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HEIGHT, GUY WIRES, AND STEADY-BURNING LIGHTS INCREASE HAZARD OF COMMUNICATION TOWERS TO NOCTURNAL MIGRANTS: A REVIEW AND META-ANALYSIS

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Communication towers in North America kill millions of birds annually, and most of these are Neotropical species that migrate at night (Banks 1979, Shire et al. 2000). Estimates of total annual mortality in the United States are about 4–5 million to an order of magnitude greater (U.S. Fish and Wildlife Service [USFWS] 2000, Erickson et al. 2005). In 2000, the USFWS proposed guidelines to minimize avian collisions with communication towers. In November 2006, the Federal Communications Commission (FCC) announced a "notice of proposed rulemaking" that sought input on a proposal to require changes to tower design to reduce avian mortality. Here, we review and analyze the literature on the features of towers that can be regulated, particularly tower design and placement, to provide a scientific basis for regulation of tower construction and operation. We prepared an earlier version of this review (Longcore et al. 2005) for the American Bird Conservancy and other conservation groups in response to a "notice of inquiry" issued by the FCC in 2003 to gather information on collisions between birds and communication towers.

The ornithological literature contains frequent reports of birds killed at lights (see references in Weir 1976, Avery et al. 1980, Kerlinger 2000, Gauthreaux and Belser 2006). Two long-term studies with periodic searches confirmed that large numbers of birds can be killed at communication towers: (1) a 38-year study of a single 305-m television tower in west central Wisconsin documented 121,560 birds of 123 species killed (Kemper 1996), and (2) a 29-year study at a Florida television tower documented the deaths of 44,007 birds of 186 species (Crawford and Engstrom 2001). Because the FCC does not require monitoring of avian mortality at towers that it registers or otherwise approves, and because tower operators do not monitor mortality, bird kills reported in the literature represent only a minimum measurement of total mortality. Most sites are never visited to find dead birds, and most of those that are surveyed are visited only sporadically. Despite a number of useful reviews of the topic (Weir 1976, Avery et al. 1980, Trapp 1998, Kerlinger 2000) and recent progress on key issues such as the influence of lighting type and tower height (e.g., Jones and Francis 2003, Gauthreaux and Belser 2006, Gehring et al. unpubl. data), an analytical synthesis of factors influencing avian mortality at towers would aid policy development and focus future research. Here, we ask how design and placement of towers affect mortality of birds. Many variables influence rates of bird mortality at communication towers; certain types of weather conditions (e.g., frontal systems) are implicated in most large kills (see review in Gauthreaux and Belser 2006). Inclement weather and other physical variables, such as the effects of the lunar cycle, are beyond the control of regulators. Therefore, we concentrate on the elements of tower design that can influence bird mortality and that can be regulated.

Methods

For each of the design features that influence mortality rates of migratory birds at communication towers (height, lighting, guy wires, and topographic position), we reviewed the published scientific literature and unpublished reports and consulted extensive bibliographies (Weir 1976, Avery et al. 1980, Trapp 1998, Kerlinger 2000). We conducted a meta-analysis of studies of bird kills at towers to investigate the influence of tower height and guy wires on bird mortality. Meta-analysis pools the results of many studies to detect relations that may be equivocal or contradictory in individual studies (Gates 2002). We included studies that met the following criteria: (1) methodology was clearly explained, (2) surveys around a tower were completed consistently through more than one fall

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season with >10 visits (i.e., at least fall and spring, or two falls), (3) tower height was provided, and (4) total number of birds killed was provided. To calculate annual mortality, we assumed that fall surveys constituted 75% of a year and that spring surveys constituted 25% (Crawford and Engstrom 2001). For each study or set of studies at the same location, we recorded mean annual mortality (total kill divided by number of years), the number of years of the study, tower height (m), and the presence and number of sets of guy wires and the presence and type of lighting if provided. When a study was done at a single location with towers of different heights, we recorded them separately. The effects of observer bias and predator removal were incorporated in some, but not all, studies, so we used unadjusted numbers for all towers. We transformed mean annual mortality ($\ln[x + 1]$) and tower height ($\ln[x]$) to normalize distributions and performed linear regressions with ln tower height and number of sets of guy wires as the explanatory variables. We also entered these variables sequentially into a multiple regression to identify any unique influence of either variable.

Results and Discussion

Tower height.—Overall, avian mortality increased with tower height. One comparative study addressed the effect of tower height on bird mortality. Karlsson (1977) sent a survey on bird mortality to operators at all 400 towers in Sweden and received 250 responses. All towers <150 m tall had continuously illuminated red lights, whereas taller towers, which ranged up to 325 m, had an additional flashing white light at the top. Tower personnel based their responses on incidental observations, without any systematic surveys. The proportion of towers at which personnel reported bird mortality increased from 4% at towers <100 m tall to 68% at towers 300–325 m tall (Karlsson 1977). A second comparative study, in Michigan, documented far greater avian mortality at towers >305 m tall than at shorter towers (116–146 m; J. Gehring et al. unpubl. data).

At a single site, Crawford and Engstrom (2001) reported decreased mortality following the reduction of a 308-m tower to 90 m. Kemper (1996) surveyed a 152-m tower for several years without recording bird mortality but immediately observed large mortality events when the shorter tower was replaced with a 305-m tower. Furthermore, in instances where a taller tower had been erected next to a shorter one, more birds began to be killed at the shorter tower than before (Stoddard and Norris 1967, Hoskin 1975), presumably because of the effect of lights on the taller tower.

We found no reports of instances where avian mortality decreased when a taller tower replaced a shorter tower or where avian mortality increased when a shorter tower replaced a taller tower. This is logical: taller towers have more surface area and, usually, more guy wires with which birds may collide. Furthermore, most migrants fly at 200–750 m (Able 1970, Bellrose 1971, Mabee et al. 2006). Mabee and Cooper (2004) found 26–46% of total migrants, depending on the season and location, in the strata up to ~396 m (although the strength of their radar may have underestimated the number of birds at higher altitude). They found that only 2–15% of migrants flew below 91 m during clear weather (Mabee and Cooper 2004). Therefore, all other variables being equal, substantially more birds will encounter taller towers and their guy wires than shorter towers, which may not require any or as many guy wires.

For our meta-analysis, 26 towers in 14 states in the eastern United States met our criteria for inclusion (Table 1). The linear regression of ln-transformed mean annual mortality by tower height was significant ($F = 68.7$, df = 1 and 24, $r^2 = 0.74$, $P < 0.0001$; Fig. 1A). The effects of tower height are amplified by lighting, so the lower mortality at shorter towers that do not require lighting, such as the two <60-m towers in the analysis, is likely to be partly attributable to the absence of lighting. It is impossible, however, to investigate the effects of height completely independent of lighting, because all towers >61 m tall require some form of obstruction lighting approved by the Federal Aviation Administration (FAA). To investigate the influence of height for the remainder of the data set, we omitted the two shorter towers and still obtained a significant, but weaker, relationship with a similar slope ($F = 17.8$, df = 1 and 22, $r^2 = 0.44$, $P < 0.0004$; Fig. 1B). This result is not surprising; we expected few fatalities at short towers, but at taller towers the influence of other variables is likely to confound the influence of height.

Our meta-analysis has a possible bias because of the tendency for researchers to report only data that show a positive result

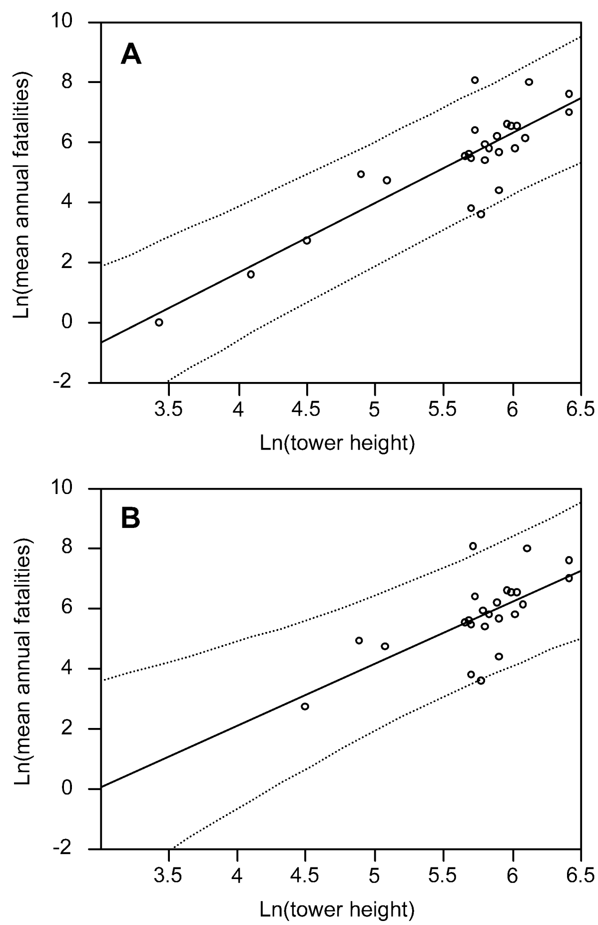

Fig. 1. Linear regression of ln-transformed mean annual avian mortality by ln-transformed tower height (m): (A) including all data points and (B) omitting two towers ≤60 m tall. Linear regression shown with 95% confidence intervals for individual values.

Table 1. Studies of birds killed at towers that provided estimates of annual mortality. No counts were adjusted for observer bias or scavenger removal except the shorter (90-m) tower reported by Crawford and Engstrom (2001), which had a predator-control program in place. See text for the method of calculating duration.

State	Tower height (m)	Sets of guy wires	Duration of study (years)	Mean annual mortality	Source
Kansas	30.5	Unknown	1	0	Young et al. 2000
Tennessee	60	Unknown	4	4	Nicholson et al. 2005
Florida	90	Unknown	1.5	14	Crawford and Engstrom 2001
New Hampshire	133	1	2	134	Sawyer 1961
West Virginia	161	Unknown	6	116	Herron 1997
Tennessee	287	4	19.75	253	Laskey 1960, 1962, 1963a, b, 1964, 1967, 1968, 1969a, b, 1971; Goodpasture 1974a, b, 1975, 1976, 1984, 1986; Bierly 1973
New York	293	5	30	267	Morris et al. 2003
Iowa	299	3	2	243	Brewer and Ellis 1958
Michigan	300	Unknown	4.5	44	Caldwell and Wallace 1966
Wisconsin	305	4	38	3,198	Kemper 1996
Florida	308	Unknown	13	618	Crawford and Engstrom 2001
New York	323	2	30	35	Morris et al. 2003
New York	328	6	30	370	Morris et al. 2003
Ohio	330	3	19	227	Morris et al. 2003
Michigan	342	Unknown	5.25	331	Caldwell and Wallace 1966
North Carolina	362	7	2	498	Carter and Parnell 1976, 1978
North Dakota	366	5	2	282	Avery and Clement 1972, Avery et al. 1977
Kansas	366	4	1.5	83	Boso 1965
Michigan	390	Unknown	5.25	757	Caldwell and Wallace 1966
Minnesota	400	5	5	701	Strnad 1962, 1975
Massachusetts	411	6	1.5	338	Baird 1970, 1971
Tennessee	417	6	29.75	689	Nehring and Bivens 1999
Kansas	439	9	2	473	Young and Robbins 2001
Florida	452	6	3	3,043	Taylor and Anderson 1973, 1974
North Carolina	608	9	2	1,111	Carter and Parnell 1976, 1978
Iowa	610	5	1.75	2,012	Mosman 1975

(Rosenthal 1979). Studies that detected no avian mortality at tall towers that were searched many times may be tucked in file drawers and never published. This type of bias is well recognized as a potential failing of meta-analysis (Gates 2002). For those towers where mortality has been reported, however, it seems that a consistent relationship exists between height and avian mortality.

Guy wires.—Most towers from which large bird kills have been reported have guy wires (but see Gregory 1975). Observational studies of birds in the vicinity of towers revealed that birds are much more likely to collide with the guy wires than with the tower itself (Brewer and Ellis 1958, Fisher 1966, Avery et al. 1976). Greater mortality caused by guyed towers would be expected because of the circling behavior exhibited by migrants under the influence of lights on towers (Gauthreaux and Belser 2006). In a study of bird mortality at transmission towers in Wisconsin, Kruse (1996) found that locations of dead birds and of guy wires were highly correlated, implicating collisions with guy wires as the cause of death. Weise (1971) searched three towers near Milwaukee daily from 1965 to 1970. Although each tower was 305 m tall, the tower with no guy wires killed "very few" birds, whereas two nearby towers with guy wires killed more birds in frequent small kills and in occasional kills of 300–500 birds in a night. Finally, J. Gehring et al. (unpubl. data) found dramatically lower mortality at freestanding towers than at guyed towers of the same height (116–146 m).

Wind power producers also have investigated the hazard of guy wires to migrating birds. Research on unguyed wind turbines and nearby guyed structures has confirmed the increased risk of guyed structures. For example, the average number of birds killed at a guyed meteorological tower was ~3× greater than the average rate of mortality at nearby turbines of a similar height without guy wires (Young et al. 2003).

In our meta-analysis, 18 studies reported the number of sets of guy wires. For other studies, the number was not stated, but no studies included towers without guy wires. Annual mortality was significantly predicted by the number of sets of guy wires ($F = 5.4$, df = 1 and 15, $r^2 = 0.25$, $P < 0.03$). In a multiple regression for this subset of studies, neither tower height nor number of sets of guy wires explains remaining variation when the other variable is entered first because of the collinearity of tower height and number of sets of guy wires (Pearson's correlation coefficient; $r = 0.69$, $P < 0.001$). Some towers have many sets of guy wires for their height (e.g., nine sets on a 439-m tower) or few sets for their height (e.g., five sets on a 610-m tower), but more studies would be needed to further specify any independent contributions of tower height and number of sets of guy wires.

Tower lighting.—The lighting scheme of communication towers is probably the most important factor contributing to bird kills at towers that can be controlled by humans (Cochran and Graber 1958, Avery et al. 1976, Gauthreaux and Belser 2006). Current federal regulations dictate the use of lighting for nighttime conspicuity for aviation safety on all obstructions ≥61 m tall and for structures within 5.6 km of an airport (FAA 2007). The only purpose in placing lights on communication towers and other structures is to provide for aviation safety by ensuring that pilots can see human-made obstructions.

Nocturnal migrants aggregate at lights when they have become disoriented or "trapped" by the lights after entering their zone of influence. This zone increases when fog is present in the air to reflect the light and when inclement weather or topographic factors force migrating birds to fly at lower altitudes. These mechanisms have been observed not only near communication towers but also near lightships, lighthouses, fires, oil flares, ceilometers, and city lights and lighted buildings (see references in Gauthreaux and Belser 2006, Montevecchi 2006).

Historical accounts suggest that, at least for birds attracted to lighthouses, continuously illuminated white lights are more attractive to birds than colored or flashing lights. Barrington (1900) analyzed birds that were killed at 58 lighthouses and concluded that continuously illuminated lights were more attractive to migrants than blinking lights and that white lights were more attractive than red lights. Others have concluded that "fixed white lights are also more deadly than the revolving or coloured lights" (Dixon 1892:175) and that "coloured lights do not attract the birds as white ones so fatally do" (Thomson 1926:333). These observations are relevant to communication towers because, despite differences in height and lighting type, similar species are killed at lighthouses (see Allen 1880, Brewster 1886, Munro 1924, Lewis 1927) and communication towers (see Shire et al. 2000). Furthermore, the many anecdotal accounts of bird aggregations at lighthouses share common features of species composition and bird behavior with descriptions of bird aggregations at towers.

Duration of lighting is critical to whether birds are attracted to lights. The Dungeness Lighthouse in Kent, England, was well known for chronic bird kills. In 1961, its revolving beam was replaced with a bluish-white lamp that produced a 1-s flash every 10 s. A revolving beam causes the area around a light to be continuously illuminated, especially in foggy weather, even though the spot of the beam sweeps the horizon. At Dungeness, this continuous illumination was eliminated with the change to a flashing light. Observations during the transition week between lights, under similar weather conditions, showed bird aggregation with the constant revolving light but none with the intermittent light (Baldwin 1965). Reducing the intensity and breadth of a revolving beam was shown by Jones and Francis (2003) to dramatically reduce the number of avian mortalities at the Long Point Lighthouse on Lake Erie in Ontario.

Some U.S. television towers were equipped with white strobe lights (e.g., L-865) instead of steady-burning red (L-810) and flashing red (L-864) lights for the first time in 1973 (Avery et al. 1976). Only one of the large one-night kills reported in the literature since then occurred at a tower with strobe lights. A witness to the aftermath of this notorious incident, when >10,000 Lapland Longspurs (*Calcarius lapponicus*) died in one night, considers the cause to have been whiteout snow conditions and lighting at facilities at ground level, not the tower lighting (E. A. Young pers. comm.).

Bird mortality was reduced substantially when lighting of a tower in Orlando, Florida, was changed from steady-burning red and flashing red lights to white strobe lights (W. Taylor pers. comm.). The tower was the site of large bird kills, and Taylor and colleagues had collected >10,000 birds over the years (Taylor and Anderson 1973, 1974). In 1974, the ~305-m guyed tower blew down and was replaced with a taller guyed tower with white strobe lights. Following the replacement, bird mortality was reduced drastically and no mass kills (i.e., >100 birds) were ever again reported at the site (Taylor 1981), despite many return visits following weather conditions previously associated with mortality events (W. Taylor pers. comm.).

Gauthreaux and Belser (2006) investigated the influence of lighting type on behavior of nocturnal migrants through direct observation at towers with different lighting schemes in Georgia and South Carolina. They found that although towers lit by white strobe lights can affect the path of birds during migration, no greater number of birds accumulated around them than at control sites. Furthermore, significantly more nonlinear flights per minute were seen at towers with red flashing and steady-burning lights than at control areas or towers with white strobe lights. These results suggest that although white strobe lights can cause birds to take more nonlinear flight paths, they do not result in birds accumulating around the tower. Gauthreaux and Belser (2006) concluded that the significantly greater number of paths per minute around the tower with red lights resulted from the attraction of the lights, added to the influence of the lights on orientation, leading to accumulations of individuals near the towers with steady-burning red and flashing red lights (see also Graber and Cochran 1960, Avery et al. 1976).

The evidence indicates that use of strobe or flashing lights on towers results in less bird aggregation and, by extension, lower bird mortality, than use of steady-burning lights. Indeed, the use of strobe lights has been recommended by a series of researchers investigating this topic. Verheijen (1985:13) concluded that "success has been achieved in the protection of nocturnal migrant birds through interrupting the trapping stimulus situation by . . . replacing the stationary warning lights on tall obstacles by lights of strobe or flashing type." Jones and Francis (2003) similarly concluded that strobe lights with a complete break between flashes would reduce bird mortality at tall structures.

The report by Evans et al. (2007) also supports the conclusion that flashing lights with a dark phase have less effect on birds than solid lights. In an experimental comparison, Evans et al. (2007) reported more calls of migrating birds around white, blue, and green steady-burning lights installed at ground level than during control periods or around flashing lights or red steady-burning lights. Although Evans et al. (2007) presented convincing evidence that some wavelengths of continuous light influence the rate of calling in birds, further inference is limited because control sites were distant (107 km) and the relationship between calls and abundance is not well established. Data from Cochran and Graber (1958) showed a negative correlation between birds seen per minute and calls heard per minute (our analysis, Pearson's correlation coefficient, $r = -0.71$; $n = 16$ sampling periods ranging from 2 to 10 min). Farnsworth et al. (2004) found that hour-to-hour variation in calling rate of migrating birds was only weakly explained by hour-to-hour density of migrating birds measured by weather surveillance radar only 60 km from the study sites in South Carolina and New York. The failure of red steady-burning lights to result in additional calls of migrants in the unique experimental situation presented by Evans et al. (2007) does not weaken the repeated observation that such lights cause aggregations when installed on towers.

Researchers analyzing bird kills at wind turbines have observed that red strobe-type lights do not attract night-migrating birds (P. Kerlinger et al. unpubl. data). Furthermore, Gehring et al. (unpubl. data) compared mortality of birds at towers with red strobe, red flashing, and white strobe lights and found that all three configurations resulted in less mortality than towers with steady-burning lights. From these studies, and the repeated identification of the importance of a dark phase for minimizing avian mortality, we conclude that removal of steady-burning lights and use of only synchronously flashing lights would reduce avian mortality at communication towers.

To reduce avian mortality, it is also important that accessory structures at towers not have constant exterior lighting. Studies at wind turbines reveal greater bird kills at turbines near lighted structures (P. Kerlinger et al. unpubl. data). Avoidance of lights on accessory structures for towers in natural areas would also reduce adverse effects on other taxa (Longcore and Rich 2004, Rich and Longcore 2006).

Topography.—Topography is known to concentrate migrants in certain locations (i.e., coastlines, mountain ridges, rivers, and hills). Considerable evidence of this effect has been gathered in Europe (Eastwood 1967, Bruderer and Jenni 1988, Bruderer 1999), with fewer studies in North America (Williams et al. 2001). Results of Williams et al.'s (2001) study in New Hampshire revealed the effect of the topography of the Appalachian Mountains on migratory birds, including Neotropical migrants traversing southeast over the mountain chain. At two ridgeline sites, the researchers observed "exceptional numbers of migrants at 2 to 30 m AGL [Above Ground Level]" (Williams et al. 2001:394). They concluded, in agreement with the European studies, that it should not be assumed that birds migrate in a broad front across mountains. Indeed, they described situations that resulted in large numbers of birds concentrated near crests of ridges and in passes. Although studies with weather surveillance radar provide evidence for broad-front migration (Gauthreaux and Belser 2003), such studies usually detect migrants flying at relatively greater heights. Consequently, low-flying migrants are often missed by weather surveillance radar and, because of their proximity to the ground, are more likely influenced by local topography. However, Mabee et al. (2006) found that very few birds changed their behavior in response to ridgelines in a study along the Allegheny Front in West Virginia. This is not inconsistent with the observations of Williams et al. (2001) but suggests that large numbers of birds are not found at crests of all ridges.

These studies provide evidence that placement of communication towers along ridgelines may result in higher bird mortality than at other locations. Birds can be killed at a tower whenever large numbers are flying near it at the same elevation as the tower. This can occur because the tower is tall or because it is placed topographically where birds are concentrated close to the ground. At ridgeline locations, inclement weather is not required for concentrations of birds to be found at low elevation (Williams et al. 2001). Radar studies can be conducted before siting a tower in an area that may concentrate night migrants so that the tower can be located to avoid such sites (e.g., Mabee and Cooper 2004, Mabee et al. 2006).

Policy implications.—Enough reliable information is available to implement communication tower guidelines that would reduce existing and future significant adverse effects on birds. Although additional research would be useful, avian mortality would be reduced by restricting the height of towers, avoiding guy wires, using only red or white strobe-type lights as obstruction lighting, and avoiding ridgelines for tower sites. These recommendations are included in current guidelines established by the USFWS (2000), and implementing them within an adaptive management approach is advisable (Holling 1978, Walters 1986, Haney and Power 1996). Adaptive management allows for a management action to be taken—such as requiring only strobe-type lights on all towers or requiring that towers be constructed without, or with fewer, guy wires—while continuing to increase scientific knowledge by studying the effects of such actions. Future recommendations may be modified to incorporate the findings of such studies. Many alternative mitigation strategies could be investigated and eventually adopted under an adaptive management approach, but immediate action based on current knowledge is needed to reduce adverse effects of communication towers on birds.

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