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RESEARCH ARTICLE

Collision avoidance by migrating raptors encountering a new electric power transmission line

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ABSTRACT

Avian collisions with overhead power lines are of conservation concern, particularly in migration corridors. We studied potential collisions where an existing power line supported by towers 20–25 m tall was replaced by the Susquehanna-Roseland line (S-R line), a new line with towers 55–60 m tall. The S-R line crosses Kittatinny Ridge, a corridor for raptors migrating south through New Jersey and Pennsylvania, USA. We hypothesized that the S-R line, which on Kittatinny Ridge includes markers designed to increase its visibility to birds, would cause migrating raptors to react in 1 of 3 ways: (1) to not alter flight elevation, but to pass safely through the S-R wire zone; (2) to not alter flight elevation, and to not pass safely through the wire zone, leading to collisions; or (3) to alter flight elevation and to pass safely above or below the S-R wire zone. To evaluate these hypotheses, we recorded the flight elevations of migrating raptors in 2013 before construction of the S-R line and in 2014 postconstruction. Preconstruction, we recorded 3,698 raptor crossings. Most raptors (72%) crossed above the anticipated S-R wire zone. Some (24%) passed through the anticipated S-R wire zone, and a few (4%) passed below the anticipated S-R wire zone. Postconstruction, we recorded 4,482 crossings. Most raptors (92%) crossed above the S-R wire zone. A few passed through (5%) or below (3%) the S-R wire zone. Postconstruction, raptors responded to the new line by flying higher than they had when traversing the previous line. We did not observe any collisions. Altered flight elevations and the absence of observed collisions supported hypothesis 3. If similar patterns occur at other lines that cross diurnal migration corridors along ridges, then future monitoring may be better focused on potentially riskier settings, such as areas where migrating birds do not have deflected winds to assist with gaining elevation.

Keywords: avian, Kittatinny Ridge, PLS-CADD, Power Line Systems – Computer Aided Design and Drafting

Prevención de Colisiones por parte de Rapaces Migratorias ante una Nueva Línea de Transmisión de Energía Eléctrica de Alta Tensión

RESUMEN

Las colisiones de aves con líneas aéreas de trasmisión eléctrica de alta tensión son de interés para la conservación, particularmente en los corredores migratorios. Estudiamos las colisiones potenciales en donde una línea existente sujetada por torres de 20–25 m de alto fue reemplazada por una nueva línea Susquehanna-Roseland (línea S-R), con torres de 55–60 m de alto. La línea S-R atraviesa la Cresta Kittatinny, un corredor para rapaces que migran hacia el sur a través de Nueva Jersey y Pensilvania. Nuestra hipótesis es que la línea S-R, que en la Cresta Kittatinny incluyó marcadores diseñados para aumentar su visibilidad para las aves, causaría la reacción de las rapaces migratorias de una de tres maneras: (1) sin alterar la altura del vuelo, pero pasando de modo seguro a través de la zona de cables de S-R; (2) sin alterar la altura del vuelo, y no pasando de modo seguro a través de la zona de cables, llevando a colisiones; o (3) alterando la altura del vuelo y pasando de modo seguro por arriba o por abajo de la zona de cables S-R. Para evaluar estas hipótesis, registramos la altura del vuelo de las rapaces migratorias en 2013 antes de la construcción de la línea S-R y en 2014 luego de la construcción. Antes de la construcción, registramos 3,698 cruces de rapaces. La mayoría de las rapaces (72%) cruzaron por arriba de la zona anticipada de cables S-R. Algunas (24%) pasaron a través de la zona anticipada de cables S-R, y unas pocas (4%) pasaron por debajo de la zona anticipada de cables S-R. Luego de la construcción, registramos 4,482 cruces. La mayoría de las rapaces (92%) cruzaron por arriba de la zona de cables S-R. Unas pocas pasaron a través (5%) o por abajo (3%) de la zona de cables S-R. Luego de la construcción, las rapaces respondieron a la nueva línea volando más arriba de lo que lo habían hecho cuando atravesaban la línea previa. No observamos ninguna colisión. La alteración de la altura del vuelo y la ausencia de colisiones observadas apoyan la hipótesis 3. Si se registran patrones similares en otras líneas que atraviesan corredores migratorios diurnos a lo largo de crestas, entonces los monitoreos futuros deberían enfocarse hacia situaciones potencialmente más riesgosas, como áreas donde las aves migratorias no tienen vientos desviados que ayudan a ganar altura.

Palabras clave: aves, Cresta Kittatinny, PLS-CADD, Sistemas de Líneas de Alta Tensión – Diseño y Anteproyecto Asistido por Computadora

INTRODUCTION

Avian collisions with power transmission lines ($\geq$60 kilovolts [kV]; APLIC 2012) are a global conservation concern (Quinn et al. 2011, Barrientos et al. 2012, Rioux et al. 2013). Large, heavy-bodied species such as swans, pelicans, herons, and cranes are generally thought to be more susceptible to power line collisions than smaller, more maneuverable species (Jenkins et al. 2010, APLIC 2012; but see Pearse et al. 2016), although this may be partly a function of detection bias limiting incidental observations of smaller species (Drewitt and Langston 2008, Rogers et al. 2014). Collisions involving raptors have occurred (Mojica et al. 2009, APLIC 2012), but appear to be relatively uncommon compared with collisions involving other species groups. When encountering transmission lines, birds appear to see large-diameter energized wires (conductors) and avoid them by adjusting flight altitudes upward, subsequently colliding with smaller-diameter, less-visible overhead shield wires that are used for lightning protection (Jenkins et al. 2010, APLIC 2012). For example, across 3 studies, 72% of 373 observed collisions were with overhead shield wires (Faanes 1987, Pandey et al. 2008, Murphy et al. 2009). Power lines that bisect daily avian movement corridors, such as those between roosting and foraging sites, have historically been most associated with avian collisions (Bevanger and Brøseth 2004, Stehn and Wassenich 2008, APLIC 2012), with the risk of collision exacerbated in low light, fog, and inclement weather (Savereno et al. 1996, APLIC 2012, Hüppop and Hilgerloh 2012). The effects of power lines that bisect seasonal movement corridors used during migration have not been thoroughly investigated (Rogers et al. 2014).

Here, we describe the movements of raptors flying perpendicularly across a section of new power line crossing Kittatinny Ridge in New Jersey, USA, an important navigational feature traversed annually by tens of thousands of raptors travelling south during fall migration (Van Fleet 2001, Bildstein 2006, 2008). The new Susquehanna-Roseland line (S-R line) was built within the right-of-way of an existing power line that was supported by towers 20–25 m tall, which were removed and replaced by the 55–60 m tall towers that support the S-R line. From the center of Pennsylvania's eastern border, Kittatinny Ridge extends 300 km southwest through 12 Pennsylvania counties (National Audubon Society 2013) in the central Appalachian Mountains, and northeast into New Jersey. The ridge rises 425–475 m above sea level, 250–300 m above farm-filled valleys on each side, and is covered in second-growth deciduous forest ~20 m tall. The geography of the area creates updrafts when westerly winds hit Kittatinny Ridge. Raptors glide southwest on these deflected winds, avoiding powered flight and thus conserving energy during migration (Van Fleet 2001, Bildstein 2006, 2008). Kittatinny Ridge is an Important Bird Area (National Audubon Society 2013) and is home to Hawk Mountain, a research center focused on raptor conservation science and education worldwide (Hawk Mountain 2013). The movement of migrating raptors along this high-traffic corridor has been monitored since 1934 (Bildstein 2008), lending Kittatinny Ridge important social as well as conservation values.

The newly constructed power line, which is 2.5 times taller than the previous line and has a wire zone entirely above the forest canopy, poses a collision risk for the thousands of raptors that migrate along Kittatinny Ridge annually. We hypothesized that raptors would react to the S-R line in 1 of 3 ways: (1) that raptors would not alter their flight elevations above ground level, but would pass safely through the S-R wire zone; (2) that raptors would not alter their flight elevations and would not pass safely through the S-R wire zone, leading to collisions; or (3) that raptors would alter their flight elevations to pass safely above or below the S-R wire zone. To evaluate our competing hypotheses, we collected data on the flight elevations of migrating raptors prior to construction of the S-R line as raptors traversed an existing line, and after construction as raptors traversed the S-R line. This design allowed us to evaluate whether raptors changed their flight elevations with increased obstacle height.

METHODS

The S-R line was built within the right-of-way of an existing line that was supported by towers that were 20–25 m tall. The existing line was removed and replaced by the S-R line during February through April of 2014, between the 2 fall migration seasons that we monitored. The S-R line included a new 230 kV line and a new 500 kV line that were installed together on towers 55–60 m tall. The line was composed of 4 parallel planes of wires (Figure 1A), with the top plane of wires composed of 2 optical ground wires (OPGWs), each 1.9 cm in diameter. The OPGWs provided lightning protection to the energized wires below, and supported bundles of fiber-optic communication lines. The presence of fiber-optic bundles increased the diameter of the wires, potentially increasing their visibility to birds.

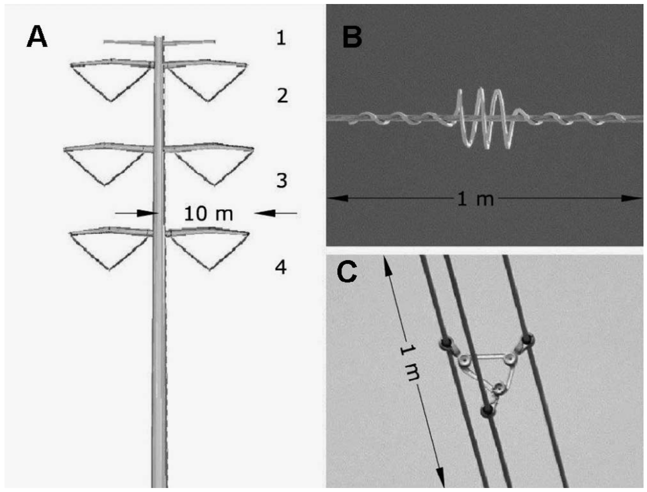

FIGURE 1. (**A**) Schematic of structures supporting the Susquehanna-Roseland 230/500 kilovolt (kV) transmission line (S-R line) crossing Kittatinny Ridge, New Jersey, USA. Numbers indicate locations of wire planes. (**B**) The upper crossarm, wire plane #1, was composed of optical ground wires marked with Swan Flight Diverters (SFDs). The SFDs were 0.2 m tall at the widest point. (**C**) The lower 3 crossarms, wire planes #2, #3, and #4, supported single (230 kV) and bundled (500 kV) conductors, with bundled conductors separated by a 60 cm spacer.

On the S-R line, the OPGWs were marked every 10 m with Swan Flight Diverters (Preformed Line Products, Cleveland, Ohio, USA) on the 3 spans (totaling 1.4 km) crossing Kittatinny Ridge, to help to increase the visibility of the line to flying birds (Figure 1B). The Swan Flight Diverters were staggered on each OPGW, so that, although they were at 10 m intervals on each OPGW, they appeared to be at 5 m spacing when viewed perpendicularly to the line. The lower 3 planes of wires were composed of bundled conductors consisting of 3 wires, each 3.9 cm in diameter, connected via spacers that separated the conductors by 60.0 cm in a triangular configuration (Figure 1C). The 4 sets of wires occurred at heights from 25 m (lowest) to 60 m (highest) above the contours of Kittatinny Ridge, creating an S-R wire zone from 25 to 60 m above ground level. In contrast to the previously existing line, the wires of which were partially shielded by the surrounding tree canopy, the entire S-R wire zone is above the canopy and in the potential flight path of migrating raptors.

We reviewed historical fall migration count data from nearby Raccoon Ridge (HMANA 2013) to identify a survey period (September 1 through November 25) that was likely to document 95% of raptors migrating along Kittatinny Ridge. In 2013, the initiation of counts was delayed by permitting arrangements related to construction of the S-R line. This resulted in preconstruction surveys being conducted from September 24 through November 25 in 2013, and postconstruction surveys being completed from September 1 through November 25 in 2014. Variation in survey periods can lead to bias in migration counts, but only if the variation is not accounted for in analyses (Crewe et al. 2016). We considered the consequences of survey duration by evaluating differences in counts for Broad-winged Hawks (*Buteo platypterus*), which could have been missed in our 2013 counts because they migrate early in the fall season (HMANA 2013). We followed the Hawk Migration Association of North America's (HMANA) protocols for counting migrating raptors (HMANA 2014), surveying from 08:00 to 16:00, Monday through Friday.

We counted raptors passing between 500 m west of Kittatinny Ridge and 650 m east of the ridge in northwestern New Jersey, USA (Figure 2). These distances allowed us to count all raptors flying along the contours of Kittatinny Ridge from the top of the ridge to the valley floors on either side. We used observers trained and experienced in HMANA methodology. During each count, we used 2 observers simultaneously, with 1 observer counting raptors passing along the northwestern side of Kittatinny Ridge, and 1 observer counting raptors passing along the southeastern side. One observer was the same person during all counts, ensuring consistency across the entire study, while the second observer changed among counts. Observers were stationed at the top of Kittatinny Ridge, within an area cleared of vegetation as required for safe installation and operation of the S-R line. To avoid double-counting individual raptors, observers communicated via radio as individual birds crossed the ridge. Observers identified raptors to the lowest taxonomic level possible, and used a laser range finder (RX-1000i TBR W/DNA; Leupold & Stevens, Beaverton, Oregon, USA) equipped with a clinometer to identify the distance and angle to each bird as it crossed the power line. This enabled precise vertical and horizontal locations to be identified for each raptor as it traversed the S-R wire zone. Thus, we quantified each raptor's position relative to the S-R wires in both years, even though the line was not yet in place during the 2013 surveys.

We used chi-square (χ^2) tests to evaluate any differences in the proportions of raptors passing above the S-R wire zone, within the S-R wire zone, and below the S-R wire zone in 2013 vs. 2014. We conducted χ^2 tests that included all raptors observed, and separate tests that evaluated subsets of raptors by species or taxonomic group. Multiple comparisons of subsets of data increase the probability of type I error. To address this concern, we used a Bonferroni correction (Sokal and Rohlf 1995), dividing our initial significance level ($\alpha = 0.05$) by the number of tests that we conducted (5), to yield a corrected significance level of $\alpha = 0.01$. We used the seasonal pattern of detection of individual species to consider the consequences of the shorter sampling period in 2013 (63 days) compared with 2014 (86 days).

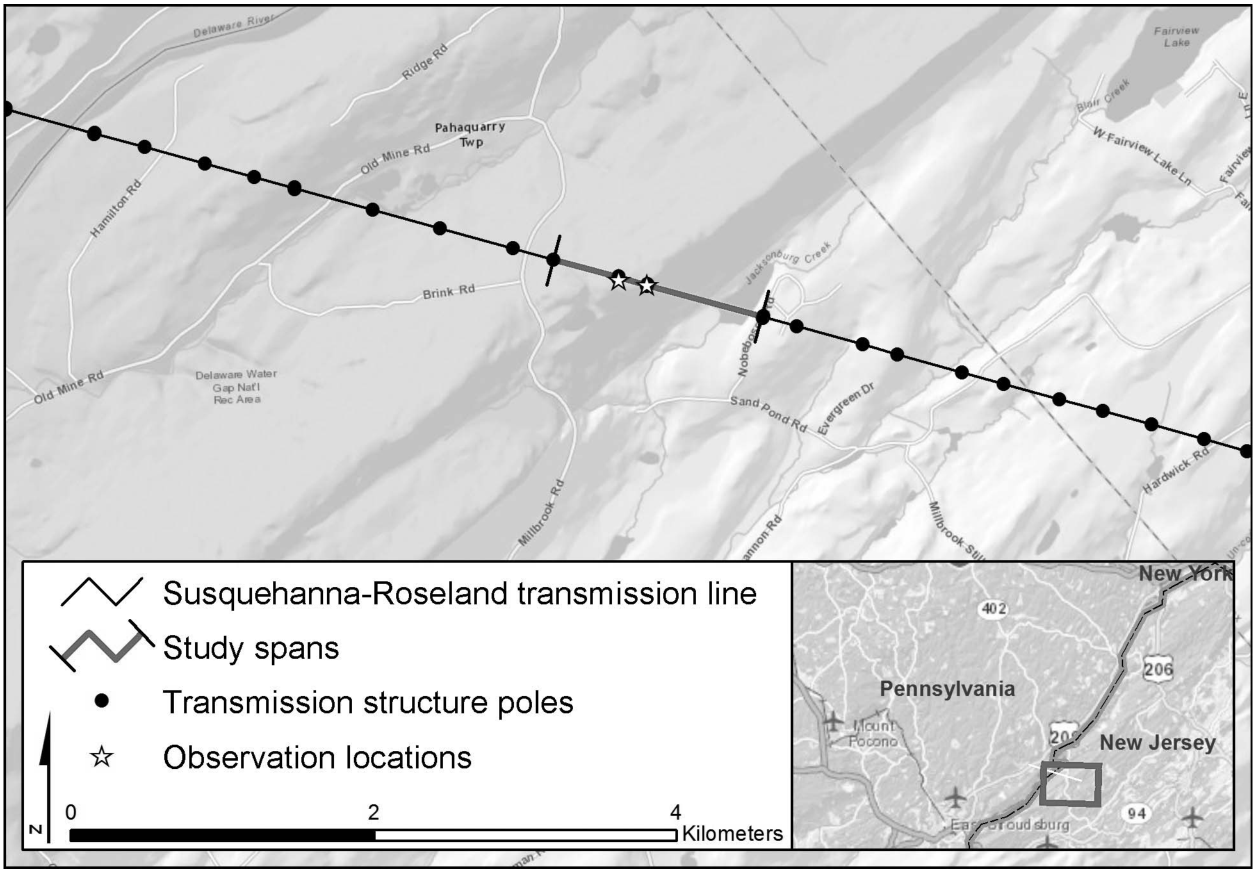

FIGURE 2. Locations of observers, study spans, and study site within the region for recording flight locations of migrating raptors crossing the Susquehanna-Roseland 230/500 kilovolt (kV) transmission line (S-R line) on Kittatinny Ridge, New Jersey, USA (Base map: World Street Map; ESRI, Redlands, California, USA).

We used a Geographic Information System (GIS; ArcGIS Desktop 10.2, ESRI, Redlands, California, USA) and Power Line Systems – Computer Aided Design and Drafting (PLS-CADD; Power Line Systems, Madison, Wisconsin, USA) to visually display the accumulated spatial locations of raptors crossing the S-R line. To do this, we used a 9 m (1-arc-second) digital elevation model to calculate the absolute elevation above sea level for each raptor. We then used the Linear Referencing Toolbox in ArcGIS and ET GeoWizards (ET Spatial Techniques, Pretoria, South Africa) to model location data in 3-dimensional (3-D) space. We integrated the 3-D raptor observation data into PLS-CADD, facilitating simultaneous evaluation of raptor flight elevation data and an engineering model of the S-R transmission line, depicting the wires and supporting towers. The use of PLS-CADD enabled us to precisely identify the location of the S-R wire zone in 3-D space, and thus to precisely quantify a migrating raptor's potential collision risk where flight elevations transected the S-R wire zone, despite the curve of the wires. Because wires sag between towers, the use of PLS-CADD allowed us to identify with certainty when a raptor flying below the height of the top of the towers was nevertheless flying above a sagging wire.

RESULTS

We did not observe any raptors collide with any wires. During 9 weeks of observation in 2013, and 12 weeks of observation in 2014, we recorded 3,698 preconstruction (2013) and 4,482 postconstruction (2014) raptor crossings of the S-R line survey area (Table 1, Figure 3). Our study showed a 21% increase in the number of raptors counted from 2013 to 2014, driven largely by a 9,514% increase in the number of Broad-winged Hawks counted. Specifically, only 7 Broad-winged Hawks were recorded in 2013, and nearly all of the 673 Broad-winged Hawks counted in 2014 were counted prior to the initiation date of the 2013 preconstruction surveys.

In 2013, most (72%) raptors crossed above the S-R wire zone. Some (24%) crossed within the S-R wire zone, and a few (4%) crossed below. In 2014, most (92%) raptors again crossed above the S-R wire zone, but a few crossed within (5%) or below (3%) the S-R wire zone.

TABLE 1. Flight elevation relative to the S-R wire zone of the Susquehanna-Roseland 230/500 kilovolt (kV) transmission line (S-R line) for raptors crossing the S-R line along Kittatinny Ridge, New Jersey, USA. The 2013 columns indicate preconstruction data, and the 2014 columns indicate postconstruction data.

	Individuals counted			Flight elevation relative to the S-R wires					
				Above (%)		Within (%)		Below (%)	
Group and species	2013	2014	PD [a]	2013	2014	2013	2014	2013	2014
Vultures									
Black Vulture (*Coragyps atratus*)	357	117	−67	92	99	6	1	2	0
Turkey Vulture (*Cathartes aura*)	2,001	2,459	23	66	91	29	6	5	3
Ospreys									
Osprey (*Pandion haliaetus*)	25	72	188	88	100	12	0	0	0
Eagles									
Bald Eagle (*Haliaeetus leucocephalus*)	58	81	40	86	96	14	3	0	1
Golden Eagle (*Aquila chrysaetos*)	14	9	−36	100	100	0	0	0	0
Unidentified eagle (*Aquila* or *Haliaeetus* sp.)	1	0	−100	100	0	0	0	0	0
Harriers									
Northern Harrier (*Circus cyaneus*)	48	52	8	92	88	8	8	0	4
Accipiters									
Sharp-shinned Hawk (*Accipiter striatus*)	553	462	−17	59	77	32	14	9	9
Cooper's Hawk (*Accipiter cooperii*)	73	84	15	77	93	16	2	7	5
Northern Goshawk (*Accipiter gentilis*)	1	1	0	0	100	100	0	0	0
Unidentified accipiter (*Accipiter* sp.)	5	8	60	80	74	20	13	0	13
Buteos									
Red-shouldered Hawk (*Buteo lineatus*)	32	4	−88	78	100	19	0	3	0
Broad-winged Hawk (*Buteo platypterus*)	7	673	9,514	72	100	14	0	14	0
Red-tailed Hawk (*Buteo jamaicensis*)	411	347	−16	92	95	7	3	1	2
Rough-legged Hawk (*Buteo lagopus*)	1	0	−100	100	0	0	0	0	0
Unidentified buteo (*Buteo* sp.)	4	0	−100	100	0	0	0	0	0
Falcons									
American Kestrel (*Falco sparverius*)	59	68	15	47	77	44	19	9	4
Merlin (*Falco columbarius*)	22	21	−5	55	80	36	10	9	10
Peregrine Falcon (*Falco peregrinus*)	15	17	13	73	100	27	0	0	0
Unidentified falcon (*Falco* sp.)	9	4	−56	56	75	33	25	11	0
Unidentified									
Unidentified raptor	2	3	50	50	100	50	0	0	0
Total	3,698	4,482	21	—	—	—	—	—	—
Average	—	—	—	72	92	24	5	4	3

[a] PD indicates the percent difference in the number of raptors counted between 2013 and 2014.

Raptors were more likely to pass above the S-R wire zone following construction of the S-R line ($\chi^2 = 613.6$, df = 2, $P < 0.001$). Two species, Turkey Vulture (*Cathartes aura*) and Sharp-shinned Hawk (*Accipiter striatus*), included enough crossings within and below the S-R wire zone to conduct species-specific analyses (i.e. $n \geq 5$ for all count categories). Both species passed more frequently through the preconstruction anticipated S-R wire zone than through the postconstruction actual S-R wire zone, with significantly higher proportions passing above the S-R wire zone postconstruction (Turkey Vulture: $\chi^2 = 458.0$, df = 2, $P < 0.001$; Sharp-shinned Hawk: $\chi^2 = 45.6$, df = 2, $P < 0.001$). These 2 species accounted for most of the data for vultures (90%) and accipiters (86%), respectively, so we did not conduct family-level analyses for these 2 groups. Individual species within 2 taxonomic groups, buteos and falcons, did not include enough crossings within and below the S-R wire zone to consider any species-specific differences, so we evaluated these groups at a higher level, and found similar patterns. Individuals in both groups were more likely to pass above the S-R wire zone following construction (buteos: $\chi^2 = 50.6$, df = 2, $P < 0.001$; falcons: $\chi^2 = 19.6$, df = 2, $P < 0.001$). The other groups examined, ospreys, eagles, and harriers, did not include enough crossings within and below the S-R wire zone to be evaluated statistically, but qualitatively followed the patterns of the more abundant species.

DISCUSSION

We hypothesized that raptors encountering the newly constructed S-R line where the line crossed Kittatinny Ridge would either (1) fly safely through the S-R wire

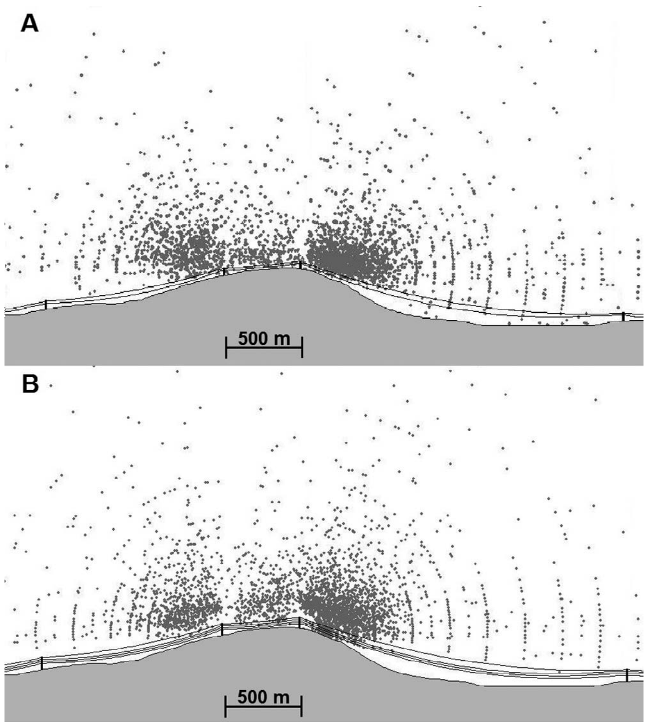

FIGURE 3. Flight locations of migrating raptors (gray dots) crossing the Susquehanna-Roseland 230/500 kilovolt (kV) transmission line (S-R line) on Kittatinny Ridge, New Jersey, USA, in **(A)** 2013, with towers 20–25 m tall, and **(B)** 2014, with towers 55–60 m tall. The tree canopy (not illustrated) was 20–25 m tall in both years.

zone, (2) collide with wires in the S-R wire zone, or (3) avoid the S-R wire zone by flying above or below all wires. In comparing preconstruction (2013) flight elevations with postconstruction (2014) flight elevations, we found that most of the raptors that we observed avoided the postconstruction S-R wire zone by passing above it, supporting hypothesis 3. Specifically, hypothesis 3 was supported by a 28% increase in the proportion of birds flying above the S-R wire zone postconstruction compared with preconstruction values. Although 21% more raptors were observed in 2014 than in 2013, removing Broad-winged Hawks from the analysis reduced this difference to 3%. Therefore, we believe that the difference in flight heights between years represents a behavioral response by raptors to avoid colliding with the S-R line. Shifting flight elevation to pass above the S-R wire zone suggests that raptors were able to identify the full extent of the S-R wire zone and to simply alter their flight altitudes upward to pass higher over the S-R wire zone postconstruction. This is true even though the preexisting line protruded only partially above the surrounding forest, while the postconstruction wire zone occurred entirely above the top of the surrounding forest canopy.

In cases where avian collisions with power lines have been documented, most have involved collisions with overhead static wires (Faanes 1987, Pandey et al. 2008, Murphy et al. 2009). The S-R line included OPGWs instead of traditional overhead static wires, and included Swan Flight Diverters on the OPGWs. Both the OPGWs and the Swan Flight Diverters increased the diameter of the top wires relative to traditional, unmarked overhead static wires. This larger diameter may have made the top wires more visible, enabling migrating raptors to detect and avoid them. The conductors on the S-R line were composed of 3 wires bundled together, increasing their collective diameter, and likely also increasing visibility and avoidance. These engineering features likely enabled diurnal migrating raptors to detect and fly above the S-R line. The implications of our study for future placement of transmission lines are substantial. Specifically, our results suggest that well-marked lines, even within high traffic corridors, may pose little collision risk to diurnally migrating raptors, although the cumulative energetic costs associated with making a series of adjustments in flight elevation as a raptor encounters transmission lines throughout its migratory route have not been explored. However, because we did not also evaluate a power line of similar height to the S-R line in similar circumstances, but without line marking, OPGWs, and bundled conductors, we do not know the extent to which any of these specific features contributed to the apparent visibility of the S-R line.

Avian collisions with power lines are associated primarily with transmission systems (≥60 kV; APLIC 2012), which typically exceed the height of distribution lines by 2–4 times. Despite the height difference, the influence of power line height on collision risk has not been well explored. A primary obstacle to evaluating the effects of line height is that studies in which sufficient numbers of carcasses are found for analyses typically involve lines of similar height across the study area (e.g., Mojica et al. 2009, Sporer et al. 2013, Rogers et al. 2014), and large studies of different types of lines typically include little data on actual collision mortality (e.g., Quinn et al. 2011), reducing the inference from rare events to population-level effects (Loss 2016). A second obstacle is that most collisions with transmission lines involve overhead shield wires (Faanes 1987, Pandey et al. 2008, Murphy et al. 2009), which are rarely present on distribution systems, confounding the effects of height with the effects of other aspects of line design. One study that explicitly evaluated the effects of line marking on transmission and distributions lines found no difference when line type was included in multivariate analyses (Barrientos et al. 2012), and thus no implications of line height. Studies of collisions at wind energy facilities and cell towers have shown much stronger effects of structure height on collision risk, with taller structures associated with greater risk (de Lucas et al. 2008, Gehring et al. 2011). The tallest cell towers can be >300 m high (Gehring et al. 2011), and the rotor-swept areas of the tallest terrestrial wind turbines can be as high as 200 m (New et al. 2015), 7.5 and 5.0 times the height of typical transmission lines, respectively. This difference in structure design and associated biological consequences highlights the reality that problems and solutions for one aspect of tall structures or electric energy generation and transmission do not necessarily transfer well to other aspects of the electricity industry, particularly given the influence of lighting type or siting on behavior and ultimately collision risk (Gehring et al. 2009, Smith and Dwyer 2016, Watson et al. 2016).

Energy infrastructure can raise conservation concerns when tall structures occur within migration corridors (de Lucas et al. 2004, Johnston et al. 2014, Rogers et al. 2014). Typical preconstruction surveys use radar or flight position estimates together with estimates of the future location of energy infrastructure to evaluate preconstruction vs. postconstruction differences in risk in relation to flight elevation. Typical postconstruction surveys seek carcasses to infer collision risk. Our study included the novel use of a laser range finder equipped with a clinometer combined with the novel use of PLS-CADD to precisely identify the locations of raptors in 3-D space relative to the S-R wire zone. Because preconstruction surveys of this type are relatively rare, our study provides the first example of merging these technologies. Other studies could benefit from integrating PLS-CADD into GIS methodology and analyses to more precisely identify the locations of raptors and potential obstacles in 3-D space. Adopting these techniques may increase the ability of conservation scientists and resource managers to identify the specific characteristics of energy infrastructure that affect avian collision risk, facilitating the focusing of mitigation efforts to greatest effect. For example, if diurnal raptors are consistently found to avoid well-marked transmission lines in migration corridors, then the substantial effort and expense required to conduct postconstruction monitoring may be better invested in researching and mitigating more pressing risks to migrating birds (Loss et al. 2014a, Loss 2016).

Annual numbers of avian collisions with power lines suggested by meta-analyses are substantial; for example, between 8 and 57 million annually in the U.S. (Loss et al. 2014b), and between 2.5 and 25.6 million annually in Canada (Rioux et al. 2013). Studies that have independently supported the findings of these meta-analyses typically have involved research into daily movements in breeding areas or wintering areas (e.g., Mojica et al. 2009, Barrientos et al. 2012, Sporer et al. 2013), or at migratory stopover sites (e.g., Stehn and Wassenich 2008, Murphy et al. 2009). Few published studies have explicitly considered collision with power lines specifically during migratory flight (but see Rogers et al. 2014), so we investigated a site where avian collisions with a new power transmission line were of potential concern with regard to migrating raptors. During migration, studies have also examined avian collisions with buildings (Loss et al. 2014b), cell towers (Gehring et al. 2009, 2011), and wind turbines (Pearce-Higgins et al. 2012, Johnston et al. 2014, Pearse et al. 2016). Specifically with respect to wind turbines, but with broad conceptual implications for avian collisions in general, Piorkowski et al. (2012) advocated 4 research priorities for wind energy and migratory wildlife: standardize protocols and definitions; develop new methods and models for assessing and forecasting risk; document lethal and sublethal effects; and improve access for researchers. We tried to address these goals with this project. Specifically, we used new methods to quantify avian responses to an anthropogenic structure within a migration corridor, we investigated lethal effects, and we relied on cooperation with industry to conduct our study. To maximize the applicability of information across studies, we encourage future researchers to also explicitly consider the 4 research priorities of Piorkowski et al. (2012) when designing studies of collisions involving other sites, focal species, and possible anthropogenic obstacles.

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