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Influence of local weather on collision risk for nocturnal migrants near an electric power transmission line crossing Kittatinny Ridge, New Jersey

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ABSTRACT—Collisions with tall anthropogenic structures (power lines, wind turbines, communication towers, and buildings) are a regular cause of mortality for nocturnal avian migrants. To better understand relationships between weather and migrant collision risk, we compared nocturnal hourly mean barometric pressure, temperature, relative humidity, wind direction, and wind speed to avian passage rates (targets/km/h) and flight heights during 1 year of spring and fall migrations near a recently reconstructed transmission line crossing Kittatinny Ridge, New Jersey, using 2 marine radars. We found lower spring flight heights associated with decreasing barometric pressures, temperatures, and relative humidity across all wind directions. Spring flight heights showed the strongest decreases with increasing wind speeds for headwinds and crosswinds while flight heights slightly increased with stronger tailwinds. Spring passage rates increased with lower relative humidity and higher temperatures. With increasing wind speeds, spring passage rates declined faster with headwinds and crosswinds, and only slightly with tailwinds. We found lower fall flight heights with decreasing temperatures and relative humidity, but the relationships varied by wind direction. The lowest flight heights occurred under tailwind and crosswind conditions. Increasing fall passage rates were associated with increasing barometric pressures and when wind speeds were lowest. Fall passages rates declined with higher wind speeds but were more gradual under tailwinds and crosswinds when compared to headwinds. Overall, 2–4% of birds migrated under conditions that would have placed them at risk of collision with the transmission lines. Similar studies conducted along migratory pathways could be used to predict nights where birds exhibit low flight heights around other obstacles along their migration path. These predictions could improve detection rates for carcass searches documenting relatively rare collision events. For sites with topographic features likely to concentrate nocturnal migrants, radar studies could be conducted before siting towers so that impacts to migratory birds could be avoided at these sites. *Received 15 March 2019. Accepted 22 July 2021.*

Key words: artificial structures, collision, nocturnal bird migration, northeast US, radar, weather patterns.

Influencia del estado del tiempo local en el riesgo de colisiones por aves migratorias nocturnas cerca de una línea de transmisión eléctrica que cruza la Kittatinny Ridge, New Jersey

RESUMEN (Spanish)—Las colisiones con estructuras antropogénicas altas (líneas de transmisión, turbinas eólicas, torres de comunicación y edificios) son una causa regular de mortandad para aves migratorias nocturnas. Para entender mejor las relaciones entre el estado del tiempo y el riesgo de colisión, comparamos el valor medio por hora de la presión barométrica, la temperatura, humedad relativa, dirección del viento y velocidad del viento con la tasa de paso de aves (registros/km/h) y sus alturas de vuelo durante 1 año de migraciones de primavera y otoño cerca de la recientemente reconstruida línea de transmisión que cruza la Kittatinny Ridge, New Jersey, usando 1 radares marinos. Encontramos alturas de vuelo más bajas asociadas con presiones barométricas decrecientes, temperaturas y humedad relativa para todas las direcciones del viento. Las alturas de vuelo de primavera tuvieron los decrementos más fuertes con el incremento de velocidades del viento bajo vientos de cola y laterales, mientras que las alturas de vuelo incrementaron ligeramente con vientos de cola más fuertes. Las tasas de paso de primavera se incrementaron con bajas humedades relativas y más altas temperaturas. Con el incremento de velocidades del viento, las tasas de paso de primavera declinaron más rápido con vientos en contra y lateral, y solo ligeramente con vientos de cola. Encontramos alturas de vuelo más bajas en otoño con el decremento de temperaturas y humedad relativa, si bien la relación varió con la dirección del viento. Las alturas de vuelo más bajas tuvieron lugar bajo condiciones de viento de cola y viento lateral. Los incrementos en las tasas de paso en otoño estuvieron asociados con incrementos en la presión barométrica y cuando las velocidades de viento fueron menores. Las tasas de paso en otoño declinaron a mayores velocidades de viento aunque fueron más graduales con vientos de cola y vientos laterales en comparación con viento en contra. En general, 2–4% de las aves migraron bajo condiciones que les pudiesen poner en riesgo de colisiones con líneas de transmisión. Estudios similares que se condujeron a lo largo de rutas migratorias podrían ser utilizados para predecir las noches donde muestran menores alturas de vuelo alrededor de obstáculos ubicados a lo largo de su paso migratorio. Estas predicciones podrían mejorar las tasas de detección para búsquedas de cadáveres que documental los relativamente raros eventos de colisión. Para sitios con características topográficas proclives a concentrar migratorias nocturnas, los estudios de radar podrían llevarse a cabo antes de establecer torres con el propósito de evitar impactos a aves migratorias en estos sitios.

Palabras clave: colisión, estructuras artificiales, migración nocturna de aves, noreste de los EUA, patrones del estado del tiempo, radar.

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Most small birds migrate at night. Presumably, this enables migrants to avoid aerial predation from diurnal raptors while in flight, to minimize heat buildup and moisture loss due to solar exposure in flight, to use stars for navigation (Sauer 1958), and to forage at stopover locations during the day (Rappole 2013). Patterns of

nocturnal avian migration are becoming increasingly well documented through weather radar studies. Most weather radar studies have focused on the basic ecology of avian migration, building toward answering big questions in migration biology, such as how, when, where, and why birds migrate (Bowlin et al. 2010).

In most cases, these studies record avian migrations across broad fronts and correlate those fronts with weather systems (Gauthreaux and Belser 1998, Diehl and Larkin 2005, Farnsworth et al. 2016). For example, in North America and Europe, where most studies of migration phenology and departure cues have been conducted, barometric pressure (Bagg et al. 1950), temperature (Lack 1960), relative humidity (Nisbet and Drury 1968), wind direction (Richardson 1978), and wind speed (Richardson 1978, 1990) have each been identified as important weather features correlated with migratory flight, and have been suggested, either singly or in combination, as important proximal cues birds may use as triggers to initiate or continue migration.

The conservation implications of these studies to collision risk have not been thoroughly explored, perhaps because critical information on migration flight heights is rarely reported, although flight heights are likely associated with specific weather conditions (Eastwood and Rider 1965, Kerlinger and Moore 1989, Bruderer et al. 1995, Dokter et al. 2011). Birds migrate above the height of tall trees and migrate above or along major terrain features. However, anthropogenic structures often extend above treetops and project from the tops of terrain features, creating obstacles that birds may not be evolutionarily prepared to avoid. For example, some birds may not be looking forward during flight (Martin and Shaw 2010) or have anterior blind spots (Martin 2011, Tyrrell and Fernández-Juricic 2017). Birds may also fail to recognize that freestanding obstacles such as electrical transmission towers are associated with suspended obstacles such as power lines (Sporer et al. 2013, Murphy et al. 2016), including conductor wires and static wires. Or similarly, that obstacles such as communication towers are associated with guy wires (Longcore et al. 2008, 2012). Collision rates are influenced by structure type, location, and weather, with taller structures within migratory corridors more likely to cause collisions, particu-

larly when poor weather limits a bird's ability to see oncoming obstacles (Longcore et al. 2013).

Collisions of nocturnal migrants with anthropogenic structures are a developing conservation concern due to the high numbers of birds involved, the diversity of species affected, the threatened and endangered status of some of them, the wide array of structure types, and an increasing number of structures across various landscapes (Longcore et al. 2008, Kerlinger et al. 2010, Smith and Dwyer 2016). Mean estimates of annual fatalities at tall structures in the United States and Canada include 6.5 million birds at communication towers (Longcore et al. 2012), 2.9 million birds at high-rise buildings (Machtans et al. 2013, Loss et al. 2014a), 48.4 million birds at distribution and transmission lines (Rioux et al. 2013, Loss et al. 2014b), and 234,000 birds at wind turbines (Loss et al. 2013), for a total of over 58 million annually. These estimates suggest collisions with anthropogenic structures are a substantial source of direct mortality for bird species. These estimates will continue to increase as new structures are built in airspace used by migrants, further increasing their risk of collision (Erickson et al. 2005, Manville 2016).

Collision risk for migrating birds can be modeled with radar monitoring at planned or existing anthropogenic structures. Radar is used to develop risk indices for aircraft flying in the same airspace as nocturnal migrants, ultimately guiding planes to use different flight heights and flight times to avoid birds (Zakrajsek and Bissonette 2001). Radar can also provide collision risk estimates for migrating birds in rotor swept zones of proposed or existing wind energy projects (Mabee et al. 2006, Fijn et al. 2015, D'Entremont et al. 2017), can identify the presence of birds and trigger curtailment of turbine activity (Tomé et al. 2017), and can document weather conditions that may increase avian collision risk with turbines (Thomas et al. 2011). A key outcome from these studies is the ability to quantify the flight heights of nocturnal migrants, because flight height directly correlates with collision risk and assuming that if birds are generally flying above the height of a potential obstacle, their collision risk is minimal.

In this study, we used radar monitoring of nocturnal migrants to assess flight heights, passage rates, and the role that local weather could play in

collision risk of nocturnal migrants with electrical transmission lines and associated ground wires. We studied the Susquehanna-Roseland 230/500 kilovolt (kV) transmission line (S-R line), which transmits electric power between Berwick, Pennsylvania, and Roseland, New Jersey. The S-R line bisects the Kittatinny Ridge Corridor, a globally significant migration flyway in spring and fall for tens of thousands of hawks and eagles, and millions of songbirds (Goodrich 1999).

Methods

Study area

We conducted this study from atop Kittatinny Ridge in northwest New Jersey, USA (Fig. 1), by installing a radar station 10 km southwest of where the S-R line crosses Kittatinny Ridge, and where we previously studied the collision risk for diurnal raptors crossing the S-R line (Luzenski et al. 2016, Mojica et al. 2020). The terrain in this area consisted of alternating ridges and valleys, where most ridgetops were inaccessible or privately owned, and most valleys were inappropriate for radar studies.

The specific location where we installed our radar station (41.0078°N , 75.0442°W) was the nearest location to the S-R line where we could place a radar station on the ridge top (472 m above sea level), allowing the horizontal radar to scan the top of the ridge and provide 360° coverage of the landscape without interference from nearby higher elevation terrain or vegetation.

We evaluated flight height relative to collision risk at 2 heights, 60 m above ground level (agl) and 125 m agl. These 2 heights were important because 60 m agl was the height of the tallest structure of the S-R line crossing the Kittatinny Ridge, and 125 m agl is currently a common tower height for other anthropogenic structures (Kunz et al. 2007). Along the Kittatinny Ridge's ~360 km length from southern New York to southern Pennsylvania, there are 376 anthropogenic structures within 10 km of the ridge (FAA 2018). Of these obstacles, 39% are transmission lines and supporting towers, 38% are communication towers and antenna, and 23% are other vertical structures (i.e., flagpoles, smokestacks). A majority are <125 m agl with only 3 obstacles between 125 and 220 m agl.

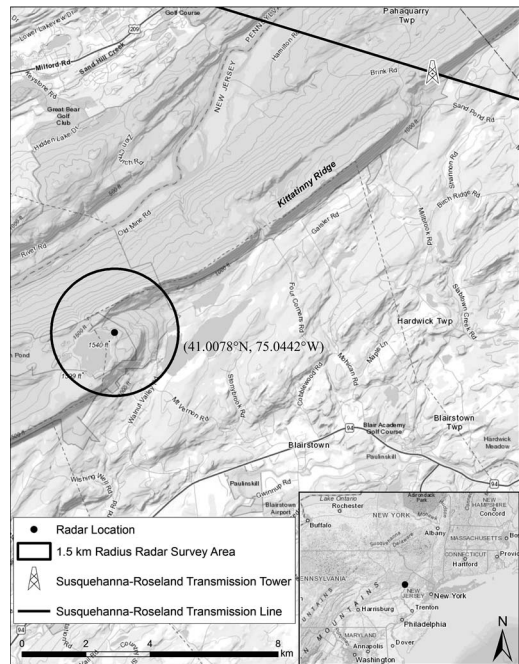


Figure 1. Study area including Kittatinny Ridge, the Susquehanna-Roseland Transmission Tower on the ridgetop, and the radar survey location next to the Upper Yards Creek Reservoir, New Jersey.

Marine radar data

We conducted radar sampling nightly from 22 March to 29 May and from 11 September to 15 November 2015. Within sampling periods, we initiated radar operation 30 min after sunset and ended 30 min before sunrise, matching our survey timing to a civil-twilight definition of night because that is when migrant passerines are typically in flight (Lowery 1951, Gauthreaux 1971, Alerstam 1990, Kerlinger 1995). We monitored a minimum of 6 d per week except when precipitation or lightning prevented effective or safe operation, respectively. Because nocturnal migrants typically avoid flying during storms (Richardson 1990), our breaks in monitoring correlated with likely breaks in bird migration.

We used simultaneous operation of 2 separate X-band marine radars to facilitate monitoring bird migration in the airspace surrounding our monitoring location. X-band radar is commonly used to monitor passage rates and altitudinal distributions of migrating birds (Kunz et al. 2007) because of the radar's capability to collect data in both

horizontal and vertical orientations. X-band radar differs from other types of radar, such as S-band (10 cm) radar, since the fine resolution of X-band (3 cm) allows for detection of small birds such as passerines.

We used a vertical radar (FAR-1510, Furuno Electric Company, Nishinomiya, Japan) to record horizontal and vertical distances to each bird and calculate flight height (agl), and a horizontal radar (FAR-2117, Furuno Electric Company) to record flight direction, path, and speed. Both antennas were the same length (6.5 m), with a vertical beam width of 20° and 1° horizontally, a rotation speed of 24 rotations per min, a range of 3 km, and a range accuracy of $\pm 0.9\%$ or 8 m, whichever is greater.

Because we were interested specifically in detecting individual nocturnal migrants, we used a radar pulse length of 0.07 μ s. This limited our effective detection radius on the horizontal and vertical radar to ~ 1.5 km. However, the flight height of most nocturnal migrants is 200–700 m (Able 1970, Bellrose 1971, Mabee et al. 2006), indicating our radar would document the majority of migrating birds. We used automated hardware (XIR3000C, Russel Technologies, Vancouver, Canada) and software (radR, radR-project, Nova Scotia, Canada) to consolidate signals from the vertical and horizontal radars into individual flight tracks that allowed us to quantify numbers of radar targets passing our station, flight heights of each target, and to filter insects from our dataset. We assumed most targets were passerines, based on time of year and similar radar studies in the region (Mabee et al. 2006, Farnsworth et al. 2016). We defined birds as targets because we could not always distinguish a single bird from a small flock.

Weather data

We used a model 6250 weather station (Vantage Vue, Davis Instruments, Hayward, California, USA) mounted on a post extended 5 m above our radar station to record barometric pressure (millibars), temperature (°C), relative humidity (%), wind direction (°), and wind speed (km/h) every 5 min during collection of radar data. We calculated mean values for each weather variable for each hour of radar sampling. We quantified these specific weather variables because each has been hypothesized to serve as an evolved proximal

cue used by avian migrants to migrate (Bagg et al. 1950; Lack 1960; Nisbet and Drury 1968; Richardson 1978, 1990). These variables are also relatively independent of one another because they measure distinctly different aspects of the atmospheric environment, although given the general understanding that birds tend to migrate ahead of weather fronts (the leading edges of weather systems), these weather features often co-varied in ways that were impossible to avoid.

Analyses

To focus our analysis on nocturnal avian migrants, we censured (removed from the dataset) small targets (speckle size) with lower energy reflectivity, targets flying erratically, targets detected in < 5 consecutive sweeps, and targets moving at ground speeds (uncorrected for wind) of < 21.6 km/h. These censures removed insects and foraging bats from the dataset because they tend to fly erratically as they forage, and because insects in particular fly at < 21.6 km/h (Tuttle 1988, Larkin 1991, Bruderer and Boldt 2001). Migratory bats could not be distinguished from birds because they fly at similar speeds (> 21.6 km/h; Tuttle 1988, Larkin 1991, Bruderer and Boldt 2001), therefore an unknown proportion of targets in our study were bats.

To assess flight height on the vertical radar, we recorded the target's minimum flight height each time we tracked a target. We focused on minimum heights because this defined—for each individual target—whether any part of the flight we observed was low enough to potentially encounter the S-R line in our study area (60 m agl), or other anthropogenic structures in the area in general (125 m agl). We calculated mean minimum flight heights (± 1 SE) each hour for all targets to generate hourly minimum flight heights (± 1 SE). This made each night of observations a replicate, rather than each individual target. We did not use individual targets as replicates because nocturnal migrants often fly in flocks whose individual flight heights are not independent. Using data from the horizontal radar, and keeping with the industry standard of quantifying passage rate per linear kilometer, we calculated passage rates as the mean number of targets detected per 3 km of migration front (the radar's beam diameter) per h (targets/km/h). This approach standardizes the count of targets

and facilitates comparisons of data between avian radar studies, even when data collection is interspersed with occasional interruptions due to rain or insect clutter. We also calculated the total of the number of targets detected by our radar each night.

We created 4 sets of candidate models, including one set each for spring flight height, spring passage rate, fall flight height, and fall passage rate. In each process, we modeled mean flight height or passage rate as a response variable to 5 or 6 explanatory variables: mean barometric pressure, mean temperature, mean relative humidity, mean wind direction, and mean wind speed, and their 2-way interactions. All variables other than wind direction were continuous. We converted wind direction to a categorical variable with 3 levels from the perspective of a bird in flight: tailwind, headwind, and crosswind. These were defined by the angle difference (Δ) between the bird flight direction and the wind direction. A delta of $0\text{--}45^\circ$ was defined as a tailwind, $46\text{--}134^\circ$ a crosswind, and $135\text{--}225^\circ$ a headwind. Hereafter, we use the term wind direction to refer to tailwinds, headwinds, or crosswinds.

We used ordinary least squares regression models to fit mean flight height observations for fall and spring seasons. We used negative binomial regression models to fit passage rate observations for spring and fall seasons. We conducted all analyses in R 4.0.3 (R Core Team 2020) and RStudio 1.4.1103 (RStudio Team 2020). Ordinary least squares fits used the *lm* function in base R. The negative binomial models were fitted using *glm.nb* from the MASS library (Venables and Ripley 2002). We defined our candidate model sets starting with all possible combinations of variables as main effects. We also considered 3 specific 2-way interactions: (1) mean relative humidity and mean temperature as a surrogate for heat index, (2) mean humidity and mean windspeed as a surrogate for wind chill, and (3) mean wind speed and direction.

We used AIC to select the best-fitting model given the data for all 4 model sets. We chose the models with the lowest AICs as best-fitting models, although there were 1–4 competing “good” models with values $<2 \Delta\text{AIC}$ as well as numerous models with ΔAIC values of 2–7 that also had meaningful support (Anderson 2008). While we acknowledge that model uncertainty

exists, we chose to focus on the single “best” models rather than using model averaging because we were looking at broad patterns and were not focused on specific coefficient values. The negative binomial models for passage rates are not linear in predictor parameters, and averaging models with interactions can make interpretations more difficult (Cade 2015). We looked at correlations among the continuous variables; the final models did not contain any highly correlated variables. We also examined the empirical relationship between passage rates and flight heights for spring and fall 2015 by calculating the mean and maximum passage rates when mean flight heights were ≤ 125 m and ≤ 60 m agl.

Results

The radar documented 323,710 targets in spring and 446,724 in fall flying through our study area. The mean flight height was 236.9 ± 0.3 m agl in spring and 307.2 ± 0.3 m agl in fall. The radar range accuracy of 0.9% or 8 m (whichever is greater) led to a high accuracy in our height estimates. For example, using real data collected on the radar for a bird detected near the ridgetop at a horizontal distance of 565 m (near the ridge), and with a range of 600 m from the radar (the distance of the radar beam), the recorded height was 68 m. If we apply the estimated accuracy of ± 8 m to the range (608 m and 592 m, respectively), which is greater than $\pm 0.9\%$ of 600 m, we get a ± 1 m difference (67–69 m) for the calculated height. The percentage of targets flying ≤ 60 m agl was 3.9% in spring and 1.8% in fall. The percentage of targets flying ≤ 125 m agl was 24.0% in spring and 16.4% in fall. Mean passage rates were 246 ± 59 targets/km/h in spring and 216 ± 30 targets/km/h in fall.

Our best model for flight heights and passage rates consistently included mean temperature, mean relative humidity, wind direction (tailwind, headwind, or crosswind), and mean wind speed, except for fall passage rates, which did show association with temperature or relative humidity (Table 1). Additionally, mean barometric pressure showed significant associations with spring flight heights and fall passage rates (Table 1). These variables were included in all top models, along with some combinations of 2-way interactions

Table 1. Predictors of nocturnal avian migration along the Kittatinny Ridge, New Jersey, during spring and fall migration. Best fitting models as selected by $\Delta AIC = 0$ and competing models with a $\Delta AIC \leq 2$ for flight heights and passage rates. BP = mean barometric pressure, RH = mean relative humidity, TE = mean temperature, WD = mean wind direction, WS = mean wind speed.

Spring flight height

$\Delta AIC = 0$; BP + TE + RH + WD + WS + (WD*WS)
 $\Delta AIC = 0.19$; BP + TE + RH + WD + WS + (WD*WS) + (RH*WS)
 $\Delta AIC = 0.46$; BP + TE + RH + WD + WS + (WD*WS) + (RH*TE)
 $\Delta AIC = 0.55$; BP + TE + RH + WD + WS + (WD*WS) + (RH*WS) + (RH*TE)

Spring passage rate

$\Delta AIC = 0$; TE + RH + WD + WS + (WD*WS) + (RH*TE)
 $\Delta AIC = 1.31$; TE + RH + WD + WS + (RH*TE)
 $\Delta AIC = 1.58$; BP + TE + RH + WD + WS + (WD*WS) + (RH*TE)

Fall flight height

$\Delta AIC = 0$; TE + RH + WD + WS + (RH*TE)
 $\Delta AIC = 1.65$; BP + TE + RH + WD + WS + (RH*TE)
 $\Delta AIC = 1.99$; TE + RH + WD + WS + (RH*WS) + (RH*TE)

Fall passage rate

$\Delta AIC = 0$; BP + WD + WS + (WD*WS)
 $\Delta AIC = 0.66$; BP + TE + WD + WS + (WD*WS)
 $\Delta AIC = 1.33$; BP + RH + WD + WS + (WD*WS)
 $\Delta AIC = 1.34$; BP + WD + WS
 $\Delta AIC = 1.49$; BP + TE + RH + WD + WS + (WD*WS) + (RH*TE)

between wind speed and wind direction, or between relative humidity and temperature (Table 1 and Supplemental Tables S1–S4). The AIC values associated with simpler models omitting some of these factors indicated poorer fitting models, and in all 4 model sets, the null model was the worst performing model (Supplemental Tables S1–S4).

Spring flight heights decreased with decreasing barometric pressures, temperatures, and relative humidity across all wind directions (Supplemental Table S1). We found a substantial interaction between wind speed and wind direction. Spring flight height showed the strongest decreases with increasing wind speeds for headwinds and crosswinds. Tailwinds resulted in slightly increasing flight heights with increasing wind speeds (Fig. 2). Spring passage rates declined with increasing wind speed, but the rates varied by wind direction (Fig. 3a). Modeled spring passages declined at a faster rate when birds migrated with headwinds or crosswinds and showed only slight declines when tailwinds were present. Higher spring passage rates correlated with lower humidity when temperatures were higher regardless of wind direction (Fig. 3b–

d). In spring, passage rates were consistently low when mean flight heights were ≤ 125 m. The empirical mean and maximum passage rates were 39.3 and 120.0 targets/km/h, respectively, when

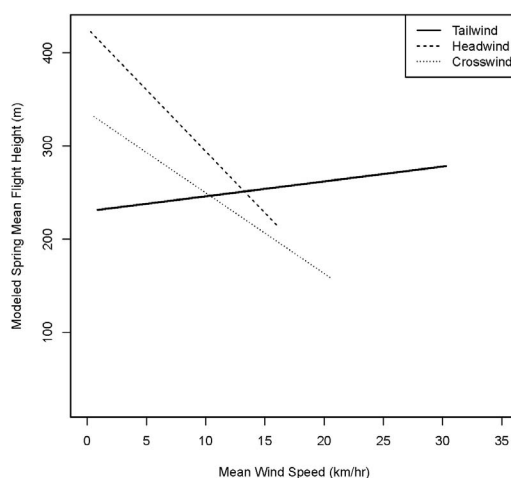


Figure 2. Interaction plots of wind direction (tailwind, headwind, or crosswind) and mean wind speed for modeled spring flight heights of nocturnal migrants along the Kittatinny Ridge, New Jersey. All other model variables are held constant at their mean values.

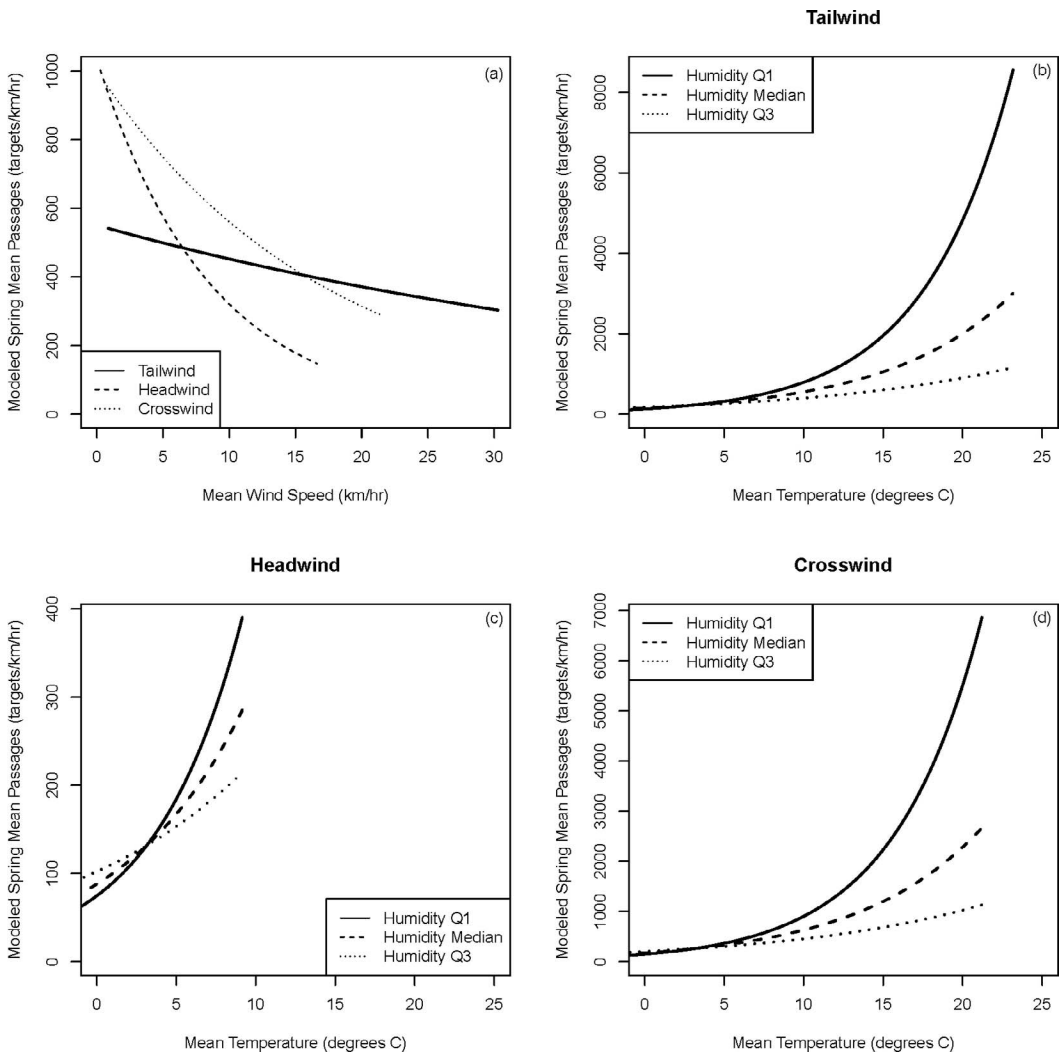


Figure 3. Interaction plots for modeled spring passage of nocturnal migrants along the Kittatinny Ridge, New Jersey: mean wind speed by wind direction with all other variables held constant at their mean values (a). Interactions between mean relative humidity and mean temperature by wind direction. Mean relative humidity is held constant at its quartiles and all other model variables are held constant at their means (b–d).

mean flight heights were ≤ 125 m, compared to a mean passage rate of 246 ± 59 targets/km/h during the entire spring season, indicating relatively low passerine collision risk during spring migration for the area we studied. Passage rates were also consistently low during nights when mean flight heights were ≤ 60 m.

Fall flight heights decreased with decreasing temperatures and relative humidity, but the relationships varied by wind direction (Fig. 4a–c). Decreases in fall flight heights with decreasing

temperatures were less rapid when relative humidity was higher; although, when temperatures fell below 5°C , flight heights were lower with lower relative humidity for tailwinds and crosswinds. We collected no observations with temperatures below 5°C for headwinds. The lowest flight heights occurred under tailwind and crosswind conditions when temperatures were below 5°C (Fig. 4a, 4c). Fall passage rates increased with increasing barometric pressure and were highest when wind speeds were lowest for all wind directions (Fig. 4d

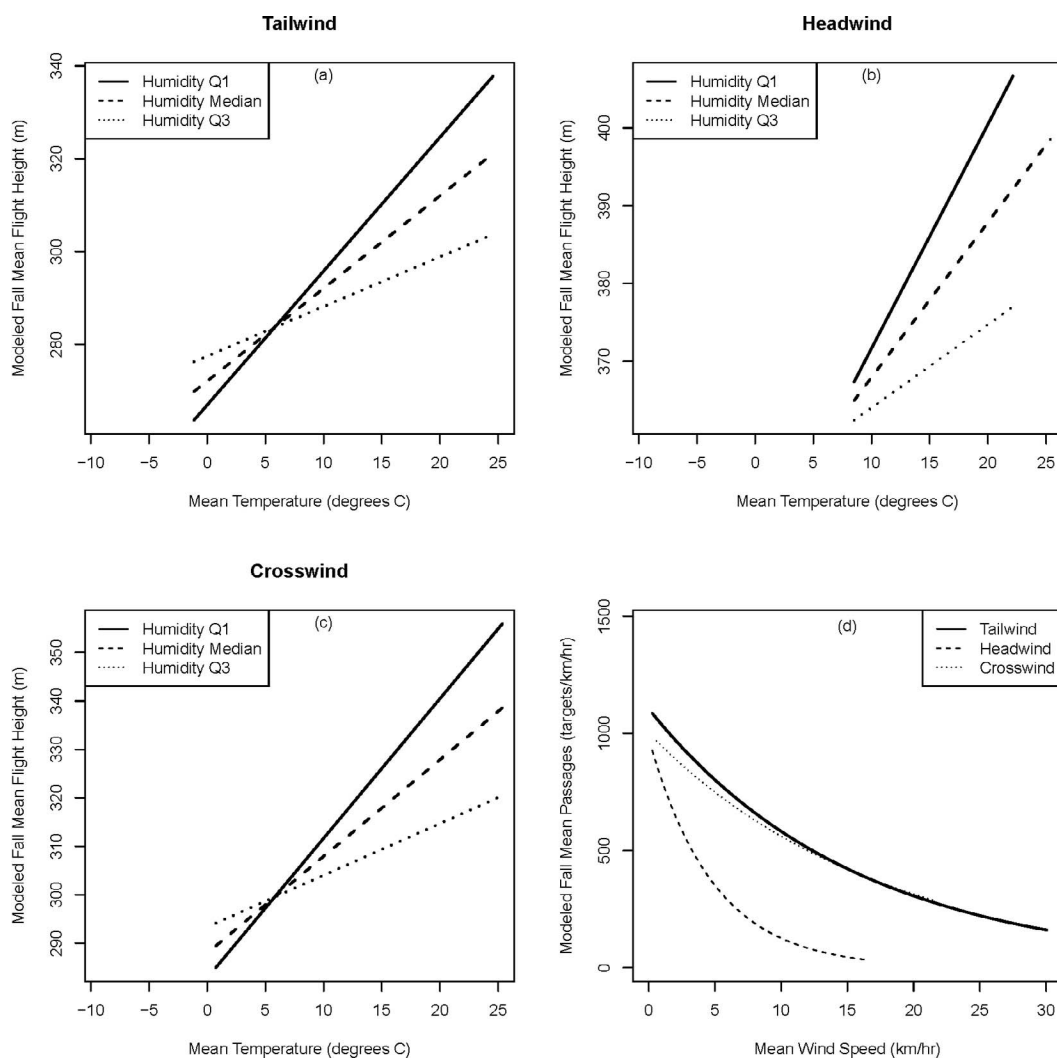


Figure 4. Effect of weather variables on nocturnal migration along the Kittatinny Ridge, New Jersey. Interaction plots between mean relative humidity and mean temperature by wind direction (tailwind, headwind, or crosswind) for modeled fall flight heights (a–c). Mean relative humidity is held constant at its quartiles and all other variables held constant at their mean values. Interaction between wind speed and wind direction for modeled fall passages (d), with all other model variables held constant at their means.

and Supplemental Table S4). The decline of fall passages with higher wind speeds was more gradual under tailwinds and crosswinds when compared to headwinds (Fig. 4d). In fall, passage rates were consistently low when mean flight heights were ≤ 125 m. The empirical mean and maximum fall passage rates were 26.1 and 53.3 targets/km/h, respectively, when mean flight heights were ≤ 125 m, compared to a mean passage rate of 216 ± 30 targets/km/h for the

entire fall season, indicating relatively low passerine collision risk during fall migration for the area we studied.

Discussion

To our knowledge, this is the first study to evaluate collision risk of nocturnal migrants near a transmission line using marine radar and weather data. Radar monitoring to detect or prevent avian

collisions is more frequently conducted at airports, communication towers, and wind energy facilities (Blokpoel and Burton 1975, Gauthreaux and Belser 2003, Gauthreaux and Schmidt 2013, D'Entremont et al. 2017).

For instance, at a proposed wind energy site in West Virginia, 28% of the ~17,000 nocturnal fall migrants flew below 200 m, potentially entering the rotor swept zone of planned turbines (Mabee et al. 2006). At an offshore wind facility site in The Netherlands, radar identified 50% of the 2.2 million birds flying within the rotor swept zone <115 m (Fijn et al. 2015), while D'Entremont et al. (2017) found that less than 20% of targets detected by radar used the airspace around the wind turbines (120 m tall). The collection of weather condition data as explanatory variables of flight heights and passage rates allows the development of statistical models to predict increased collision risk for nocturnal migrants along the Kittatinny Ridge and elsewhere.

Higher collision risk would likely occur when flight heights are low and passage rates are high. However, we observed consistently lower passage rates in spring and fall when mean flight heights were ≤ 60 m and ≤ 125 m, indicating relatively lower avian collision risk for this site. In our study area, several other factors also suggest limited collision risk at the S-R line. We only recorded ~2–4% of targets flying ≤ 60 m agl where risk of collision with the S-R line was a concern. Secondly, the line is positioned below the 200–700 m agl flight height of most migrants (Able 1970, Bellrose 1971, Mabee et al. 2006). Additionally, aviation warning lights on the S-R transmission towers only illuminate when triggered by signals from nearby aircraft. In a review of studies of avian collisions at communication towers, Longcore et al. (2008) concluded that removal of steady-burning lights and use of only synchronously flashing lights would reduce avian mortality at these towers.

Little is known about passerine collision risk on transmission lines, but research published on communication towers and wind generation facilities provides useful insight on how the height of an obstacle and other site variables can affect collision risk during nocturnal migration. Factors known to influence collision risk at communication towers include obstacle height, lighting color

and frequency, presence of guy wires, and obstacle position on the landscape (Longcore et al. 2008).

The addition of migrant flight height data to these risks is also important for comparison to heights of planned or existing flight obstacles. Longcore et al. (2013) concluded that weather conditions, such as strong winds that affect flight maneuverability or other conditions that reduce visibility, seem to increase avian collisions with anthropogenic structures.

In a worldwide literature review on avian collision at wind farms, Marques et al. (2014) stated that in areas with a high concentration of birds, such as migratory pathways, birds seem to be particularly at risk of collisions during migrations. Nocturnally migrating passerines are the most abundant species at wind farms and constitute the most common fatalities (Marques et al. 2014).

We observed variation in bird flight height between seasons related to weather conditions. In spring and fall, migrants flew lower with lower temperatures and decreased relative humidity across all wind directions. With increasing wind speeds, spring flight heights decreased rapidly for tailwinds and cross winds with the lowest heights when winds were > 10 km/h, while flight heights slightly increased with increasing wind speeds for tailwinds only. In fall, the lowest flight heights occurred when temperatures were $< 5^{\circ}\text{C}$ with low relative humidity and tailwinds or crosswinds. However, our measurements of wind direction, wind speed, and other weather variables occurred 5 m above ground level so, we had no information on the vertical distribution of wind or other weather variables at the heights many of the birds were migrating, which likely affected the accuracy of our models.

Birds in the Northern Hemisphere typically migrate when weather fronts create favorable tailwinds that include a southerly component in spring and a northerly component in fall (Able 1973, Alerstam 1990, D'Entremont 2017). Our findings along the Kittatinny Ridge add another datapoint to that general observation for the Atlantic Flyway. Our results were consistent with numerous other studies indicating the importance of wind direction and wind speed in avian nocturnal migration (Thomas et al. 2011, Kemp et al. 2013).

As reviewed in Kemp et al. (2013), several other studies concluded that migrants generally fly at higher heights with tailwinds than with headwinds (Kerlinger and Moore 1989, Richardson 1990, Bozó et al. 2018). In our study, spring and fall flight heights were lower with a tailwind, except in spring when wind speeds were >10 km/h. Other researchers have found that migration activity was higher when tailwinds were present (Åkesson and Hedenström 2000) and this was true for our study during fall for most wind speeds and for spring when mean wind speeds were >15 km/h. In a literature review of bird collisions with power lines, Bernardino et al. (2018) concluded that high tailwinds and crosswinds can increase collision risk as birds approach power lines faster and with less flight control and collision risk can also increase when birds are forced to fly lower under headwind conditions.

Although wind direction and wind speed were predictive in all 4 of our best models of flight height and passage rate, the final models also indicated that other variables such as temperature (3 of 4 models), relative humidity (3 of 4 models), and barometric pressure (2 of 4 models) were important. Our spring passage rate results were consistent with numerous other studies indicating birds prefer to migrate during warm, calm days with low relative humidity (Harmata et al. 1999, Gordo 2007, Bozó et al. 2018). Higher temperatures likely lead to increasing food resources during migration and warmer conditions may also relate to more benign weather, which would improve environmental conditions for migratory flight (Gordo 2007).

The use of marine radar is a useful tool for documenting flight heights of migrants around transmission lines. The radar, however, had limited monitoring capabilities at very low heights in our study due to the presence of trees on the top of Kittatinny Ridge. We were, however, able to detect low-flying birds at a minimum height of 12 m agl (fall) and 20 m agl (spring). Therefore, an unknown number of birds in our study could have gone undetected at very low flight heights. However, it is unlikely there are many birds migrating this low to the ground (Gauthreaux and Schmidt 2013), especially in a forested environment.

Although the S-R line comprised only 2% of the obstacles along the ridge, it was part of a broader

landscape of flight obstacles navigated bi-annually by nocturnal migrants. The results of this study and other similar studies conducted along migratory pathways could be used to predict nights where birds exhibit low flight heights around other obstacles along their migration path. These model predictions could improve detection rates for carcass searches, identify relatively rare collision events, or help evaluate design applications to further reduce collisions. For sites with topographic features that are likely to concentrate nocturnal migrants, Longcore et al. (2008) stated that radar studies could also be conducted before siting a tower (or other tall structures) so that impacts to migratory birds could be avoided at these sites.

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