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RESEARCH ARTICLE

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Heavy migration traffic and bad weather are a dangerous combination: Bird collisions in New York City

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Abstract

1. Bird–building collisions account for 365–988 million bird fatalities every year in the United States alone. Understanding conditions that heighten collision risk is critical to developing effective strategies for reducing this source of anthropogenic bird mortality. Meteorological factors and regional migration traffic may increase collision rates but also may be difficult to disentangle from other effects.
2. We used 5 years of bird collision counts in New York City to examine the influence of nocturnal weather conditions and bird migration traffic rates on collisions with buildings during spring and fall.
3. We found that seasonally unfavourable winds and conditions that impede visibility are important factors that increase the rates of bird–building collisions during both seasons. Specifically, northerly and westerly winds and low visibility in the spring and southerly and westerly winds and low cloud ceiling height in the fall are associated with higher collision risks.
4. Generally, these weather variables associated most strongly with increased collisions when nocturnal bird migration traffic was high, with the exception of low visibility in spring, which was predicted to triple collision rates compared to high visibility, independent of bird migration traffic.
5. *Synthesis and applications*: Although legislation to turn off unnecessary nocturnal lighting for the entirety of the migration seasons may be an ultimate goal, a proximate goal invaluable for reducing collisions will be predicting which nights will be of highest risk and using this information to determine when mitigation efforts could be most effective.

KEYWORDS
anthropogenic mortality, bird–building collisions, bird–window collisions, migration, nocturnal, urban, weather

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1 | INTRODUCTION

North American bird populations have dramatically declined during the past five decades (Rosenberg et al., 2019). Whereas the majority of these decreases have been attributed to habitat loss and degradation, collisions with buildings and other human-made structures are recognized as a significant source of mortality and a major threat to the conservation of bird populations (Loss et al., 2015; Rosenberg et al., 2019). Globally, the number of birds killed each year by collisions with buildings is likely in the billions, representing one of the greatest sources of human-related bird mortality on Earth (Klem, 2009). In the United States and Canada alone, building collisions may account for more than one billion bird fatalities annually (Loss et al., 2015).

Increased awareness of the substantial bird mortality caused by building collisions has led governments, building owners and conservation organizations to identify and implement solutions to reduce such mortality, which often include efforts to increase the visibility of glass to birds and initiatives to reduce night-time lighting during migration. However, these mitigation methods are not 100% effective (Basilio et al., 2020; Sheppard, 2019) and would be improved by better understanding the conditions that most influence collisions. Bird collisions are thought to be influenced by numerous interacting factors including urban design, artificial light at night, migration patterns and weather conditions (Basilio et al., 2020; Hager et al., 2017; Lao et al., 2022).

Urban architecture may impact the distribution and extent of bird collisions at multiple scales in the built environment through regional land use, individual and municipality-wide building architecture, building operations such as outdoor and indoor illumination and local- and landscape-scale layout of buildings and green spaces (Hager et al., 2017). At the building and local level, large facades that reflect nearby vegetation or that provide a line of sight to other outdoor spaces are associated with glass collisions (Gelb & Delacretaz, 2009; Hager et al., 2013, 2017). Daytime collision risk is therefore typically greatest at buildings that have relatively large amounts of glass on their facade, highly reflective glass and habitat nearby to attract birds (Hager et al., 2013; Riding et al., 2020). Many urban areas host high densities of migratory birds that use cities as stopover habitat. This may be due to the locations of many cities along migratory routes and the high proportion of impervious surfaces funnelling birds into remaining green spaces (Cohen et al., 2021; Mehlman et al., 2005; Seewagen et al., 2011).

Moreover, nocturnal light pollution draws migrating birds, which may be more prone to collision risk (Elmore, Hager, et al., 2021), towards cities (La Sorte, Hochachka, Farnsworth, Sheldon, Fink, et al., 2015; McLaren et al., 2018; Van Doren et al., 2021). The majority of North America's migratory birds are nocturnal migrants, and two and a half to five billion birds migrate through the United States at night annually (Dokter et al., 2018). Artificial light at night (ALAN) is thought to attract and disorient these nocturnally migrating birds (Korner et al., 2022; Lao et al., 2020; Riding et al., 2020; Van Doren et al., 2017; Winger et al., 2019). This may be reflected in the findings that bird collision rates are often highest overnight or in the early morning (Elmore, Riding, et al., 2021; Gelb & Delacretaz, 2009; Parkins et al., 2015; Riding et al., 2020). Even individually lit facades on a single building can have higher collision rates than darker facades (Van Doren et al., 2021). To mitigate the effect of ALAN on migrating species, local organizations have developed programmes to encourage building managers to retrofit dangerous glass and turn off unnecessary lights at night (Loss et al., 2023).

Migration patterns affect the abundance of birds in an area and strong correlations exist between daily migration passage numbers and building collisions (Van Doren et al., 2021). Pulses in bird migration traffic have led to extreme collision events (e.g. Bartels, 2017; Leffer, 2023). But large migration pulses do not always coincide with higher numbers of collisions; other variables, including weather, may also play an important role (Korner et al., 2022; Van Doren et al., 2021).

Weather affects migration patterns in many species by influencing when individuals start and end migratory flights (Erni et al., 2002; La Sorte, Hochachka, Farnsworth, Sheldon, Fink, et al., 2015; Richardson, 1990) and where they stop to rest and refuel (Clipp et al., 2020; Newcombe et al., 2019). Factors such as cloud ceiling height, visibility and wind speed also influence the flight altitudes and behaviour of nocturnally migrating birds (La Sorte, Hochachka, Farnsworth, Sheldon, Van Doren, et al., 2015). For example, extremely low cloud ceiling heights create low-visibility conditions that inhibit birds' navigation abilities (Panuccio et al., 2019), disorient and ground birds (Pastorino et al., 2017) and potentially increase the influence of ALAN (Panuccio et al., 2019).

However, little is known about the influence of weather conditions on bird collisions at the city scale (e.g. local scale, kilometres; Lao et al., 2022) and few studies have accounted for migration traffic when examining the relationships between weather and collisions (but see Scott et al., 2023). This is an essential consideration for separating weather conditions that encourage or support migration from those that increase an individual migrant's collision risk.

Here, we examined bird collisions over 5 years at 27 buildings in New York City, United States (NYC) to determine the effects of weather conditions (wind, visibility, temperature and cloud ceiling height) and nightly regional migration traffic on bird collisions. Based on the knowledge of how weather conditions influence migratory bird behaviour and the findings of Van Doren et al. (2021), we hypothesized that wind conditions and factors that influence visibility are related to collision rates and that these effects vary based on migration traffic. We assessed these effects separately for spring and fall and expected that the relationship between winds and collision rates would differ between the two migration seasons. Light reduction recommendations will thus be specific to each season to target nights of highest collision risk.

2 | MATERIALS AND METHODS

2.1 | Study site

New York City is one of the most densely populated cities in the United States, with a population of more than 8.8 million people within 487 km^2 (U.S. Census Bureau, 2021). It is a coastal city at the confluence of the Hudson River and Atlantic Ocean. An estimated 15–25 million birds pass over this metropolitan area annually (Migration Dashboard—BirdCast, n.d.). High densities of migrating birds that pass through the city use its parks and other green spaces as stopover habitat (Seewagen et al., 2011).

We used bird–building collision survey data from New York City Audubon's (NYC Audubon) Project Safe Flight (PSF) for spring and fall of 2017–2019, fall 2020, spring 2021 and fall 2021 to model relationships of collisions with weather conditions and regional migration traffic rates. PSF was suspended during spring 2020 due to the COVID-19 pandemic. Eleven buildings in downtown Manhattan were surveyed during the 2017–2020 spring and fall migration seasons. Eight additional buildings from uptown Manhattan, Brooklyn and Queens were surveyed during spring 2021. A total of 20 buildings in Manhattan and Brooklyn, nine repeated from previous seasons and 11 new, were surveyed during fall 2021 (Figure 1, Figure S1). This study's sample is not necessarily representative of citywide collision rates as buildings that were known or expected to be high collision hazards (i.e. buildings with large, unmitigated glass facades, near green spaces) were identified through local knowledge or a crowdsourced incidental collision reporting map (DBird, 2023) and specifically chosen to increase the likelihood of detecting collision events under a range of weather conditions.

2.2 | Bird collision data collection and cleaning

Project Safe Flight is an ongoing citizen science program that has monitored bird collisions in NYC during spring and fall migration since 1997. For our study, we designed survey routes that could each be covered in 10–60 min. Each route was monitored in one 'pass' around each building for every day of the week and covered one to six buildings, depending on the size of the buildings and their proximity to other buildings selected for monitoring. From 2017 to 2020, volunteers walked routes that totalled 2725 m in length each day, increasing to 5352 m in spring 2021 and to 5278 m in fall 2021. Volunteers walked their routes once per day and, for each building, recorded monitoring start and end time and the number of birds they found.

Most areas on the survey routes were sidewalks, but volunteers were instructed to also check for birds under nearby shrubs and other vegetation. All birds were removed to avoid double counting and injured birds were taken to a rehabilitation centre. All salvaging was conducted under a USFWS Special Purpose Salvage Permit (#MB107750-0) and New York State Department of Environmental Conservation License to Collect or Possess (#2541). No additional ethical permissions were needed for this research.

Collision monitoring for the spring took place from early April to early June, averaging 66 days each season (range 61–69), with the start and end dates varying depending on migration traffic. Collision monitoring in fall took place from late August to mid-November, averaging 70 days each season (range 67–76). All routes were walked between sunrise and 10:00 EST because collisions in NYC are thought to mainly occur during the early morning (Gelb & Delacretaz, 2009; Parkins et al., 2015). However, our collision counts are likely underestimates as collisions do also occur throughout the day and night and some birds may have been removed before a volunteer arrived (e.g. carried away by predators or swept up by janitors). We assumed that carcass removal rates were similar across all days of monitoring, as established in a similar area in NYC (Parkins et al., 2015). Birds that were injured from colliding with glass and succumbed later a distance away may have also gone unnoticed (Korner et al., 2022).

2.3 | Weather data collection

Wind conditions, temperature and precipitation strongly affect bird migration (Richardson, 1990). We obtained the mean nocturnal (dusk–dawn) values of the following measurements: zonal (east–west) and meridional (north–south) wind components, cloud ceiling height, visibility distance and air temperature (Table 1). Positive values of zonal wind indicate winds blowing from the west (westerly winds) and positive values of meridional wind indicate winds blowing from the south (southerly winds). We used weather data from the LaGuardia Airport weather station (station 725030; National Centers for Environmental Information, 2021), which is approximately 16 km from the farthest building monitored. This provided a local, proximate measure of observed weather conditions at ground level. We used these data because ground-level weather represents and correlates with the conditions birds experience when they interact with buildings and other ground-based structures and local weather conditions have been shown to affect collision rates in other cities (Van Doren et al., 2021). Cloud ceiling height and visibility distance are included as two measures of atmospheric conditions that may impact the altitudes at which birds fly and their ability to navigate. While low cloud ceiling height reduces visibility, other factors including haze and precipitation can also affect visibility. Therefore, although related, these two metrics have been shown to associate with bird collisions in different ways (Van Doren et al., 2021). Both may influence the navigational cues available to migrating birds and how they perceive skyglow from ground-based artificial lighting. Due to a highly skewed distribution, we converted visibility distance into a categorical variable and considered visibility "low" when visibility distance was <10 km, "medium" when visibility distance was between 10 and 16 km and "high" when visibility distance was >16 km.

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FIGURE 1 Twenty-seven buildings surveyed for bird collisions during spring and fall 2017–2021. The locations of these buildings within NYC are shown in the top map. Aerial image examples of buildings e, m and t are shown below the top map. The façades surveyed at each building are outlined in red and the seasons in which they were surveyed are shown in blue on the bottom right-hand table on each building map. Maps of the other 25 buildings can be found in Figure S1.

TABLE 1 Individual predictor variables included in the final spring and fall generalized linear mixed effects models of the effects of weather and migration traffic on bird collisions with buildings in New York, NY, 2017–2021.

				Min–max		Mean	
Variable	Units (abr.)	Source	Definition/how it was measured	Spring	Fall	Spring	Fall
Cloud ceiling height	Meters (m)	LaGuardia Airport weather station	The height above ground level (AGL) of the lowest cloud or obscuring phenomena layer aloft with 5/8 or more summation total sky cover, which may be predominately opaque, or the vertical visibility into a surface-based obstruction	75.18 to 22,000	126.81 to 22,000	9372	11,222
Zonal wind[a]	ms^{-1}	LaGuardia Airport weather station	East–west wind component (speed and direction) with positive values indicating winds coming from the west	−9.42 to 10.00	−7.96 to 8.46	0.28	0.35
Meridional wind[a]	ms^{-1}	LaGuardia Airport weather station	North–south wind component (speed and direction) with positive values indicating winds coming from the south	−6.55 to 6.48	−7.04 to 6.89	−0.57	−0.38
Temperature[a]	Degrees celsius (°C)	LaGuardia Airport weather station	The temperature of the air	2.11 to 29.31	3.75 to 28.65	13.63	17.57
Visibility	Low, medium, or high	LaGuardia Airport weather station	Visibility distance is the horizontal distance at which an object can be seen and identified	"low": <10,000 m; "medium": 10,000–16,000 m; "high": >16,000 m	"low": <10,000 m; "medium": 10,000–16,000 m; "high": >16,000 m	—	—
Average migration traffic	Number of individuals per kilometre per hour (# individuals/km/hr)	KOKX radar	The average number of individual birds passing by the radar per night	0.00 to 11481.98	0.00 to 9997.26	324.78	838.76
Year	—	—	The year	2017–2021	2017–2021	—	—
Date	—	—	The day of the year	91–159	224–319	—	—
Building	—	PSF	The building surveyed	—	—	—	—
Volunteer	—	PSF	The volunteer or pair of volunteers who conducted the survey	—	—	—	—
Collision counts	Individual birds per building per day	PSF	Recorded collisions from PSF	0–3	0–136	0.06	0.49

[a]Variables measured at 9 m AGL.

2.4 | Migration data collection

Weather surveillance radar is an important tool for monitoring bird movement and predicting migration densities (Clipp et al., 2020; Newcombe et al., 2019), and it has previously been used to link migration traffic to collisions (Elmore, Riding, et al., 2021; Van Doren et al., 2021). In brief, radar, which is commonly used for detecting meteorological events, also detects biological objects in the atmosphere (e.g. birds, bats, insects; Lack & Varley, 1945). The current network of weather surveillance radars in the United States provides near continuous coverage of the airspace above the contiguous United States, and the use of machine learning and cloud-based computational power and storage facilitates historical and near real-time analyses of meteorology and biology (Eschliman & Horton, 2020). The "MistNet" algorithm separates biological targets (e.g. birds) from non-biological targets (e.g. precipitation) (Lin et al., 2019). These data can be summarized as vertical profiles of reflectivity, which capture migration activity from 0 to 3000 m above-ground level approximately every 15 min. We obtained and processed radar data from the closest NEXRAD station (KOKX; 40.515° N, − 72.515° W) using the R package bioRad (Dokter et al., 2019), and used this to calculate nightly averages of regional migration traffic rates at KOKX (full methods in Appendix 2). The KOKX radar station is located just under 100 km from NYC, so this metric was not a direct calculation of the number of migrants in NYC and was treated as a regional measure of migration activity in the NYC area.

We conducted all downstream analyses in R (R Core Team, 2020). We subset the migration data into spring and fall dates for each year using the filter_vpts function from bioRad. We filtered out all diurnal scans using the check_night function and calculated nightly averages of migration traffic rate (# individuals/km/h).

We defined medium migration traffic as average migration traffic ($\bar{x} = 9.46 \times 10^2$ individuals/km/h in spring and 1.69×10^3 individuals/km/h in fall), low migration traffic as $\bar{x} - 1$ SD (4 individuals/km/h in spring and 9 individuals/km/h in fall) and high migration traffic as $\bar{x} + 1$ SD (1.86×10^3 individuals/km/h in spring and 3.42×10^3 individuals/km/h in fall).

2.5 | Statistical analyses

We standardized cloud ceiling height, zonal wind component, meridional wind component, temperature, day of year and average migration traffic variables to have a mean of 0 and a variance of 1 to aid model convergence. We did this using the scale() base R function, which uses the following equation: $(\frac{x - \bar{x}}{\mathrm{SD}})$, where $\bar{x}$ is the mean and SD is the standard deviation (R Core Team, 2020). We used ggpairs() from the GGally package (Schloerke et al., 2020) to check for correlations among cloud ceiling height, zonal wind, meridional wind, temperature and average migration traffic (Table S4).

We fit models as generalized linear mixed effects models (GLMM) with a log-link function and negative binomial distribution using the lme4 package (Bates et al., 2015). We chose a negative binomial distribution over a Poisson distribution due to overdispersion. We constructed separate models for spring and fall with the number of collisions as the response variable and included the following predictors in both models: cloud ceiling height, visibility (categorical), zonal wind, meridional wind, air temperature, average migration traffic, day of year (polynomial) and year (categorical). We included polynomial (quadratic and cubic) terms for day of year because of known non-linearity of collision rates across each season (e.g. Scott et al., 2023). We expected that migration traffic could affect how ceiling height, visibility, zonal wind and meridional wind influence collision rates. Therefore, in addition to the main effects, we included pairwise interactions between average migration traffic and these variables. Building and volunteer identity were included as random intercept terms to account for average differences in collision counts among buildings and volunteers (e.g. in building size and volunteer effort/skill). The building term also captures variation in the amount of distance covered because the lengths of the facades surveyed remain constant regardless of the day and volunteer.

To visualize model results, we generated model predictions while varying a given predictor and holding all other continuous predictors at their mean, except for day of year, which was held at its median value. For the categorical variables, we held year at 2017 and visibility at its reference value of "high". The 95% confidence intervals shown in Figure 2 are based on uncertainty from the fixed effects only and do not account for random effect variances, which quantify additional uncertainty across buildings and volunteers.

3 | RESULTS

Volunteers documented a total of 279 birds of 49 identified species (2.8×10^{-4} birds/m) during the four spring migration seasons and 1806 birds of 76 identified species (2.1×10^{-3} birds/m) during the five fall migration seasons. The number of casualties found per building per day ranged between 0 and 8 birds in spring and 0–136

FIGURE 2 Predicted number of collisions per building per day by zonal wind (a and d), meridional wind (b and e), visibility distance (c) and cloud ceiling height (f). Plots show model predictions for three important interaction variables for spring (a–c) and fall (d–f). Positive values of the zonal wind component indicate winds blowing from west to east and positive values of the meridional wind component indicate winds blowing from south to north. All other variables are held at their average value (except day of year which is held at its median value) or reference level (categorical variables). Continuous predictions are shown between the 0.05 and 0.95 quantiles of observed data. See Tables 2 and 3, Tables S4 and S5 for all model coefficient estimates.

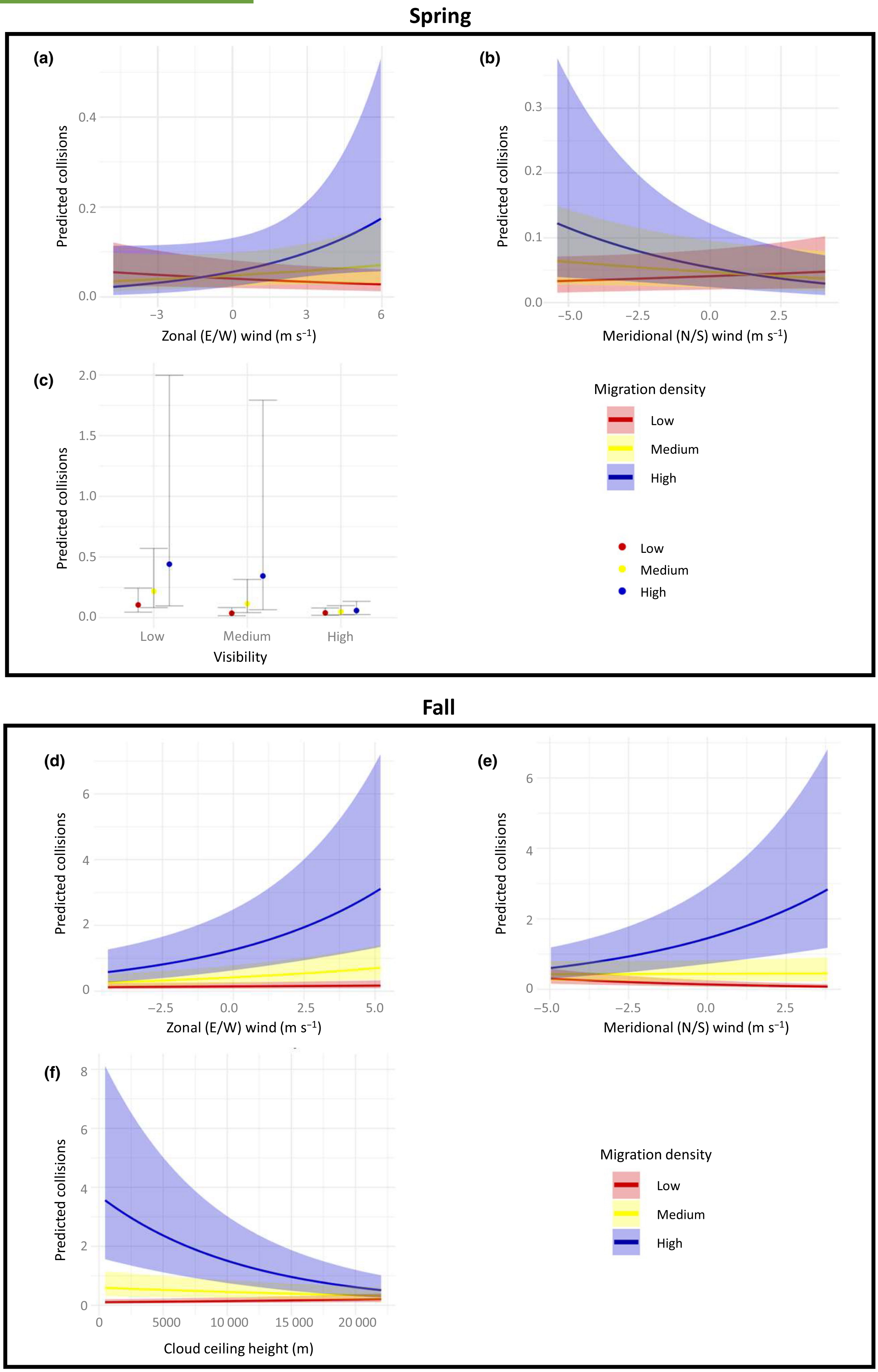
Spring
(a)
Predicted collisions
Zonal (E/W) wind (m s⁻¹)
(b)
Predicted collisions
Meridional (N/S) wind (m s⁻¹)
(c)
Predicted collisions
Low
Medium
High
Visibility
Migration density
Low
Medium
High
Low
Medium
High
Fall
(d)
Predicted collisions
Zonal (E/W) wind (m s⁻¹)
(e)
Predicted collisions
Meridional (N/S) wind (m s⁻¹)
(f)
Predicted collisions
Cloud ceiling height (m)
Migration density
Low
Medium
High

TABLE 2 Spring generalized linear mixed effects model of the effects of weather and migration traffic on bird collisions with buildings in New York, NY, spring 2017–2019 and 2021. See Table 1 for full details on the predictors. Predictors were scaled by calculating ($\frac{x-\bar{x}}{SD}$), where $\bar{x}$ is the mean and SD is the standard deviation.

Predictor	Exponentiated effect size	*z*-value	*p*-value
Ceiling height (scaled)	1.116	0.944	0.320
Visibility <10 km	3.185	4.291	<0.001
Medium visibility = 10 km–16 km	1.290	1.064	0.287
Zonal wind (scaled)	0.945	−0.479	0.632
Meridional wind (scaled)	1.014	0.146	0.884
Temperature (scaled)	1.017	0.126	0.900
Average migration traffic (scaled)	1.221	1.408	0.159
Date (scaled cubic)	1.519	0.057	0.954
Date^2 (scaled cubic)	1.378	−4.795	<0.001
Date^3 (scaled cubic)	1.289	−5.794	<0.001
Year = 2018	1.636	1.657	0.097
Year = 2019	0.816	−0.619	0.536
Year = 2021	1.855	1.795	0.073
Ceiling height (scaled) × average migration traffic (scaled)	0.905	−1.349	0.177
Visibility <10 km × average migration traffic (scaled)	1.705	1.238	0.216
Visibility = 10–16 km × average migration traffic (scaled)	2.567	2.032	0.0422
Zonal wind (scaled) × average migration traffic	1.525	2.303	0.021
Meridional wind (scaled) × average migration traffic	0.744	−2.713	0.007

TABLE 3 Fall generalized linear mixed effects model of the effects of weather and migration traffic on bird collisions with buildings in New York, NY, fall 2017–2021. See Table 1 for full details on the predictors. Predictors were scaled by calculating ($\frac{x-\bar{x}}{SD}$), where $\bar{x}$ is the mean and SD is the standard deviation.

Predictor	Exponentiated effect size	*z*-value	*p*-value
Ceiling height (scaled)	0.996	−0.066	0.948
Visibility <10 km	3.797	2.147	0.032
Medium visibility = 10–16 km	0.768	−1.754	0.079
Zonal wind (scaled)	1.236	4.000	<0.001
Meridional wind (scaled)	0.793	−4.055	<0.001
Temperature (scaled)	0.891	−1.285	0.199
Average migration traffic (scaled)	2.390	12.415	<0.001
Date (scaled cubic)	$2.291e^{-10}$	−4.583	<0.001
Date^2 (scaled cubic)	0.001	−2.694	0.007
Date^3 (scaled cubic)	33.570	1.281	0.200
Year = 2018	0.598	−2.273	0.023
Year = 2019	0.658	−1.538	0.124
Year = 2020	1.179	0.727	0.467
Year = 2021	1.492	1.540	0.123
Ceiling height (scaled) × average migration traffic (scaled)	0.704	−6.029	<0.001
Visibility <10 km × average migration traffic (scaled)	40.226	2.744	0.006
Visibility = 10–16 km × average migration traffic (scaled)	0.707	−1.505	0.132
Zonal wind (scaled) × average migration traffic	1.191	3.073	0.002
Meridional wind (scaled) × average migration traffic	1.512	7.977	<0.001

birds in fall. For the cumulative total collisions across all 4 years of spring monitoring, the most common species found were black-and-white warbler (*Mniotilta varia*), common yellowthroat (*Geothlypis trichas*), northern parula (*Setophaga americana*), ovenbird (*Seiurus aurocapilla*) and white-throated sparrow (*Zonotrichia albicollis*; Table S1). However, these patterns did not hold true within each season (Table S1). Other top species within at least two seasons included American redstart (*Setophaga ruticilla*) in spring 2017, spring 2019, fall 2019 and fall 2021; American woodcock (*Scolopax minor*) in spring 2017 and spring 2021; magnolia warbler (*Setophaga magnolia*) in spring 2017 and spring 2018; and pine warbler (*Setophaga pinus*) in spring 2019 and fall 2019. More than 96% of the individuals identified to species in our data set are classified as nocturnal migrants (Table S1).

Nightly migration traffic averaged 337 ± 951 birds/km/h across the four spring monitoring seasons (range = 0–11,482 birds/km/h) and 795 ± 1311 birds/km/hr across the five fall monitoring seasons (range = 0–9997 birds/km/h).

3.1 | Spring model

Collision numbers varied throughout the spring, slightly decreasing from early April until mid-April before increasing and peaking around mid-May. Collisions then continuously decreased throughout the rest of the season. Migration traffic alone and wind conditions alone were not significant predictors of spring collisions. However, when migration traffic was high, northerly (negative meridional) and westerly (positive zonal) winds were strongly associated with an increased number of collisions (Figure 2a,b; model interaction terms Table 2). Low visibility conditions were associated with significantly more collisions, with a 3.18-fold mean increase in the number of collisions compared to high visibility conditions (Figure 2c; Table 2). Differences in collision counts were not statistically significant under medium visibility conditions compared to high visibility conditions. In addition, although there was some evidence of an interaction between medium visibility and migration traffic, overall, medium visibility did not have a meaningful effect on collisions (Figure 2c; Table 2). Cloud ceiling height and temperature were not significantly associated with spring collisions.

3.2 | Fall model

Collisions during the fall were highest in September, peaking around mid-September and then decreasing until the end of the season in mid-November. Wind, cloud ceiling height and migration traffic were significant predictors of fall bird collisions (Table 3). When fall migration traffic was high (model interactions terms Table 3), southerly (Figure 2d) and westerly (Figure 2e) winds as well as lower cloud ceiling heights (Figure 2f) were associated with increases in bird collisions. Our results indicated no significant relationship between fall collision rates and visibility or temperature.

4 | DISCUSSION

Collision monitoring efforts provide a unique opportunity to study a major source of mortality for birds during their annual cycles, and each new study fills a gap in our still imperfect knowledge about the true magnitude of birds killed in collisions with buildings. The effects of weather conditions (Lao et al., 2022; Lin et al., 2019; Panuccio et al., 2019; Scott et al., 2023) and nocturnal migration traffic (Elmore, Riding, et al., 2021) have been identified individually as factors in bird–building collisions. Our study provides evidence that these factors should be considered in tandem to predict bird collisions and to provide more nuanced guidance for the timing of collision mitigation programs such as Lights Out initiatives. Across a major urban centre, we found collisions increased with unfavourable wind directions and low visibility in spring and low cloud ceiling height in fall. The influence of these weather conditions generally intensified when migration traffic was high. This highlights the importance of both weather and migration traffic for predicting and attempting to mitigate scenarios in which bird collision potential is high, and how strongly collision risk varies within migration seasons.

4.1 | Weather associations

We found higher collision counts to be associated with northerly and westerly winds in spring and southerly and westerly winds in fall. In spring, birds migrate north and, therefore, headwinds from the north are unfavourable. Conversely, in fall, when birds are flying south towards their wintering grounds, winds coming from the south are unfavourable. These relationships may be partly explained by the effect of unfavourable wind conditions on migratory flight behaviours: Birds are expected to fly at lower altitudes when flying against unfavourable winds, which may increase their risk of collision with ground-based structures during migratory flight (Gauthreaux, 1991; Komenda-Zehnder et al., 2010).

Westerly winds were associated with increased collision counts under high migration traffic in both seasons. This likely reflects the geography of the region: NYC lies on the east coast of North America, and westerly winds push migrating birds towards the coast (Horton et al., 2016), causing migrants to concentrate in coastal areas where they may also fly at lower altitudes while attempting to maintain or regain an overland track (Van Doren et al., 2016). A similar effect occurs in Chicago (flanked to the east by Lake Michigan) where westerly winds are also associated with increased collision risk (Van Doren et al., 2021).

In our study, collision counts were strongly associated with low visibility conditions in spring and low cloud ceiling height in fall, the latter primarily after nights of high migration traffic. These unfavourable visibility conditions reduce birds' navigational abilities, which can lead them to fly to lower altitudes in search of suitable stopover habitat while they wait for conditions to improve (Panuccio et al., 2019; Pastorino et al., 2017). Low cloud ceiling and fog also disorient birds by reflecting light and amplifying ALAN and skyglow (Panuccio et al., 2019). Unfavourable weather conditions may also lead to birds becoming grounded or making navigational or flight errors in close proximity to dangerous glass expanses (Lao et al., 2022; Scott et al., 2023).

We opted to use weather data from LaGuardia airport's weather station because it provided a local, proximate measure of real weather conditions at ground level (and ceiling cloud height), and our results demonstrate that these conditions are important predictors of bird collisions. An alternate measure of weather could account for high altitude winds, which may have particularly important effects on high-altitude migration. We recommend that further research examine potential altitude effects of winds and migration traffic on bird collision rates. Similarly, our study examined bird–building collisions at a city scale and we assumed our use of weather variables represented atmospheric conditions across the entire city (i.e. ~500 km^2). However, tall buildings can sometimes introduce high wind speeds at pedestrian-level altitudes (Blocken et al., 2016). Our findings may not necessarily hold true in parts of the city that experience such "wind tunnel effects". We recommend future studies to gather building-level weather condition data as part of bird collision monitoring.

4.2 | Migration effects

More birds migrate through NYC in fall than in spring. This difference stems from the presence of migrating juveniles in fall (Dokter et al., 2018) and the use of more easterly routes in fall compared to spring (La Sorte et al., 2014). As expected, and similar to studies in other cities in North America (Lao et al., 2022; Scott et al., 2023), we found that radar-measured migration densities were generally higher in fall and that more collisions were recorded in NYC in fall than the spring.

We found strong evidence that migration traffic affected the influence of weather on collision counts within seasons as well as between them. Specifically, the effects of wind conditions and cloud ceiling height on collisions were greatly amplified on nights with high migration densities. In other words, these weather conditions only influenced collision counts when there was a relatively high abundance of birds migrating over NYC the previous night. Lao et al. (2022) also found that collision risk in Minneapolis increased during nights with unfavourable weather conditions, especially when following conditions that had favoured migration.

It is currently unclear how overnight radar-estimated migration traffic is correlated with the number of live birds on the ground the next morning. Some studies have found evidence of a correlation (Elmore, Riding, et al., 2021; Komenda-Zehnder et al., 2010) while others, including from NYC, have not (Fischer et al., 2012). Stopovers in NYC and other cities can span several days (Seewagen & Guglielmo, 2010), so not all birds in a city on a given morning migrated the previous night. Additionally, many nocturnal migrants are likely to pass over cities without stopping. However, our results do suggest that migration traffic is a driving factor in collision rates.

4.3 | Species composition

Most birds found were migrant species, with few records of resident species. This supports Parkins et al. (2015) and other previous findings that collisions that occur at locations without bird feeders mainly involve migrants (Elmore, Hager, et al., 2021; Gelb & Delacretaz, 2009; Loss et al., 2014). The most frequent collision victims in our study were similar to studies in Chicago, IL and Cleveland, OH (Winger et al., 2019) as well as in continent-scale analyses (Elmore, Hager, et al., 2021; Loss et al., 2014). Our study did not compare collision counts to overall abundance of each species in NYC, so we cannot comment on whether certain species were more at risk of colliding with buildings. The higher collision counts of neotropical warblers in ours and other studies do bring to question whether collisions are an outsized problem for longer distance migrants, which is a topic that warrants further research.

4.4 | Conservation implications

ALAN and the use of glass in building facades are two major contributors to bird–window collisions. To prevent collisions, two mitigation methods are often employed. One aims to make glass windows safer for birds by retrofitting them with bird-safe materials, and legislation has been introduced in NYC and other urban areas to require the use of such materials in new construction. The second mitigation method addresses ALAN. Lights Out community-led initiatives are an important tool for decreasing bird–building collisions, and Lights Out campaign efforts can help to reduce the impacts of ALAN on migrating birds (Loss et al., 2023). While it is difficult to eliminate all night-time lighting in urban centres like NYC, targeting nights of highest collision risk can improve the efficacy of these programs as some building managers may be more willing to participate if they only need to turn off night lighting during a subset of the migratory season. Current Lights Out efforts and migration alerts are based solely on the number of birds aloft, but we show that weather conditions are important determinants of collision risk at a city scale. We recommend that Lights Out efforts in NYC target spring nights when visibility is low and nights with predicted heavy migration and northerly or westerly winds. In the fall, Lights Out campaigns in NYC should focus on nights of forecasted high migration combined with low cloud ceiling height and/or southerly or westerly winds. Enacting city-wide, permanent collision reduction policies can be a slow process. In the meantime, weather and migration forecasts will be a valuable tool to help building owners and managers take smaller steps towards contributing to a safer environment for birds.

AUTHOR CONTRIBUTIONS

Katherine Chen, Sara M. Kross, Kaitlyn Parkins, Chad Seewagen, Andrew Farnsworth and Benjamin M. Van Doren conceived the ideas and designed the methodology; Katherine Chen, Kaitlyn Parkins and Benjamin M. Van Doren collected the data; Katherine Chen and Benjamin M. Van Doren analysed the data; Katherine Chen, Sara M. Kross and Benjamin M. Van Doren led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.41ns1rnmw (Chen et al., 2024).

STATEMENT OF INCLUSION

Our study was conducted by a team of researchers based in and around our study area.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix 1. Further details on avian species represented in collision data, study sites and correlation coefficients for predictor variables.
Appendix 2. Expanded methods for quantifying regional migration traffic.

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