# Low migratory flight altitudes may explain increased collision risk for American Woodcock (*Scolopax minor*)

# Abstract

Understanding bird migration at low altitudes is critical to evaluating risk of collision with obstacles. Recent advances in satellite tracking technologies allow quantifying use of low altitudes by small migrating birds with a high level of precision, allowing species-level inference into potential collision risk based on flight altitude. The American Woodcock (*Scolopax minor*) is suspected to be a low altitude migrant due to its frequent collisions with buildings, and subsequent mortality during migration may be contributing to population declines. We investigated migratory flight altitudes using satellite transmitters deployed on woodcock in 2020–2024 and examined how flight altitudes compare to the heights of common airspace obstacles. Each transmitter recorded a nocturnal GPS location with an altitude reading every 1–3 days during fall and spring migrations. We implemented a Bayesian hierarchical mixture model to identify whether locations were recorded on the ground or during flight, isolate measurement error, and describe the distribution of flight altitudes. We found that migrating woodcock fly at mean altitudes of 379 m above ground level, flying higher during spring (mean: 444 m, 95% credible interval: 333–578 m) than fall (338 m, 95% CRI: 267–423 m). Woodcock flight altitudes were frequently lower than could be observed using weather radar (27% of observations), and 57% of observations fell within the altitude range of ≥1 airspace obstacle. Our results suggest that woodcock fly at altitudes lower than reported for most nocturnal migrants, which likely contributes to their vulnerability to obstacle collisions. Woodcock provide an example of how vulnerability to obstacle collisions during nocturnal migratory flights are often species-specific, and mitigation efforts should incorporate measures aimed at reducing collisions during both diurnal stopovers and nocturnal migratory flights to effectively reduce bird collision mortality.

Keywords

American Woodcock, *Scolopax minor*, migration, altitude, airspace, collision, transmitter

# Lay summary

* Collision with airspace obstacles (including buildings, wind turbines, and communication towers) is a major source of mortality for migratory birds.
* In this study, we examined the flight altitudes of American Woodcock equipped with GPS transmitters in 2020–2024 and compared their flight altitudes to common airspace obstacles.
* We found that woodcock fly lower than most nocturnal migrants, and 57% of observations fell within the altitude range of at least one airspace obstacle.
* These low altitude flights may contribute to American Woodcocks’ increased vulnerability to collisions with airspace obstacles.

# Introduction

Avian migratory flights can be studied using a wide range of techniques, including GPS and satellite telemetry, altimeters, imaging, and radar (Thaxter et al. 2016). These tools can be used to describe the altitudinal distributions of nocturnal avian migrants and examine how those altitudes shift in response to wind, weather, and artificial light during migration (Bauer et al. 2019). Research has focused on how these factors influence the risk of bird collision with obstacles (Lao et al. 2020), although there are still knowledge gaps regarding low altitude flights that put birds within range of airspace obstacles (<200m above ground level, hereinafter AGL). Obstacles present at these altitudes include buildings (365–988 million bird collisions per year, Loss et al. 2014), wind turbines (234,000 bird collisions per year, Loss et al. 2013), and communication towers (4–5 million bird collisions per year, Gehring et al. 2011). Flights at obstacle height can be difficult to study due to blind spots in weather radar at low altitudes (Rogers et al. 2020), although some radar studies have had success in quantifying their prevalence. Cohen et al. (2022) estimated that 35% of birds migrating along the Great Lakes shorelines passed through the rotor swept zone of a wind turbine at some point during their migratory flight, and White et al. (2020) found that migrating bird densities near Lake Erie remained highest below 400 m, even during peak migratory periods. Despite the utility of these studies, radar is generally limited to making inferences about overall patterns in bird migration and cannot provide insights into susceptibility to obstacle collisions at a species level. Species-level insight is particularly important as not all species are equally susceptible to obstacle collisions; Nichols et al. (2018) identified 13 species and 7 genera as “supercolliders”, or taxa that are found more often after obstacle collisions than expected, given their population size. Gathering species-level data regarding use of low altitudes would allow one to determine whether flight altitude is contributing to the increased risk of collision with obstacles for these species.

Gaining species-level insight into flight altitudes requires the use of bird-borne telemetry equipment, usually altimeters or GPS transmitters (Thaxter et al. 2016). Transmitters come with their own set of drawbacks: they are expensive to deploy, collect far less data than other techniques, and are usually limited to birds above a specific mass. However, telemetry equipment can be used to make inferences about species-specific flight altitude, including both high and low altitudes, and in the case of GPS transmitters, can often do so with very high precision. Several studies have described low altitude flights using GPS transmitters, including Bowlin et al. (2015), who found that of 13 tracked Swainson’s Thrush (*Catharus ustulatus*) migratory flights, one bird spent over an hour flying at altitudes <100 m before rising to altitudes of 300–500 m. A second thrush spent the entirety of its ~2 hr migratory flight at an altitude of ~40 m. Galtbalt et al. (2021) found that Whimbrel (*Numenius phaeopus*) and Far Eastern Curlew (*Numenius madagascariensis*) have overwater median flight altitudes of 132 m and 156 m above sea level, respectively, although those altitudes increase to 718 m and 538 m when flying over land. Further transmitter studies focusing specifically on birds that are highly susceptible to collisions with airspace obstacles may allow one to better understand the prevalence of low altitude flights among these species, and how those flights influence collision risk.

American Woodcock (*Scolopax minor*) are an upland species of Scolopacid distributed throughout eastern North America. They are among the earliest avian migrants in spring (February–May) and the latest migrants in fall (October–December), likely timing their migration based on the availability of earthworms, which are their preferred prey (Fish et al. 2024, Berigan 2024, McAuley et al. 2020). Woodcock have long been thought to migrate at low altitudes; even before tracking data were available, Mendall and Aldous (1943) estimated that woodcock migrate at altitudes of 12–15 m based on the high rate of woodcock collisions with power, telephone, and telegraph lines. Woodcock deaths are frequently attributed to building collisions in major USA cities such as Minneapolis (Loss et al. 2019) and Chicago (Van Doren et al. 2021), and mass building collision events occurred when woodcock were caught in snowstorms during their early spring migration (Loss et al. 2020). Woodcock migratory mortality may be a potential causal factor in their decline of 0.8% per year since the 1960s (Cooper and Rau 2012, Loss et al. 2020). No studies, to the best of our knowledge, have quantified woodcock flight altitudes, or examined how those altitudes might impact their vulnerability to collision with airspace obstacles.

Here we investigated the propensity for the American Woodcock to fly at low altitudes during migratory flights and examined how flight altitudes compared to the altitudinal distributions of common airspace obstacles. We also quantified the proportion of woodcock flight locations that fell below a threshold detectable by weather radar to provide some context for comparing our estimates to other studies. We hypothesized that woodcock flight altitudes would fall below mean estimates for nocturnal migrants (418–459 m AGL; Horton et al. 2016) and would frequently fall within altitudinal ranges corresponding with obstacles such as buildings, wind turbines, and communication towers, based on high rates of collisions for this species (Mendall and Aldous 1943, Loss et al. 2020). We also postulated that woodcock flight altitudes would be lower in fall than spring, in accordance with general trends in nocturnal migrants (Horton et al. 2016), and that flight altitudes would be similar among age and sex classes due to minimal differences in morphological characteristics among these classes (McAuley et al. 2020, Agostini et al. 2023). Our analysis aimed to determine the vulnerability of woodcock and other nocturnal migrants to airspace collisions during migratory flights, and the necessity for further study of low altitude movements of birds in general.

# Methods

## Data collection and preprocessing

We collected woodcock locations with altitude readings from 2020 to 2024 using GPS transmitters as a part of a larger collaborative effort by the Eastern Woodcock Migration Research Cooperative (Blomberg et al. 2023, Clements et al. 2024, Fish et al. 2024). We captured woodcock at 100 sites across the eastern portion of their range, including Alabama, Florida, Georgia, Louisiana, Maine, Maryland, New Jersey, New York, North Carolina, Nova Scotia, Ontario, Pennsylvania, Québec, Rhode Island, South Carolina, Vermont, Virginia, West Virginia, and Wisconsin. We caught woodcock using a combination of spotlights and mist nets (McAuley et al. 1993). We aged and sexed birds upon capture, where we classified birds undertaking their first fall and spring migrations as juveniles, and all other birds as adults. We then attached 4–7 g PinPoint transmitters (Lotek Wireless Inc., Newmarket, Ontario, CA) using a rump-mounted leg loop harness (Fish et al. 2024).

We programmed transmitters to collect locations every 1–3 days during migration, with locations alternating between diurnal (1300–1500 hours Eastern Time) and nocturnal (0000–0100 hours) times. Transmitters recorded time, latitude, longitude, and GPS-derived altitude above the WGS84 ellipsoid, and transmitted data back to the ARGOS satellite constellation after every third location. We subset these locations to include only those within the migratory classification dataset produced by Berigan (2024). This dataset classified individual locations as migratory or non-migratory based on the assumption that migration starts after the first ≥16.1km movement and ends after the final ≥16.1km movement of the season. We used ArcGIS Pro 3.2.1 (ESRI 2024a) to calculate the difference between the altitude and orthometric elevation recorded for each location (ESRI composite elevation layer; ESRI 2024b), providing a measurement of altitude above ground level for each point.

We classified data for our models based on prior descriptions of woodcock activity patterns. Woodcock are ground-feeding birds that rarely fly outside of crepuscular hours (Rabe et al. 1983). When rare diurnal flights do occur, they are generally brief, comprising 1–3% of diurnal time budgets, and close to the ground (McAuley et al. 2020). We therefore made a modeling assumption that all diurnal locations could be treated as though they were known to be recorded on the ground (hereinafter “known ground locations”). As woodcock are nocturnal migrants, we define potential flight locations as all points that were nocturnal, occurred during migration based on the classification in Berigan (2024), and were preceded and followed by >6.68 km steps (defined as lines connecting consecutive locations). The 6.68 km threshold was based on the 99th percentile of step lengths recorded within a stopover site (Berigan 2024). Ensuring that the preceding and following steps were >6.68 km increased the likelihood that the bird had moved away from a stopover site before the point was recorded.

## Modeling altitude distributions

Our model of woodcock flight altitudes included both potential flight locations and known ground locations, with each class of data informing a different aspect of the model. Known ground locations were assumed to always have a true altitude of 0 m, making their recorded altitudes solely attributable to measurement error by the GPS units. The recorded altitude of a ground location *i* can be modelled as follows:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 1 |

where represents degrees of freedom, is the mean error observed across all observations and is the scale parameter associated with the error. As such, the known ground locations can be used to directly inform the measurement error term , which we assume remains consistent between ground and flight locations. We chose to model using a Student’s t-distribution due to the distribution’s flexibility in modeling heavy tails, which are frequently observed in altitudinal measurement error distributions (Péron et al. 2017).

For potential flight locations there are two possible outcomes. They can be recorded on the ground, in which case = , or recorded in flight with altitude , in which case = + . This can be modelled as follows:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 2 |

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 3 |

Where for each location *i* that is identified in flight (i.e., = 1) is drawn from a log-normal distribution with location parameter and scale parameter . We chose a log-normal distribution because it accommodated a heavy right tail, which is a common feature of bird altitude distributions (White et al. 2020). The flight status of the birds is the function of a Bernoulli distribution

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 4 |

Where is the proportion of true flight locations among all potential flight locations. As the programming language we used (i.e., Stan) does not support sampling discrete parameters, we expressed Eq. 4 through a latent discrete parameterization described in Stan Development Team (2024).

All parameters in the model received vague priors. The measurement bias in the data, , and location parameter for the flight distribution, both received normal priors with mean 0 and standard deviation 1. The standard deviation of the measurement error, , and the scale parameter for the flight distribution, both received half-normal priors with mean 0 and standard deviation 1. The proportion of true flight locations among all potential flight locations, , received a beta distribution prior where both the α and β shape parameters were set to 2. The degrees of freedom in the measurement error distribution, , received a gamma distribution prior with an α of 2 and a β of 0.1, following suggestions for vague priors of ν in Juárez and Steel (2010).

Season, age, and sex models received a similar formulation to the base model, with the only difference being the use of group-specific (*g*) , , and parameters

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 5 |

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 6 |

where the , , and parameters were dependent on the season, age, or sex class associated with any given altitude observation. This model structure allowed the distribution of flight altitudes to be estimated for each season, age, and sex class separately, but with shared inference of error terms and as we had no *a priori* reason to believe that GPS measurement error would change as a function of these classes.

We implemented these models in a Bayesian framework using the R package *rstan* (Stan Development Team 2024, R Core Team 2024) running 4 chains at 15,000 iterations with 7,500 warmup iterations. We checked all models for convergence using trace plots and ensured that potential scale reduction values were <1.1 (Brooks and Gelman 1998). As Bayesian models often perform better with scaled variables, we scaled our estimated flight altitudes between 0 and 1 for modeling, and back-transformed all parameter estimates into meters above ground level for evaluation. We described the posteriors of flight altitude distribution parameters by simulating a log-normal distribution for each posterior value of and , and sampling the mean, median, standard deviation, and skewness of each simulated distribution. We estimated the number of flight locations from the base, season, age, and sex models by multiplying posterior values of by the number of potential flight locations in each dataset. We summarized posteriors for all parameters using median values and highest density credible intervals (CRI) since they allow for more conservative estimates when posterior densities are skewed (Kruschke 2014, Makowski et al. 2019). We also calculated the probability of superiority, or the likelihood of one group having a higher parameter value than another group, for season, age, and sex models following Ruscio (2008).

## Comparison of flight altitudes to weather radar and airspace obstacles

We used derived metrics from our model to assess how often woodcock flight altitudes occurred in the altitude range typically detected by ground-based radar and how they coincided with height intervals associated with common airspace obstacles that pose collision risk. We calculated these metrics by simulating a log-normal distribution for each posterior value of and , and measuring the proportion of each simulated distribution which fell below or within the given height interval. We compared woodcock flight altitudes to the minimum altitude (120 m) detected by Horton et al. (2016) using the Next Generation Weather Radar (NEXRAD) system, a weather radar system in the USA frequently used to study bird migration (DeMott et al. 2022, Horton et al. 2023). We quantified the proportion of simulated flight altitudes that fell below a 120-m threshold, representing the proportion of locations that would not be detectable by weather radar. As low-rise buildings (defined as residential buildings 4–11 stories and non-residential buildings ≤11 stories) result in the majority of window collision mortalities in the United States (Loss et al. 2014), we also quantified the proportion of simulated flight altitudes below the height of an 11-story building (47 m). We estimated the proportion of simulated flight altitudes that fell within the rotor swept zone of the average land-based wind turbine installed in 2022 (32–164 m; Wiser et al. 2023). Finally, we measured the proportion of simulated flight altitudes that fell below the height of a 305-m communication tower, as these towers are responsible for 5–70x as many collisions as shorter towers (Gehring et al. 2011).

# Results

We collected 16,293 GPS locations with altitude recordings from 344 individuals. Most of these locations (9,658) were recorded at 1300–1500 Eastern Time and were classified as known ground locations. Of those locations remaining, 258 met the criteria to be possible migratory locations (106 individuals). These locations were broadly distributed throughout the eastern portion of the woodcock’s range (Figure S1). The base model predicted that 144 of these locations were most likely recorded when the bird was in flight (95% CRI: 127–161; Table 1). Estimated median flight altitude above ground level was 262 m, and mean flight altitude was 379 m. Woodcock flew at mean altitudes of 338 m in fall and 444 m in spring, with 94% probability that mean flight altitudes were lower in fall than spring. Adult woodcock flew at mean altitudes of 431 m while juveniles flew at altitudes of 371 m, with 79% probability that mean flight altitudes were higher for adults than juveniles. Male woodcock flew at mean altitudes of 417 m while females flew at altitudes of 352 m, with 82% probability that mean flight altitudes were higher for males than females (Figure 1). Additional statistics describing the shape of these distributions are provided in Table S1.

Over half (57%) of simulated flight altitudes were below 305 m, posing potential risks for collisions with low-rise buildings, wind turbines, and communications towers (Table 2, Figure 2). Woodcock were equally likely to fly within range of low-rise buildings in fall and spring, while they were 6% more likely to fly within the rotor swept zone of wind turbines and 9% more likely to fly at communication tower altitude during fall. Twenty seven percent of simulated flight altitudes were below the minimum flight altitude reported in Horton et al. (2016) and likely would not have been detectable using NEXRAD weather radar.

Table 1. Sample size and distribution of American Woodcock (*Scolopax minor*) altitudes above ground level during migratory flights, measured using the base model as well as season, age, and sex models. Estimates indicate the median value of the posterior distribution, while highest density credible intervals are provided in parentheses. Note that some individuals were missing age and sex data and were excluded from respective models. Altitude data were collected using GPS transmitters in the eastern portion of the woodcock’s range from 2020 to 2024.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Model | Individuals1 | Locations2 | Estimated number of flight locations3 | Mean altitude (m) | Median altitude (m) |
| **Base** | 106 | 258 | 144 (127–161) | 379 (320–447) | 262 (218–304) |
| **Season** |  |  |  |  |  |
| *Fall* | 54 | 118 | 76 (65–88) | 338 (267–423) | 242 (188–296) |
| *Spring* | 59 | 140 | 67 (54–80) | 444 (333–578) | 295 (220–376) |
| **Age** |  |  |  |  |  |
| *Adult* | 44 | 98 | 55 (45–65) | 431 (317–581) | 291 (218–374) |
| *Juvenile* | 49 | 134 | 75 (63–88) | 371 (295–465) | 266 (210–324) |
| **Sex** |  |  |  |  |  |
| *Male* | 52 | 121 | 72 (61–83) | 417 (326–532) | 289 (225–356) |
| *Female* | 49 | 128 | 66 (54–78) | 352 (270–456) | 247 (184–310) |

1 Number of individual birds which recorded potential flight locations.

2 Number of potential flight locations. The criteria for potential flight locations included being 1) recorded at night, 2) recorded during migration, and 3) preceded and followed by >6.68 km steps.

3 Calculated by multiplying posterior values of by the number of potential flight locations in each dataset (Equation 6).

Table 2. Proportion of American Woodcock (*Scolopax minor*) flight altitudes within height intervals related to weather radar and airspace obstacles. We calculated these metrics by simulating a log-normal distribution for each posterior value of and , and measuring the proportion of each distribution which fell below or within the given height interval. Results are included for the base model as well as season, age, and sex models. Estimates indicate the median expected value, while credible intervals reflect highest density intervals for each estimate. These derived metrics are based on altitude data collected using GPS transmitters in the eastern portion of the woodcock’s range from 2020 to 2024.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Model | Percent below NEXRAD detection altitude (120 m)1 | Percent below height of low-rise buildings (47 m)2 | Percent within sweep of land-based wind turbines (32–164 m)3 | Percent below height of large communication towers (305 m)4 |
| **Base** | 27 (20–35) | 2 (0–5) | 28 (21–35) | 57 (50–64) |
| **Season** |  |  |  |  |
| *Fall* | 29 (19–40) | 2 (0–6) | 31 (22–41) | 61 (51–71) |
| *Spring* | 24 (13–35) | 2 (0–6) | 25 (15–35) | 52 (40–63) |
| **Age** |  |  |  |  |
| *Adult* | 24 (13–35) | 2 (0–6) | 25 (15–35) | 52 (41–64) |
| *Juvenile* | 25 (15–36) | 2 (0–5) | 27 (18–36) | 57 (46–66) |
| **Sex** |  |  |  |  |
| *Male* | 23 (14–34) | 2 (0–5) | 25 (16–34) | 53 (42–63) |
| *Female* | 29 (17–41) | 2 (0–7) | 30 (20–41) | 60 (49–71) |

1 Minimum NEXRAD detection height is based on the lowest altitude detected by Horton et al. (2016).

2 Height of low-rise buildings based on that of an 11-story building (Loss et al. 2014).

3 Sweep of wind turbines is based on the average land-based turbine constructed in 2022 (Wiser et al. 2023).

4 Height of large communication towers based on Gehring et al. (2011).

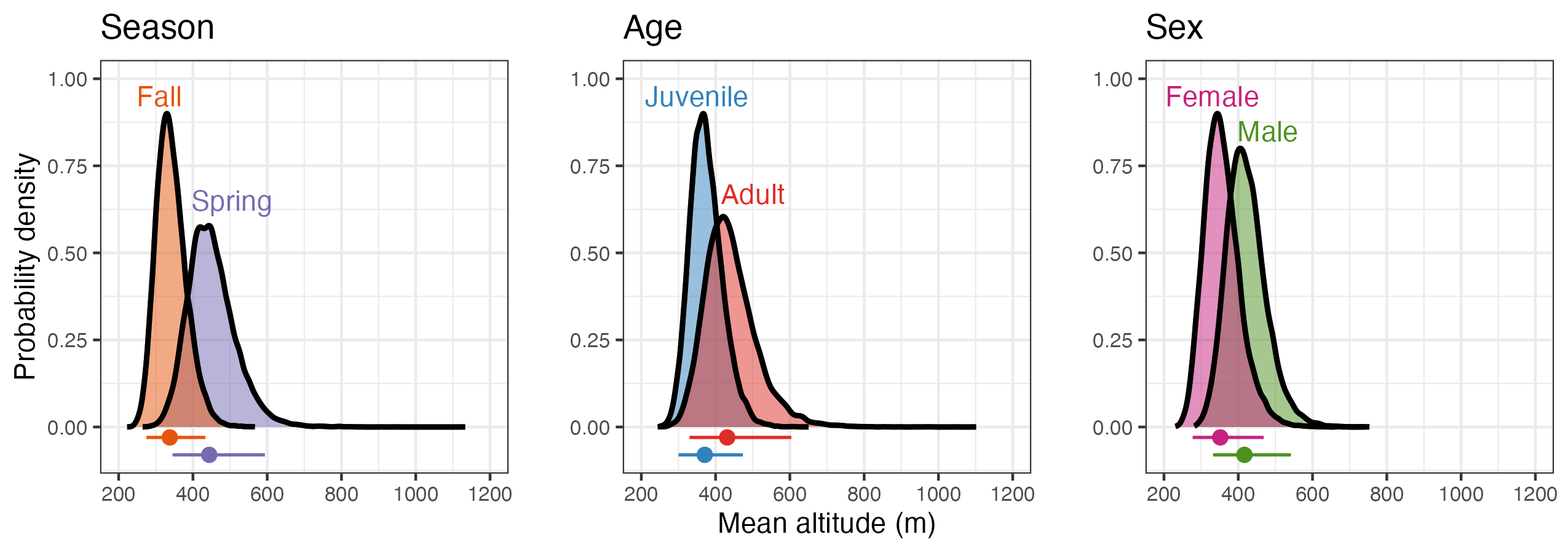


Figure 1. Posterior distributions for mean flight altitude of American Woodcock (*Scolopax minor*) flight locations, subdivided by season, age, and sex. Density plots represent posterior distributions of parameters, while point intervals represent the medians and 95% highest density credible intervals of the posteriors. Altitude data were collected using GPS transmitters in the eastern portion of the woodcock’s range from 2020 to 2024.

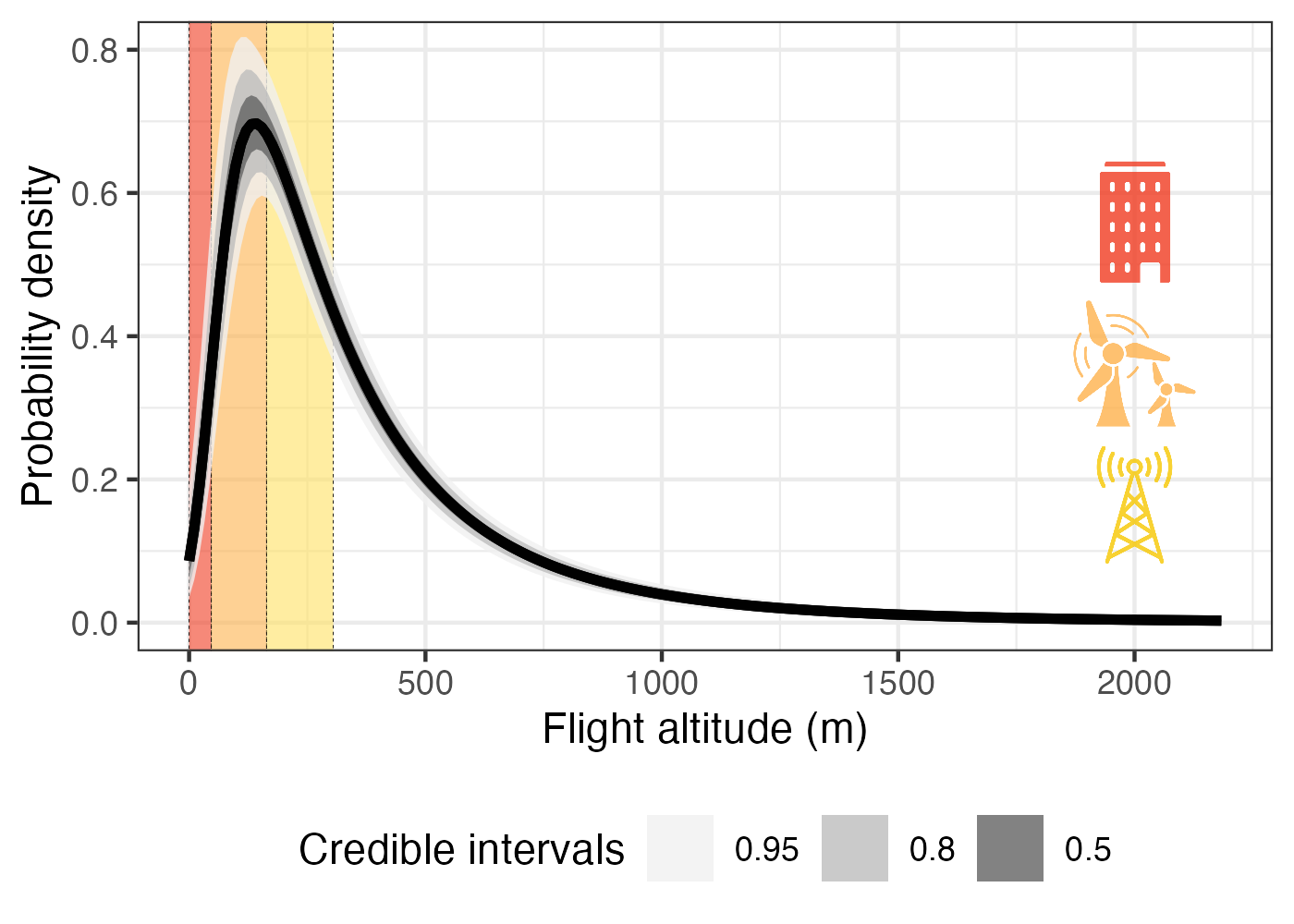


Figure 2. Distribution of American Woodcock (*Scolopax minor*) flight altitudes above ground level compared to the heights of low-rise buildings (red; 47 m), land-based wind turbines (orange; 32–164 m), and large communications towers (yellow; 244 m). The dark line represents the median flight altitude distribution calculated using the base model, while ribbons represent 50%, 80%, and 95% highest density credible intervals for the distribution. We produced these distributions by simulating a log-normal distribution for each posterior value of and . Raw altitude data were collected using GPS transmitters in the eastern portion of the woodcock’s range from 2020 to 2024.

# Discussion

We found that mean woodcock flight altitudes above ground level fell below those typical of most migrating birds during fall (woodcock: 338 m; all birds: 418–491 m) and spring (woodcock: 444 m; all birds: 438–559 m; Horton et al. 2016). This result may be due, in part, to the greater representation of lower altitude flight locations in our data, as 27% of woodcock flight locations fell below the minimum altitude normally observed via weather radar (120 m; Horton et al. 2016). However, given preexisting information about woodcock’s high susceptibility to collisions with anthropogenic structures (Mendall and Aldous 1943, Loss et al. 2020) we believe that some portion of this effect is due to a biological difference between the flight altitudes of woodcock and other nocturnal migrants. Woodcocks’ unconventional use of low altitudes may be related to morphology, as they have a greater wing loading than 79% of species sampled by Poole (1938), and their wing loading appears to be considerably higher than other birds of comparable size. Birds with a higher wing loading than woodcock were generally non-migratory gamebirds or ducks, with the most similar species in terms of wing loading and mass being the non-migratory Rock Pigeon (*Columba livia*; Poole 1938). As high wing loading is speculated to be associated with migratory inefficiency (Bowlin and Wikelski 2008), woodcock may be inefficient fliers and fly at lower altitudes as a result (Grilli et al. 2017).

As anticipated, we found little support for an age or sex difference in woodcock flight altitudes but considerable support for a seasonal difference, with woodcock flight altitudes being higher during spring (mean: 444 m, 95% CRI: 333–578 m) than fall (mean: 338 m, 95% CRI: 267–423 m). This matches seasonal variation in flight altitudes observed via radar (Horton et al. 2016), presumably due to migrants utilizing southerly low-level jet streams present at higher altitudes in the spring (La Sorte et al. 2014). Due to lower flight altitudes in fall, woodcock are more likely to fly at altitudes coinciding with wind turbines (31% vs. 25% of altitudes) and communication towers (61% vs. 52%) in fall than spring. Woodcock collisions with buildings appear to occur more frequently during the spring rather than fall (Loss et al. 2019, 2020), which is notable as flight altitudes are generally higher during spring. This may be due to a mismatch between the data collection windows for bird collision studies and the fall migratory periods of woodcock (Loss et al. 2020). These building collisions may also be associated with the frequency of migratory stopovers: woodcock spend longer migrating during spring, and the increased number of stopovers may expose woodcock to a greater risk of building collision during crepuscular flights (Berigan 2024). Other factors, such as seasonal weather (Loss et al. 2020) or male display behavior in the spring (McAuley et al. 2020) could be alternative drivers for seasonal differences in building collision rates. Despite a mean flight altitude of 379 m, we found that 57% of woodcock flight altitudes occurred below 305 m. The occurrence of so many flight locations within the range of anthropogenic obstacles during peak times for migratory flight (12–1am Eastern Time) suggests that woodcock are not solely vulnerable to collision with these obstacles during takeoff and landing, but throughout their migratory flights. While all three types of structures examined here are responsible for substantial migratory bird mortality, collisions with these structures are likely caused by different mechanisms. Low-rise buildings, for example, are responsible for more collisions of all taxa than any other structure examined in this study (est. 339 million per annum, Loss et al. 2014) despite having the lowest height (47 m). The exceptional rate of mortality associated with low rise buildings is likely the joint function of their prevalence (est. 15.1 million low rise buildings in the USA Loss et al. 2014) and a higher rate of mortality associated with birds undergoing stopovers, which can be lengthy and expose birds to mortality risk through the diurnal hours in addition to nocturnal migratory flights (Cusa et al. 2015). In comparison, communication towers kill fewer birds (4–5 million per annum) and are less prevalent on the landscape (>26,000 in the USA) but are more likely to result in collisions during migratory flights, especially if guy wires are present (Gehring et al. 2011). Understanding these differing risk profiles is an important facet of interpreting the relative mortality risk of low altitude flights and drawing connections between low altitude flights and increased rates of bird collisions.

Low flight altitudes are one of several risk factors for obstacle collisions, and these factors may differ in importance based on whether collisions occur during diurnal stopovers or nocturnal migratory flights. A proper understanding of how collision risk changes between those periods, especially on a species-level, is critical to the implementation of mitigation measures, as most measures will reduce obstacle collision chance during one period but not the other. Reduction of artificial light at night, as well as flashing lights and reduction of guy wires on communication towers, are all seen as potential mechanisms to reduce obstacle collisions during nocturnal migratory flights (Gehring et al. 2009, 2011, Van Doren et al. 2021). The application of ultraviolet reflective stickers to windows or the use of bird safe glass, on the other hand, focus on reducing obstacle collisions during diurnal hours (De Groot et al. 2022). As birds may differ in their vulnerability to obstacle collisions during diurnal vs. nocturnal hours (e.g. woodcock, which migrate at low altitudes and are likely more prone to nocturnal collisions), the impact of individual mitigation efforts on collision risk will be species-specific. A well-balanced effort focusing on reducing both nocturnal and diurnal collision risk while accommodating for local phenomena such as migratory staging areas or reduced flight altitudes during overwater crossings (Howell et al. 2020, Galtbalt et al. 2021), will be required to effectively reduce bird collision mortality.

# Literature cited

Agostini, N., M. Gustin, M. Cento, J. Von Hardenberg, and G. Chiatante (2023). Differential flight strategies of Western Marsh Harrier *Circus aeruginosus* in relation to sex and age class during spring migration in the central Mediterranean. *Acta Ornithologica* 58:41–53.

Bauer, S., J. Shamoun-Baranes, C. Nilsson, A. Farnsworth, J. F. Kelly, D. R. Reynolds, A. M. Dokter, J. F. Krauel, L. B. Petterson, K. G. Horton, and J. W. Chapman (2019). The grand challenges of migration ecology that radar aeroecology can help answer. *Ecography* 42:861–875.

Berigan, L.A. (2024). *Full annual cycle analysis of American Woodcock (Scolopax minor) distribution, habitat use, and migration ecology*. PhD dissertation. University of Maine, Orono, Maine.

Blomberg, E. J., A. C. Fish, L. A. Berigan, A. M. Roth, R. Rau, S. J. Clements, G. Balkcom, B. Carpenter, G. Costanzo, J. Duguay, C. L. Graham, et al. (2023). The American Woodcock Singing Ground Survey largely conforms to the phenology of male woodcock migration. *Journal of Wildlife Management* 87:e22488.

Bowlin, M. S., D. A. Enstrom, B. J. Murphy, E. Plaza, P. Jurich, and J. Cochran (2015). Unexplained altitude changes in a migrating thrush: long-flight altitude data from radio-telemetry. *Auk: Ornithological Advances* 132:808–816.

Bowlin, M. S., and M. Wikelski (2008). Pointed wings, low wingloading and calm air reduce migratory flight costs in songbirds. *PLOS ONE* 3:e2154.

Brooks, S. P., and A. Gelman (1998). General methods for monitoring convergence of iterative simulations. *Journal of Computational and Graphical Statistics* 7:434–455.

Clements, S. J., L. A. Berigan, A. C. Fish, R. L. Darling, A. M. Roth, G. Balkcom, B. Carpenter, G. Costanzo, J. Duguay, and K. Filkins (2024). Satellite tracking of American Woodcock reveals a gradient of migration strategies. *Ornithology* 141:ukae008.

Cohen, E. B., J. J. Buler, K. G. Horton, S. R. Loss, S. A. Cabrera-Cruz, J. A. Smolinsky, and P. P. Marra (2022). Using weather radar to help minimize wind energy impacts on nocturnally migrating birds. *Conservation Letters* 15:e12887.

Cooper, T. R., and R. D. Rau (2012). *American Woodcock: Population Status, 2012*. U.S. Fish and Wildlife Service, Laurel, Maryland.

Cusa, M., D. A. Jackson, and M. Mesure (2015). Window collisions by migratory bird species: urban geographical patterns and habitat associations. *Urban Ecosystems* 18:1427–1446.

De Groot, K. L., A. G. Wilson, R. McKibbin, S. A. Hudson, K. M. Dohms, A. R. Norris, A. C. Huang, I. B. Whitehorne, K. T. Fort, and C. Roy (2022). Bird protection treatments reduce bird-window collision risk at low-rise buildings within a Pacific coastal protected area. *PeerJ* 10:e13142.

DeMott, W. G., A. N. Stillman, J. B. Kolb, and C. S. Elphick (2022). NEXRAD highlights the effects of wind and date at a Tree Swallow (*Tachycineta bicolor*) roost during fall migration. *The Wilson Journal of Ornithology* 134:623–632.

ESRI (2024a). *ArcGIS Pro*. Redlands, CA, USA.

ESRI (2024b). *Terrain*. [Online.] Available at https://www.arcgis.com/home/item.html?id=58a541efc59545e6b7137f961d7de883.

Fish, A. C., A. M. Roth, G. Balkcom, L. Berigan, K. Brunette, S. Clements, G. Costanzo, C. L. Graham, W. F. Harvey, M. Hook, D. L. Howell, et al. (2024). American woodcock migration phenology in eastern North America: implications for hunting season timing. *Journal of Wildlife Management* 88:e22565.

Galtbalt, B., A. Lilleyman, J. T. Coleman, C. Cheng, Z. Ma, D. I. Rogers, B. K. Woodworth, R. A. Fuller, S. T. Garnett, and M. Klaassen (2021). Far eastern curlew and whimbrel prefer flying low - wind support and good visibility appear only secondary factors in determining migratory flight altitude. *Movement Ecology* 9:32.

Gehring, J., P. Kerlinger, and A. M. Manville (2009). Communication towers, lights, and birds: successful methods of reducing the frequency of avian collisions. *Ecological Applications* 19:505–514.

Gehring, J., P. Kerlinger, and A. M. Manville (2011). The role of tower height and guy wires on avian collisions with communication towers. *Journal of Wildlife Management* 75:848–855.

Grilli, M. G., S. A. Lambertucci, J. Therrien, and K. L. Bildstein (2017). Wing size but not wing shape is related to migratory behavior in a soaring bird. *Journal of Avian Biology* 48:669–678.

Horton, K. G., J. J. Buler, S. J. Anderson, C. S. Burt, A. C. Collins, A. M. Dokter, F. Guo, D. Sheldon, M. A. Tomaszewska, and G. M. Henebry (2023). Artificial light at night is a top predictor of bird migration stopover density. *Nature Communications* 14:7446.

Horton, K. G., B. M. Van Doren, P. M. Stepanian, A. Farnsworth, and J. F. Kelly (2016). Where in the air? Aerial habitat use of nocturnally migrating birds. *Biology Letters* 12:20160591.

Howell, J. E., A. E. McKellar, R. H. M. Espie, and C. A. Morrissey (2020). Predictable shorebird departure patterns from a staging site can inform collision risks and mitigation of wind energy developments. *Ibis* 162:535–547.

Juárez, M. A., and M. F. J. Steel (2010). Model-Based Clustering of Non-Gaussian Panel Data Based on Skew- *t* Distributions. *Journal of Business & Economic Statistics* 28:52–66.

Kruschke, J. (2014). *Doing Bayesian data analysis: A tutorial with R, JAGS, and Stan*, 2nd edition. Academic Press, London, United Kingdom.

La Sorte, F. A., D. Fink, W. M. Hochachka, A. Farnsworth, A. D. Rodewald, K. V. Rosenberg, B. L. Sullivan, D. W. Winkler, C. Wood, and S. Kelling (2014). The role of atmospheric conditions in the seasonal dynamics of North American migration flyways. *Journal of Biogeography* 41:1685–1696.

Lao, S., B. A. Robertson, A. W. Anderson, R. B. Blair, J. W. Eckles, R. J. Turner, and S. R. Loss (2020). The influence of artificial light at night and polarized light on bird-building collisions. *Biological Conservation* 241:108358.

Loss, S. R., S. Lao, A. W. Anderson, R. B. Blair, J. W. Eckles, and R. J. Turner (2020). Inclement weather and American woodcock building collisions during spring migration. *Wildlife Biology* 2020:wlb.00623.

Loss, S. R., S. Lao, J. W. Eckles, A. W. Anderson, R. B. Blair, and R. J. Turner (2019). Factors influencing bird-building collisions in the downtown area of a major North American city. *PLOS ONE* 14:e0224164.

Loss, S. R., T. Will, S. S. Loss, and P. P. Marra (2014). Bird–building collisions in the United States: Estimates of annual mortality and species vulnerability. *Condor* 116:8–23.

Loss, S. R., T. Will, and P. P. Marra (2013). Estimates of bird collision mortality at wind facilities in the contiguous United States. *Biological Conservation* 168:201–209.

Makowski, D., M. Ben-Shachar, and D. Lüdecke (2019). bayestestR: describing effects and their uncertainty, existence and significance within the Bayesian framework*. Journal of Open Source Software* 4:1541.

McAuley, D. G., D. M. Keppie, and R. M. Whiting Jr. (2020). American Woodcock (*Scolopax minor*), version 1.0. In *Birds of the World* (A. F. Poole, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA.

McAuley, D. G., J. R. Longcore, and G. F. Sepik (1993). Techniques for Research into Woodcocks: Experiences and Recommendations. *Proceedings of the eighth American woodcock symposium*. U.S. Fish and Wildlife Service, p. 5.

Mendall, H. L., and C. M. Aldous (1943). *The ecology and management of American woodcock*. Maine Cooperative Wildlife Research Unit, Orono, Maine.

Nichols, K. S., T. Homayoun, J. Eckles, and R. B. Blair (2018). Bird-building collision risk: An assessment of the collision risk of birds with buildings by phylogeny and behavior using two citizen-science datasets. *PLOS ONE* 13:e0201558.

Péron, G., C. H. Fleming, O. Duriez, J. Fluhr, C. Itty, S. Lambertucci, K. Safi, E. L. C. Shepard, and J. M. Calabrese (2017). The energy landscape predicts flight height and wind turbine collision hazard in three species of large soaring raptor. *Journal of Applied Ecology* 54:1895–1906.

Poole, E. L. (1938). Weights and wing areas in North American birds. *Auk* 55:511–517.

R Core Team (2024). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.

Rabe, D. L., H. H. Prince, and E. D. Goodman (1983). The effect of weather on bioenergetics of breeding American woodcock. *Journal of Wildlife Management* 47:762–771.

Rogers, R. M., J. J. Buler, C. E. Wainwright, and H. A. Campbell (2020). Opportunities and challenges in using weather radar for detecting and monitoring flying animals in the Southern Hemisphere. *Austral Ecology* 45:127–136.

Ruscio, J. (2008). A probability-based measure of effect size: robustness to base rates and other factors. *Psychological Methods* 13:19–30.

Stan Development Team (2024). *Stan Modeling Language Users Guide and Reference Manual*, Version 2.3.5. https://mc-stan.org.

Thaxter, C. B., V. H. Ross-Smith, and A. Cook (2016). *How high do birds fly? A review of current datasets and an appraisal of current methodologies for collecting flight height data: literature review*. British Trust for Ornithology, Thetford, United Kingdom.

Van Doren, B. M., D. E. Willard, M. Hennen, K. G. Horton, E. F. Stuber, D. Sheldon, A. H. Sivakumar, J. Wang, A. Farnsworth, and B. M. Winger (2021). Drivers of fatal bird collisions in an urban center. *Proceedings of the National Academy of Sciences* 118:e2101666118.

White, J. D., K. W. Heist, and M. T. Wells (2020). *Great Lakes avian radar technical report Lake Erie lakeshore: Macomb and Wayne County, MI, Fall 2018*. U.S. Department of the Interior, Fish and Wildlife Service. Available at https://www.fws.gov/sites/default/files/documents/Radar%20Report%20Fall%202018.pdf.

Wiser, R., M. Bolinger, B. Hoen, D. Millstein, J. Rand, G. Barbose, N. Darghouth, W. Gorman, S. Jeong, and E. O’Shaughnessy (2023). *Land-based wind market report: 2023 edition*. Lawrence Berkeley National Laboratory, Berkeley, California.