeding facilities. Some studies were based on questionnaires (we defined these as polls), and 6 studies relied on fault monitoring (Table 2).

6.1.3. *Assessing cause of death by necropsy*

Errors in assigning cause of death may have serious effects on the accuracy of electrocution mortality estimates. Ellis et al. (1969) and Olson (2002) found that most dead birds below power lines were victims of shooting, not electrocution, and Kroodsma (1978) determined that most bald eagles classified as collision victims in a study in the western U.S. had been electrocuted. In 110 studies evaluated for this review, only 35 reported that clinical necropsies by wildlife or veterinary pathologists were performed (27 from North America; 8 from western Europe) (Table 6). In 5 studies, researchers assumed that dead birds found below poles had been electrocuted, and those found between poles had collided with conductors. In 18 studies, carcasses were visually inspected for signs of burns or other trauma. Forty-two studies provided no information on how cause of death was assigned; cause of death was not relevant in 3 studies (because no mortalities were reported); and in 7 studies there was no attempt to distinguish among mortality factors (i.e., all mortalities were included in analyses).

6.1.4. *Scavenging rates*

Bevanger (1999) identified four sources of bias likely to affect power line mortality estimates: search, habitat, crippling, and scavenger removal bias. Search and habitat bias are considered to be relatively unimportant in electrocution studies, because electrocuted birds below poles, in principle, are recoverable and power poles typically are in accessible areas (Bevanger, 1999; Janss and Ferrer, 1999a). The extent of crippling bias in electrocution studies is not well understood (Bevanger, 1999; Janss and Ferrer, 1999a); however, Haas (1993) reported 42 electrocution victims among 236 injured raptors brought to a German rehabilitation facility from 1984 to 1988, and Dwyer (2004) trapped 15 live Harris' hawks at nests in the southwestern U.S. that had healed or partially healed injuries consistent with severe electric shock (e.g., missing or charred body parts). These hawks represented 10% of all electrocutions confirmed during the study.

Scavenger removal bias refers to carcasses removed by predators or scavengers between searches (Bevanger, 1999). Considerable evidence from wind energy studies (e.g., Kerlinger et al., 1999; Erickson et al., 2000; Osborn et al., 2000) indicates that losses of this type may bias mortality estimates; yet, only 6 of 110 studies involving raptor electrocutions conducted scavenger removal trials to estimate scavenging rates: 2 from western Europe (Ferrer et al., 1991; Janss and Ferrer, 1999a), 2 from the U.S. (Orloff and Flannery, 1993; Dwyer, 2004), 1 from Canada (Platt, 2005), and 1 from Mexico (Cartron et al., 2005). Dwyer (2004) estimated that 1 of every 3 electrocutions was undetected during his study due to scavenging and to electric shocks that did not kill birds.

6.1.5. *Estimating mortality as a rate*

Rate estimates of mortality (deaths/unit area/unit time) permit comparison of electrocution data across sampling sites, habitats, pole types, and years (Bevanger, 1999). Rate estimates also make it possible to draw valid inferences about mortality at the population level from sampling data, to extend estimates beyond the sampled population (see next section), and to compare results among independent studies. Estimating mortality as a rate requires some form of periodic, standardized sampling (e.g., monthly counts of dead birds), and a count of the number of poles surveyed. Expressing mortality as a function of pole number and time (deaths/pole/year) allows the estimate to compensate for variable pole counts in linear samples of the same length.

Less than one-third of the studies we reviewed involved on-the-ground searches for dead birds (Table 2), and only 16 of these reported electrocution mortality as a rate (Table 6). Rate estimates were reported variously as deaths per pole, deaths per km, or deaths per month or year. Only 6 studies reported rate estimates as a function of time and spatial scale.

6.1.6. *Estimating large-scale mortality*

In most regions of the world, the true magnitude of the raptor electrocution problem has remained an open question because few studies have examined the problem at large spatial scales. Estimates of mortality at large scales require a representative sample of poles (stratified if necessary to accommodate landscape heterogeneity), repeated mortality

Table 6 – Methods-based factors used to assess relevance and scientific validity of the electrocution literature and the number of studies (*n* = 65) that applied or used these methods

Evaluation factor	United States	South Africa	Spain	Other countries	Totals[a]
Necropsies	24	0	1	10	35
Scavenging effects	2	0	2	2	6
Mortality rate estimates	5	2	5	4	16
Large-scale mortality	1	0	2	4	7
Population abundance	3	1	3	3	10
Perch studies	7	5	4	2	18
Predictive models	1	0	2	1	4
Model selection procedures	1	0	0	0	1
Post-retrofit monitoring	5	2	2	2	11
Mortality rate reduction	4	0	2	1	7

a Thirty-seven studies used or applied one method; 18 applied two; 4 applied three; 3 applied four; 1 (Dwyer, 2004) applied five; 1 (Platt, 2005) applied 6; and 1 (Janss and Ferrer, 1999a) applied 7. None of these methods were used in its studies.

searches at those poles for a specified time (e.g., each month for one year), and a measure of scavenging effects. This allows the researcher to generate corrected rate estimates of mortality for all primary habitats and pole types, which can then be used to estimate mortality within areas not sampled.

Seven of 110 studies used adjusted values from sampling areas to estimate mortality at the population level or for an entire study area (Table 6): e.g., Ferrer et al. (1991) and Janss and Ferrer (1999a) estimated total mortality for Doñana National Park in southwestern Spain; and Orloff and Flannery (1993) estimated mortality for a wind energy site in the U.S. In the Doñana studies, rate estimates were calculated separately for major habitat types and pole designs.

6.1.7. *Population abundance*

Understanding the effects of electrocutions on a population or species, its significance relative to other mortality factors, and interpreting altered mortality levels after retrofitting requires a measure of population abundance. Without information on bird numbers, a post-mitigation decrease in mortality, for example, could be attributed to pole modifications, when in fact it is the result of a population decline.

Estimates of population abundance were obtained in 10 electrocution studies (Table 6). In most cases, an index of abundance (or relative abundance) was measured as an unadjusted count of individuals or percent of all birds observed during road or power line surveys, often categorized by species. In an index count, the number of birds detected within a defined or unbounded area around a point or transect is totaled and that total becomes the measure of abundance for that site.

Index methods require critical assumptions concerning detection probabilities that are nearly impossible to meet in most field studies (Anderson, 2001). The main assumption is that measures of relative abundance are related to actual abundance. For this assumption to be true, one must assume that probability of detection is equal for all comparisons. However, numerous factors affect detection probabilities, including environmental factors (weather, topography, vegetation); factors related to the observer (training, eyesight, hearing ability, motivation level, fatigue); and those relating to the target species (gender, age, physiological status) to name a few. Thus, the index is partially a function of abundance, but it is also influenced by a long list of variables that vary both spatially and temporally and are not in the researcher's control. These variables may have confounding affects on detectability and the reliability of index values. No electrocution studies have incorporated abundance data adjusted for detectabilities using techniques such as distance sampling (Buckland et al., 2001) or double observers (Nichols et al., 2000).

6.2. *Lack of tested methods for risk assessment and reduction*

Most utilities lack tested methods for assessing electrocution risks at scales large enough to justify extensive, proactive retrofitting. In spite of 30 years of research and development, industry's focus has remained, generally, on ad hoc (per pole) approaches to mitigation. Thus, we still think in terms of how to fix individual poles, not how to repair whole systems (Lehman, 2001). Some tools for planning and executing large-scale operations are available, however, and others are being developed.

6.2.1. *Perch studies*

A primary goal of any retrofitting program is to identify and correct the subset of poles that are likely to be used by raptors, and because of design considerations, likely to cause electrocutions when used. Properly designed studies of pole use and perch behavior can contribute to risk assessments in a number of ways. Perch studies can be used to determine raptor distribution in a defined area (e.g., a utility's service area), and can aid in identifying variables for risk modeling (next section), refining retrofitting standards, or designing new poles. Combined with mortality searches, perch studies represent a direct approach for targeting areas and poles for retrofitting. Combined with necropsy data, perch studies can be used to reconstruct how electrocutions occurred in considerable detail.

We found three general classes of pole use studies in the electrocution literature: perch surveys, pole inventories, and behavioral studies. Perch surveys typically involved searches for perched birds along a standardized route. During surveys, encounters with perched raptors were recorded, along with information about the habitat, pole, perch, and the bird itself (e.g., Keough et al., 2001; Olson, 2002; Pearson et al., 2002). Pole inventories, or pole censuses (if all poles in a population were checked), focused on evidence of raptor use (whitewash on the pole or ground, presence of prey remains) to identify potential problems. For example, Harness (2000) conducted pole censuses at a developed oil and gas field in the western U.S to identify specific poles and pole types for retrofitting and to establish a prioritized schedule for implementing pole modifications.

Sarria (1999) and Krüger and van Rooyen (2000) used risk management methods (Valsimakis et al., 1992) to identify hazardous poles and make recommendations for retrofitting across large areas in Spain and South Africa. Risk management requires up to four assessment phases: risk identification, evaluation, control, and financing. Sarria (1999) completed the first two steps in an assessment for Garraf Natural Park in southeastern Spain. To identify risks related to pylon structure, he assigned all pylons in the park to a risk category (very high, high, or moderate) based on structural classifications provided by Ferrer (1996). To evaluate risks, he checked all pylons on the ground and rated each according to topography, vegetation, and location relative to known raptor home ranges. The approach allowed for an initial assessment giving a general indication of power line risks, without the need for field inspections, and a refined assessment for prioritizing retrofitting needs, requiring field inspections. Krüger and van Rooyen (2000) identified retrofitting needs for a South African electrification project near the border of Botswana. They completed all required phases of a risk management assessment, and recommended retrofitting of all 6830 structures on the system. Both studies illustrate how per pole responses can be replaced by a structured, pro-active program to avoid most mortalities before they occur.

Behavioral studies can also be important tools in risk assessments and can be done in a variety of settings – in the field using trained raptors (e.g., Nelson and Nelson, 1976); or in flight enclosures with mock-up power poles (Harness, 2002). In enclosures, raptor behavior can be observed closely in a controlled setting. However, several studies of this type went further and sought to replicate experimental results (obtained in enclosures) in the field (Janss and Ferrer, 1999a,b). Unfortunately, perch and pole studies have not been prominent in raptor electrocution research. Only 18 studies worldwide made an attempt to characterize poles, perch dynamics, and/or perch behavior (Table 6).

6.2.2. *Predictive modeling*

Perch surveys and pole inventories provide a valid basis for identifying poles for retrofitting but require inspections on the ground to identify poles that show evidence of raptor use or have caused mortalities. These methods are not predictive, i.e., they do not attempt to classify poles for which no use or mortality data exist.

Predictive models are used in electrocution research to identify poles within a defined area that are likely to be used as perches and may cause electrocutions if used. Pole identification is based on physical or biological factors selected by the researcher that serve as predictors of a pole's future status as a perch or mortality pole. Predictors (independent variables) can be selected on the basis of previous knowledge or on a given set of cases for which the values of the predictors and response (dependent) variables have been measured. The response variables can be continuous (number of perch events or mortalities per pole) or categorical (e.g., mortality pole, perch pole).

Mañosa (2001) developed predictive models to identify hazardous poles in northeastern Spain based on data from a sample of 500 distribution poles. Six environmental variables (habitat type, topographic placement, pole function, grounding features, conductor arrangement, and insulator type), a bird abundance score (low, medium, high), and presence or absence of electrocuted birds were included in several combinations in five a priori models. The model that incorporated all environmental variables, the bird abundance score, and one line inspection to search for dead birds, correctly selected 78% of poles that later killed birds and rejected 72% of poles where no mortalities were observed.

In Montana (in the western U.S.), Schomburg (2003) explored a priori and post hoc prediction models for their ability to explain patterns of mortality and to discriminate between offending and non-offending poles. A priori models were composed of combinations of variables representing risk mechanisms. A model with variables describing power pole characteristics, habitat features, and social interactions among eagles was selected as the best a priori model. Post hoc models of three types – multiple logistic regression, classification and regression tree (CART), and hybrids of the two techniques – were then developed using 60% of the Montana data. The remaining data were used to validate model predictions. Hybrid models were most accurate in classifying power poles as offending or non-offending, followed by CART models (74% vs. 70% classified correctly). A final CART model using all data from Montana was validated independently in a second study area in an adjacent state. At that study site, >77% of known mortality poles were correctly classified.

6.2.3. *Model selection procedures*

Null-hypothesis testing has dominated statistical inference in the wildlife sciences for several decades, but in recent years has come under serious criticism (Cherry, 1998; Johnson, 1999; Anderson et al., 2000). The primary issues associated with the tradition are that it is overused, often misused, and is comparatively uninformative. Null hypothesis testing also has limited application in predictive modeling (Burnham and Anderson, 2001).

In contrast, information-theoretic methods of analysis are well suited to the problems of model building, and in recent years have been widely used in the wildlife sciences. With these approaches, a priori sets of models that may explain observed data are developed and models are then ranked in importance from "best to worst," using model selection procedures such as Akaike's Information Criteria (AIC). This approach has a deep foundation in information theory, and when used with caution (see Guthery et al., 2005), can provide a powerful tool for generating predictive models (Burnham and Anderson, 2001). To our knowledge, only Schomburg (2003) used model selection procedures in an electrocution study.

6.2.4. *Post-retrofit monitoring and reductions in mortality*

An important step after retrofitting is to monitor retrofitted poles or a sample of those poles to assess if structures used as perches and associated with mortalities were accurately identified, and if pole modifications prevented or reduced mortalities. Hunting (2002) argued that effectiveness of retrofitting procedures has not been validated in many parts of the world because post-retrofit monitoring often is not done, or when monitoring does occur, data are not published or otherwise shared with the industry at large (see next section).

In the U.S., we know of only 5 studies in which monitoring occurred after a retrofitting effort (Table 6). Mortality was reduced as a result of retrofitting in 4 of these studies. Benson (1981) monitored 4 power line segments retrofitted during a study in the western U.S. Pole modifications included installation of new crossarms, and raising of the center conductor to achieve 1.52-m spacing between conductors (the minimum recommended by APLIC (1996)). No mortalities were found along these segments during several post-retrofit surveys. In another U.S. study, installation of perch guards and artificial perches did not lower mortality, but lowering crossarms and installing taller poles (again to achieve 1.52-m conductor spacing) achieved a 75% reduction in mortality (Garrett, 1993). In contrast, Harness and Garrett (1999) concluded that perch guards on a 3-phase distribution line at a second study site were effective in preventing electrocutions, but probably *caused* electrocutions at a third site by forcing eagles to perch on adjacent crossarms where spacing between electrical components was inadequate (Harness, 2000). Dwyer (2004) documented a 74% decrease in Harris' hawk electrocutions in the southwestern U.S. after the local utility installed bushing covers on all transformer poles standing near occupied Harris' hawk nests.

Outside the U.S., 6 studies conducted post-retrofit monitoring, and 2 (Janss and Ferrer, 1999a,b) compared rate estimates before and after retrofitting. In both studies, a number of perch deterrents and insulation techniques were tested with live birds on enclosed mock-up steel pylons, and were also tested at a field study site. Several perch deterrents did not lower mortality rates, but all insulation techniques resulted in fewer electrocutions. Janss and Ferrer (1999a) also assessed the effects of power line modifications done in the early 1990s in Doñana National Park to reduce mortality of Spanish imperial eagles. Most dangerous power lines in the park were placed underground after Ferrer and Hiraldo (1991) predicted likely increases in survival of juvenile imperial eagles if power line risks were eliminated. Electrocution rates reported in 1999 for the imperial eagle were four times lower than those reported by Ferrer et al. (1991).

In South Africa, alternate perches were installed on 88-kV kite transmission towers to reduce Cape griffon mortality (Ledger, 1984). Also, insulation was installed on conductors of a 1-phase 22-kV power line to reduce eagle mortality (Krüger et al., 2004). In the first case, short term monitoring indicated the new perches had reduced mortality. However, many dead vultures were found under the same lines 15 years later. Mortality along the 22-kV line initially fell, but later some vultures attacked and ripped apart materials used for insulation. Ultimately, South African researchers began looking for new approaches to managing electrocutions on these poles.

Finally, Lesham (1985) reported that alternate perches installed on poles in Israel to prevent griffon vulture electrocutions failed to lower mortality. But Vincze (2000); cited by Bagyura et al. (2004), demonstrated the effectiveness of cross arm covers for steel pylons in Hungary by tracking declines in fault rates along a retrofitted 20-kV distribution line.

Thus, retrofitting procedures have been subjected to systematic follow-up work in proportionately few studies, and results were mixed. In Doñana National Park, the decline of a critically endangered species may have been halted by effective management of electrocution risks, and modifications to steel structures in Hungary reduced electrocution mortality. In contrast, efforts in other parts of the world sometimes have produced disappointing or ambiguous results.

6.3. *Failure to publish results*

Sharing of information on the effectiveness of retrofitting programs could streamline efforts to resolve raptor/power line problems and reduce duplication of effort. Yet, relatively few studies of raptor electrocutions have been published in the professional literature. Of over 225 citations contained in the 2nd edition of *Suggested Practices for Raptor Protection on Power Lines* (Olendorff et al., 1981), only 31 were from peer-reviewed journals. Of these, only 12 papers presented raptor electrocution data for the first time. In the 3rd edition of *Suggested Practices* (APLIC, 1996), only 32 of 160 new citations were from the peer-reviewed literature, and just 11 of these papers presented new mortality data. The rest of the literature cited in these volumes addressed electrocution issues generally without presenting new data, presented anecdotal accounts of one or a few electrocutions, emphasized the use of power line structures for nesting and perching, focused on raptor collisions with power lines, or addressed potential impacts of proposed power lines.

Other writers have commented on the need for better dissemination of electrocution data. Negro (1999) recommended that researchers publish in well-distributed scientific journals and observed that much worthwhile data are hidden in internal reports and local journals, or are published in languages other than English. Bevanger (1994b) included a discussion of the avian/power line literature, calling it “comprehensive” but not “easily accessible”. Janss and Ferrer (1999a) wondered why more work on the topic was not published.

7. Conclusions

In 2006, we know a great deal about the raptor electrocution problem. The basic causes of raptor electrocution from engineering and design standpoints are well understood, and the factors that pre-dispose raptors as a group, and certain species, populations, and age classes, have been explored in depth. We know that many factors increase risk, some acutely, and others increase duration and frequency of risk exposure. We have some appreciation of the factors that influence pole selection, and we know how environmental conditions such as wind, rain, and topography influence electrocution hazards. It is clear that regional differences in pole and tower design can be considerable, and can affect risk levels of whole populations and communities.

However, with a few notable exceptions, we cannot say with certainty that the incidence of electrocutions has fallen since mitigation programs began in the 1970s. Reliable estimates of electrocution mortality, including numbers of birds killed and rate estimates for different habitats and pole designs, are unavailable for most areas of the world. Many data that are available for analysis or are already published are almost certainly biased, but to unknown degrees. Predictive models for identifying pole use by raptors and for ranking risk levels at poles are being developed, but at this time most researchers cannot conclusively demonstrate the reliability of their sampling procedures or the effectiveness of mitigation programs.

On a positive note, there is evidence that the quality of electrocution research is improving. Spanish researchers, in particular, are conducting cutting-edge work on electrocution issues, and are presenting their results to a wide audience by publishing in English-language journals. Recent work in the United States and South Africa also has shown more attention to study design issues and the overall reliability and relevance of the work being done. Given continuing improvements to study design and the development of mitigation strategies that treat large areas or whole systems, as opposed to the ad hoc strategies of the past, we believe that the raptor electrocution problem can be significantly reduced over the long term. Future progress will require prospective studies that generate rate estimates of mortality, address biasing factors, and include predictions concerning risk and techniques to reduce risk that can be tested in the field or laboratory.

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Appendix A. Supplementary data

List of 110 studies used to evaluate the global raptor electrocution literature. Citations include country of origin, author, and year. Full citations for these articles can be found in the online version at doi:10.1016/j.biocon.2006.09.015.

Country and source
United States
Stewart (1969)
Coon et al. (1970)
Mulhern et al. (1970)
Belisle et al. (1972)
Smith and Murphy (1972)
Reidinger and Crabtree (1974)
Beecham and Kochert (1975)
Boeker and Nickerson (1975)
Cromartie et al. (1975)
Prouty et al. (1977)
Ansell and Smith (1980)
Kaiser et al. (1980)
Peacock (1980)
Benson (1981)
Chindgren (1981)
Reichel et al. (1984)
National Wildlife Health Lab (1985)
Phillips (1986)
Whaley (1986)
Poole and Agler (1987)
O'Neil (1988)
Estep (1989)
Wood et al. (1990)
Cline (1992)
Garrett (1993)
Orloff and Flannery (1993)
Dawson and Mannan 1994
Franson et al. (1995)
Tishendorf et al. (1995)
Franson and Little (1996)
Franson et al. (1996)
Deem et al. (1998)
Harness and Wilson (1998)
Harmata et al. (1999)
Harness and Garrett (1999)
Hunt et al. (1999)
Harness (2000)
Suazo (2000)

Appendix A – *continued*

Country and source
Harmata et al. (2001)
Harness and Wilson (2001)
Keough et al. (2001)
Olson (2002)
Pearson et al. (2002)
Wendell et al. (2002)
Liguori (2003)
Schomburg (2003)
Dwyer (2004)
Harness (2004)
Millsap et al. (2004)
South Africa
Markus (1972)
Ledger and Annegarn (1981)
Ledger (1984)
Bossoff and Basson (1993)
Lawson and Wyndham (1993)
Ledger et al. (1993)
Krüger (1999)
van Rooyen and Ledger (1999)
Krüger and van Rooyen (2000)
van Rooyen and Taylor (2002)
Krüger et al. (2004)
Spain
Ferrer et al. (1991)
Ferrer and Hiraldo (1991)
Ferrer and Hiraldo (1992)
Martínez et al. (1992)
Real et al. (1996)
Real and Mañosa (1997)
Janss and Ferrer (1999a)
Janss and Ferrer (1999b)
Sarria (1999)
Fajardo et al. (2000)
Janss (2000)
Janss and Ferrer (2001)
Mañosa (2001)
Real and Mañosa (2001)
Real et al. (2001)
Donazar et al. (2002)
Other countries
Houston (1978) (Canada)
Kenward (1981) (UK)
Stocek (1981) (Canada)
Nikolaus (1984) (Sudan)
Lesham (1985) (Israel)
Radler and Bergerhausen (1985) (Germany)
Larsen et al. (1987) (Norway)
Kerlinger and Lein (1988) (Canada)
Haas (1993) (Germany)
Houston and Francis (1993) (Canada)
Csermely and Corona (1994) (Italy)
Hess (1996) (Australasia)
Curtis (1997) (Canada)
Newton et al. (1997) (UK)

(*continued on next page*)

Appendix A – *continued*

Country and source
Bevanger and Overskaug (1998) (Norway)
Houston et al. (1998) (Canada)
Evans et al. (1999) (UK)
Cartron et al. (2000) (Mexico)
Rubolini et al. (2001) (Italy)
Marchesi et al. (2002) (Italy)
Krone et al. (2003) (Germany)
Meek et al. (2003) (UK)
Wayland et al. (2003) (Canada)
Adamec (2004) (Slovakia)
Bagyura et al. (2004) (Hungary)
Sergio et al. (2004) (Italy)
Stoychev and Karafeizov (2004) (Bulgaria)
Terrasse et al. (2004) (France)
Cartron et al. (2005) (Mexico)
Karyakin et al. (2005) (Kazakhstan)
Matsina (2005) (Russia)
Medzhidov et al. (2005) (Russia)
Platt (2005) (Canada)
Rubolini et al. (2005) (Italy)

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