A continental system for forecasting bird migration

Benjamin M. Van Doren[1]* and Kyle G. Horton[2]

Billions of animals cross the globe each year during seasonal migrations, but efforts to monitor them are hampered by the unpredictability of their movements. We developed a bird migration forecast system at a continental scale by leveraging 23 years of spring observations to identify associations between atmospheric conditions and bird migration intensity. Our models explained up to 81% of variation in migration intensity across the United States at altitudes of 0 to 3000 meters, and performance remained high in forecasting events 1 to 7 days in advance (62 to 76% of variation was explained). Avian migratory movements across the United States likely exceed 500 million individuals per night during peak passage. Bird migration forecasts will reduce collisions with buildings, airplanes, and wind turbines; inform a variety of monitoring efforts; and engage the public.

Billions of birds migrate between distant breeding and wintering sites each year, through landscapes and airspaces increasingly transformed by humans. Hundreds of millions die annually from collisions with buildings, automobiles, and energy installations (1), and light pollution exacerbates these effects (2). Pulses of intense migration interspersed with periods of low activity characterize birds' movements aloft (3, 4), and efforts to reduce negative effects on migrants (e.g., turning off lights and wind turbines at strategic times) (5) would be most effective if they targeted the few nights with intense migratory pulses. However, bird movements are challenging to predict days or even hours in advance.

For decades, scientists have studied the drivers of avian migration. Winds, temperature, barometric pressure, and precipitation play key roles (6–8). However, such general relationships have not produced migration forecasts accurate at both broad continental extents and fine spatial and temporal resolutions (9, 10). Local topography, regional geography, and time of season modify relationships between conditions and migration intensity, and hundreds of species with diverse behaviors frequently pass over a single location during migration. The complex interactions between environmental conditions and animal behavior make predicting bird migration at the assemblage level a challenge.

One major difficulty has been amassing behavioral data that appropriately characterize bird migration at a continental scale. Radar, used globally as a tool to study animal migration (3, 11–14), offers a realistic solution to monitor hundreds of species (15). In the continental United States, the Next Generation Weather Radar (NEXRAD) network comprises 143 weather surveillance radars (16) and an archive with more than two decades of data. Although designed for meteorological applications, these radars measure energy reflected by a diversity of aerial targets, including birds.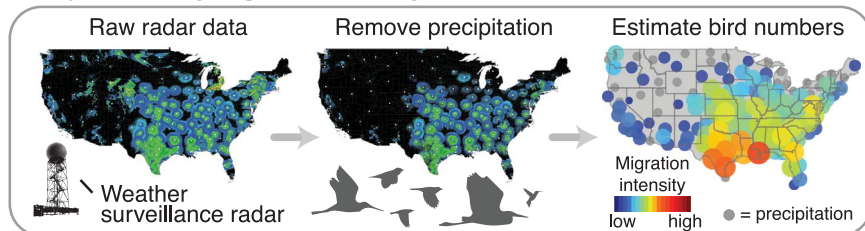 Only recently have advances in computational methods [e.g., (17)] facilitated the use of the entire radar archive for longitudinal studies of bird migration at continental scales.

Using the NEXRAD archive, we quantified 23 years (1995 to 2017) of spring nocturnal bird migration across the United States (Fig. 1). We developed a classifier to eliminate radar scans contaminated with precipitation. We then trained gradient-boosted trees (18) to predict bird migration intensity from atmospheric conditions reported by the North American Regional Reanalysis (19). Our m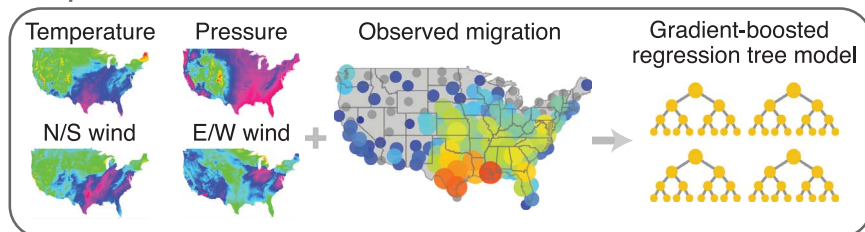odel used 12 predictors, including winds, air temperature, barometric pressure, and relative humidity (fig. S1), which we used to predict a cube-root-transformed index of migration intensity (expressed in square centimeters per cubic kilometer). The cube-root transform reduces skewness but is less extreme than a log transformation, which would have given considerable weight to biologically unimportant differences between small values. We measured migration intensity in 100-m altitude bins up to 3 km to model the three-dimensional distribution of migrating birds over the continent. To express migration intensities in numbers of birds, we assumed a radar cross section per bird of 11 cm^2. The radar cross section is a measure of reflected energy; this value is typical of medium-sized songbirds and representative of migratory species (12).

Our migration forecast model explained 78.9% of variation in migration intensity over the United States (Figs. 2 and 3A). Performance was consistent across years (mean yearly coefficient of determination $R^2 = 0.781 \pm 0.010$ SD). We quantified the importance of each predictor by calculating gain, a measure of how much predictions improve by adding a given variable. Air temperature was most important, with an average gain more than three times that of the second-ranked predictor, date (fig. S2). High temperatures coincided with large migration pulses (Fig. 4 and figs. S3 and S4). As a predictor of bird migration, temperature likely plays a dual role as an index of spring phenology and a short-term signal for movement, as favorable

Step 1. Quantify migration intensity at 143 weather radar stations

Raw radar data → Remove precipitation → Estimate bird numbers

Weather surveillance radar

Migration intensity low — high ● = precipitation

Step 2. Learn associations with weather conditions

Temperature Pressure Observed migration Gradient-boosted regression tree model

N/S wind E/W wind +

Step 3. Make predictions using weather forecasts

Predictive model Weather forecast (e.g. 24-h) Bird migration forecast

Migration intensity low — high

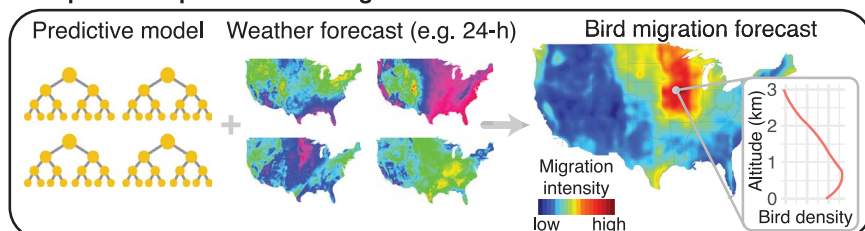Altitude (km) 3 2 1 0 Bird density

Fig. 1. Methodology for generating migration forecasts. We used weather surveillance radars to quantify 23 years of spring bird migration, modeled migration intensity as a function of observed atmospheric conditions, and used this model to forecast future migration events under predicted weather conditions.

[1]Edward Grey Institute, Department of Zoology, University of Oxford, Oxford OX1 3PS, UK. [2]Cornell Lab of Ornithology, Cornell University, Ithaca, NY 14850, USA.
*Corresponding author. Email: benjamin.vandoren@zoo.ox.ac.uk