

ORIGINAL RESEARCH

Accuracy of swallow roost locations assigned using weather surveillance radar

Jeffrey F. Kelly^{1,2} & Sandra M. Pletschet¹¹Oklahoma Biological Survey, University of Oklahoma, 111 E. Chesapeake St, Norman Oklahoma 73019²Department of Biology, University of Oklahoma, Norman Oklahoma 73019**Keywords**

Aerocology, migration, roost locations, swallow roosts, weather radar, WSR

Correspondence

Jeff F. Kelly, Oklahoma Biological Survey, 111 E. Chesapeake St., University of Oklahoma, Norman, Oklahoma 73019. Tel: 405 325 2440; Fax: 405 325 7702; E-mail: jkelly@ou.edu

Funding Information

This work was funded by National Science Foundation 1545261

Editor: Marcus Rowcliffe

Associate Editor: Doreen Boyd

Received: 15 May 2017; Revised: 22 July 2017; Accepted: 31 August 2017

doi: 10.1002/rse2.66

Abstract

Weather surveillance radars (WSR) have been used to detect roosting aggregations of swallows since the 1950s. We provide the first quantitative assessment of the accuracy of roost locations derived from WSR images. We found 265 swallow roosts in WSR images from the Eastern US (east of 100°W) between June and September over 7 years (2010–2016). We quantified error in WSR-based roost locations of 72 of these roosts by comparing them to ground-truth locations. Purple Martins (*Progne subis*) formed 67 (93%) of ground-truthed roosts. Tree Swallows (*Tachycineta bicolor*) and Bank Swallows (*Riparia riparia*) formed the other 5 roosts (7%); all of which were in the northeastern U.S. (north of 41°N and east of 80°W). Magnitude of roost-location error was 2.94 kilometers (SD = 1.63 km, $N = 72$, range = 0–7.3). This error increased slightly, but significantly, with distance from the WSR ($R^2 = 0.13$, $P = 0.002$). Location error was not influenced by wind speed. Directions of location errors (from confirmed to estimated location) were clumped in a southeasterly direction ($\bar{x} = 128.9^\circ$, SD = 1.32, $N = 72$, $P < 0.05$). Similarly, prevailing wind direction ($\bar{x} = 180.0^\circ$, SD = 1.28, $N = 71$, $P < 0.01$) tended to come from the south. Wind direction and direction to the nearest WSR were not correlated with direction of the location error. Magnitude and direction of error associated with using WSR images to assign geographic locations to swallow roosts is small. This error is largely unaffected by variation in distance and direction to WSR stations and prevailing wind conditions. These results enable future studies that seek automated approaches to roost identification and permit association with other environmental data at the appropriate level of spatial precision.

Introduction

Communal roosting is common among vertebrate aerial insectivores such as swallows, swifts and bats. In large regions of North America, populations of these species are declining without a clear single cause (Nebel et al. 2010; Michel et al. 2015). For some of these species, robust population monitoring exists in portions of their range during the breeding season (Frick et al. 2010; Fraser et al. 2012; Shutler et al. 2012). However, because these species are widely distributed, spend significant portions of their lives aloft, and often roost in locations that are inaccessible, ground-based monitoring programs can be expensive or impossible (Russell et al. 1998). These roosts are routinely detected by weather surveillance radars (WSR), which

provides an opportunity to use this remote sensing technology to augment ground surveys. A primary question about the limitations of a WSR-based roost surveillance program is what level of accuracy can be achieved in assigning geographic coordinates to roost locations using WSR images? Knowing the accuracy of radar-based locations of roosts is important because it: (1) facilitates future work on automated methods for locating and quantifying roost dynamics; (2) determines the spatial scale at which roosts can be associated with other remotely sensed and directly observed environmental data; such as land cover type; and (3) determines the magnitude of change required to conclude that a roost location has moved.

When avian aerial insectivores depart from roosts, they often create a characteristic signature in weather

surveillance radar (WSR) images; known as “ring angels” (Harper 1959) or “roost rings” (Laughlin et al. 2013). Many studies have used images and data from WSRs to: (1) locate roosts (Russell et al. 1998; Burney 2002; Tautin et al. 2005); (2) create indices of abundance of roosting animals (Russell and Gauthreaux 1999; Laughlin et al. 2013); and (3) examine ecological correlates of roosts (Eastwood et al. 1962; Chilson et al. 2011; Kelly et al. 2012; Van Den Broeke 2013; Laughlin et al. 2014; Bridge et al. 2016). Typically, these roosts are comprised primarily of individuals of one species, but there are also cases where mixtures of species form a single roost (Burney 2002). Surveillance radar images and data have been used in studies of roosts of European Starlings (*Sturnus vulgaris*; Eastwood et al. 1962), Barn Swallows (*Hirundo rustica*; Robinson et al. 2009), Rooks (*Corvus frugilegus*; Harper 1959), Jackdaws (*Coloeus monedula*; Harper 1959), and Red-winged Blackbirds (*Agelaius phoeniceus*; Ligda 1958; Larkin 1994); but most recent research has focused on Purple Martins (*Progne subis*; Russell and Gauthreaux 1998, 1999; Russell et al. 1998; Tautin et al. 2005; Kelly et al. 2012; Bridge et al. 2016) and Tree Swallows (*Tachycineta bicolor*; Burney 2002; Laughlin et al. 2013, 2014, 2016).

It is not currently possible to determine the species forming a roost ring solely from radar data or radar images. The most widespread and numerous roosts detected by radars in North America are those formed by Purple Martins in the summer (Kelly et al. 2012; Bridge et al. 2016). These roosts tend to re-form daily in the same location through a season and between years. For these reasons, we focused on times and places where this species was likely to be roosting. In North America, Purple Martin roosts are active from the end of the breeding season (June in the south) continuing into September (Kelly et al. 2012; Tarof and Brown 2013). Bridge et al. (2016) recently reported on the landscape characteristics around Purple Martin roosts, but they did not investigate location error. Our analysis includes data on many of the roosts studied by Bridge et al. (2016), as well as those found in the radar in 2015 and 2016.

Our objective was to determine location error of WSR-based geographic assignments of roosts by comparing them to confirmed locations on the ground. We also examine effects of proximity to the nearest WSR station and wind conditions on location error. We suspected that the error in assigned locations might increase with distance from the radar because both the spatial grain (sample volume) and the lowest elevation of the data increase with distance from the WSR (Crum and Albery 1993). We also expected that roosting birds might be drifted by prevailing winds or otherwise affected by wind conditions in ways that would impact the estimation of the roost location from WSR images.

Materials and Methods

Data collection

Assigning WSR-based roost locations

We searched for roost rings in images of radar reflectivity. The images we used were produced by the Multi-Radar Multi-Sensor System project (<http://www.nssl.noaa.gov/projects/mrms/>) from the U.S. National Weather Service's Next Generation Weather Radar network (NEXRAD). This process creates mosaic images from level II radar data collected at individual WSRs (Zhang et al. 2011, 2016). The mosaicked images we used are referred to as non-quality controlled composite reflectivity (currently known as Merged Reflectivity Composites). These images include radar reflectivity from biological and meteorological sources as well as anomalous propagation, ground clutter, and sun spurs. Images were available at 2-minute intervals with a spatial resolution of about 1 kilometer. According to Zhang et al. (2016), ‘The MRMS grid has a horizontal resolution of 0.01° in both latitude and longitude directions, which is equivalent to about 1.11 km in the north–south direction throughout the domain. In the west–east direction, the grid resolution varies from about 1 km at the southern bound to about 0.6 km at the northern bound’. We visually inspected these images for the characteristic roost ring pattern associated with swallow roosts for seven summers (1 June to 30 September) from 2010 through 2016. Although these mosaicked images were available for much of 2009, crucial images from August do not exist, so we do not include 2009 roosts. We started searching radar images about an hour before local sunrise and stopped about 30 minutes after sunrise (between 9:00 and 12:30 UTC). Our search area encompassed the portion of the U.S. east of 100°W longitude. We categorized a roost as active in a given year if it was detected in the radar for at least seven days between 1 June and 30 September. More information on methods for determining presence of roosts is provided in Bridge et al. (2016).

We estimated the location (latitude and longitude) for each roost in each year that it was active. Roosts locations that were within 15 km of a roost from a previous year were treated as the same roost among years (i.e., the same roost ID number). We set this distance threshold to be (1) larger than the observed change in local ground-truthed roost locations among years (<10 km) and (2) smaller nearest neighbor distances between roosts within a year (85 ± 38 km; Bridge et al. 2016). Roost locations were assigned on at least three mornings in each year when the roost was clearly visible in the radar. We stratified these observations through the activity

period of each roost with one taken near roost initiation, one in mid-season, and one near the end of roost activity. Exact dates for estimating location for each roost depended on when radar provided a clear image of the birds emerging from the roost. We did not estimate locations on mornings when radar images were cluttered with precipitation or other sources of reflectivity. Latitude and longitude were estimated when the roost first became visible in the composite reflectivity image (Fig. 1). To estimate latitude we counted the radar image's pixels from the northern end of the roost signature to southern end and took the midpoint. Likewise, to estimate longitude we counted the image's pixels from the eastern end of the roost signature to the western end and took the midpoint. For most roosts, the initial appearance in the radar image was a small cluster of high reflectivity, but some roosts were always first visible as larger rings. We averaged locations from these three mornings and this average was used as the radar-based location for each roost in each year.

Ground-truth observations to confirmed roost locations

To determine the actual roost locations and species composition, we visited roosts and used citizen-science

observations available on the Internet. We matched these confirmed locations to radar locations in both space and time. The citizen observations we accessed were primarily from the Purple Martin Conservation Association (PMCA, purplemartin.org) and eBird (eBird.org), but we also searched local Audubon Society websites, birding list-serv groups, and other wildlife websites. We searched many online sources, but those that yielded usable information were: Kentucky Ornithological Society's Listserv (<http://biology.ehu.edu/kos/listserv.htm>); Orleans Audubon Society (<http://www.jjaudubon.net>); South Carolina Department of Natural Resources Wildlife Magazine (<http://www.scwildlife.com>), South Carolina Wildlife Federation YouTube channel (<https://www.youtube.com/user/SCWildlifeFederation>); Mann's Harbor Purple Martin Roost YouTube (<http://www.purplemartinroost.com>) and The Wood Thrush Shop (<http://www.thewoodthrushshop.com/>).

We used the PMCA's publicly available database of Purple Martin roost locations (Project Martin Roost). This database primarily contains the observations of citizen scientists who have visited a martin roost and then posted their observations and the location of the roost. We only used observations that were based on actual visits to roosts between 2010 and 2016 as ground-truth confirmations of roost locations and species composition.

eBird is an online citizen-science program where bird-watchers record their species observation which are then stored in a centralized database (Sullivan et al. 2014). These data are publicly available at their website (eBird.org). Each observation consists of species, number of individuals, date, time, exact location (latitude and longitude) and comments, thus we were able to associate these observations with our radar observations. We searched the eBird species maps available online, looking within about 30 km of every roost ring we had identified in WSR images. Also, we requested and received all eBird records of Purple Martin, Tree Swallow, Bank Swallow (*Riparia riparia*), and Barn Swallow observations for 2010 through 2016. We narrowed our search of eBird observations to those reporting more than 1000 individuals and we searched for those that refer to roosts and observations made during the evening. We focused our search on evening observations because roosting swallows are most conspicuous in the evening. By contrast, they typically leave the roost before sunrise and are rarely reported by observers at that time. We also viewed observer's comments and primarily used observations that were described as roosts. After identifying a ground-truth observation of a roost location we paired these observations with the nearest WSR-based roost location.

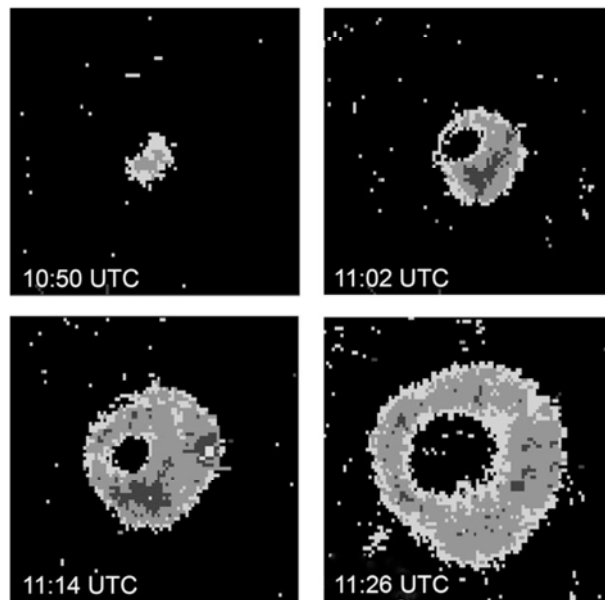


Figure 1. Time series of images of composite reflectivity from weather surveillance radars (WSR) showing emergence of Purple Martins from a roost located near Decatur, AL (34.62°N, 86.97°W) from 1050 UTC to 1126 UTC (5:50 AM to 6:26 AM CDT) on 4 August 2015. WSR-based location estimates of roosts were made using images similar to that from 1050 UTC, although the subsequent time series evolution of roost rings was critical for identifying roosts.

Wind data

We used Weather Underground (<https://www.wunderground.com/history>) to collect historical surface wind data for each roost that had a confirmed location. We collected wind speed and wind direction for each date and time where we estimated a WSR-based roost location. We used wind data from the weather station that was closest to the roost. The mean distance between weather stations and associated roosts was 16.65 km (SD = 11.40, $N = 70$). The majority (91%) of the weather stations from which we collected data were operated by the FAA and located at airports. These weather stations collected measurements at least hourly, so we were able to get wind data within 30 minutes of the WSR images used to estimate roost location.

Data analysis

We calculated the distances between geographic coordinates with the PostGIS `st_distance` function, which returns the 2D Cartesian distance between points. In order to minimize distortion in our calculations, we selected the USA Contiguous Lambert Conformal Conic projection with standard parallels at 33° and 45°.

We used least-squares regression to test for relationships between roost-location error and distance to the closest WSR as well as between location error and wind speed. We tested whether the direction of the location error was correlated with wind direction and direction to the closest WSR. We also tested for a directional tendency in the location error, direction to nearest WSR, and wind direction with a Rao's spacing tests. All analyses were performed in R and all directional analyses were performed with package Circular (R Core Team 2013).

Results

We used WSR images to assign geographic coordinates for a total of 265 unique swallow roosts each of which was active for between 1 and 7 years. We identified ground-truth locations for 72 of these unique roosts (28.3%). Each of the 72 ground-truth locations was confirmed in at least one year and up to seven years (mean = 2.3 years, SD = 1.5) for a total of 165 roost confirmations across all years. We obtained ground-truth locations of 49 roosts from the PMCA website, 18 of which were found only on PMCA. We confirmed 43 roosts using eBird records, 15 of which were only found on eBird. We confirmed 10 roosts by direct observation, of which 2 were only confirmed by us. Finally, we obtained 7 additional roost locations by searching birding and wildlife websites, of which 2 roosts were only verified in this manner.

Of the 72 ground-truthed roosts, 67 roosts were formed by Purple Martins (93%) while a mixture of Tree Swallows and Bank Swallows formed 5 roosts. The 5 Tree Swallow/Bank Swallow roosts were all located in the northeastern U.S. (north of 41°N and east of 80°W), only Purple Martin roosts were found in the overwhelming majority of the eastern U.S. (Fig. 2).

The mean distance between radar-based roost locations and confirmed locations, location error, was 2.93 km (SD = 1.63, $N = 72$, range = 0–7.3; Fig. 3). If we treat annual roost locations as independent measures, the mean location error for all 165 annual site verifications was 3.05 km (SD = 1.89, $N = 165$, range = 0–9.3). There was a weak, but significant, positive relationship between distance from the confirmed location to the closest WSR and the location error ($R^2 = 0.12$, $F_{1,70} = 10.5$, $P = 0.002$; Fig. 4). There was no relationship between wind speed and location error ($R^2 = 0.01$, $F_{1,69} = 2.0$, $P = 0.16$).

WSR-based locations tended to be east-southeast of ground-truth roost locations and virtually none were found to the north or northwest ($\bar{x} = 128.9^\circ$, SD = 1.32, $N = 71$, Fig. 5). This tendency was significantly directional (Rao's Spacing Test Statistic = 153.5, $0.01 < P < 0.05$). The direction from confirmed roosts to the nearest radar also tended to be southeasterly ($\bar{x} = 122.1^\circ$, SD = 1.73, $N = 72$); however, this distribution was not significantly different from uniform (Rao's Spacing Test Statistic = 135, $P > 0.1$). The direction of location error was not correlated with the direction to the nearest WSR ($r = 0.06$, $P = 0.59$). Wind direction was significantly non-uniform, primarily coming from the

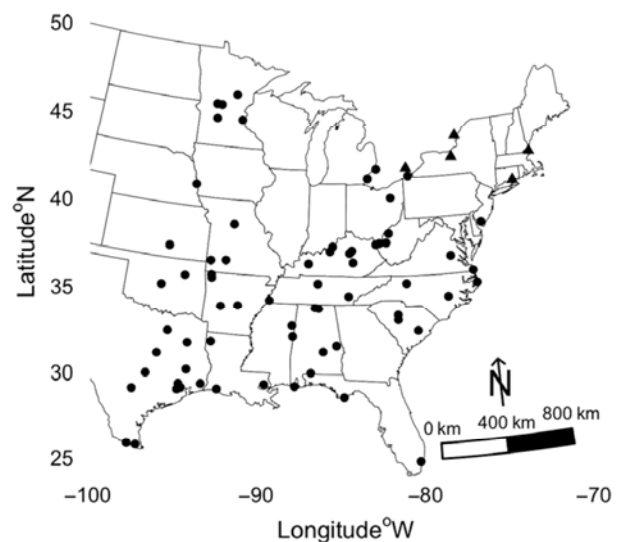


Figure 2. Locations of confirmed roosts. Circles are roosts confirmed to be Purple Martins and triangles are roosts confirmed to be formed by Tree Swallows and Bank Swallows.

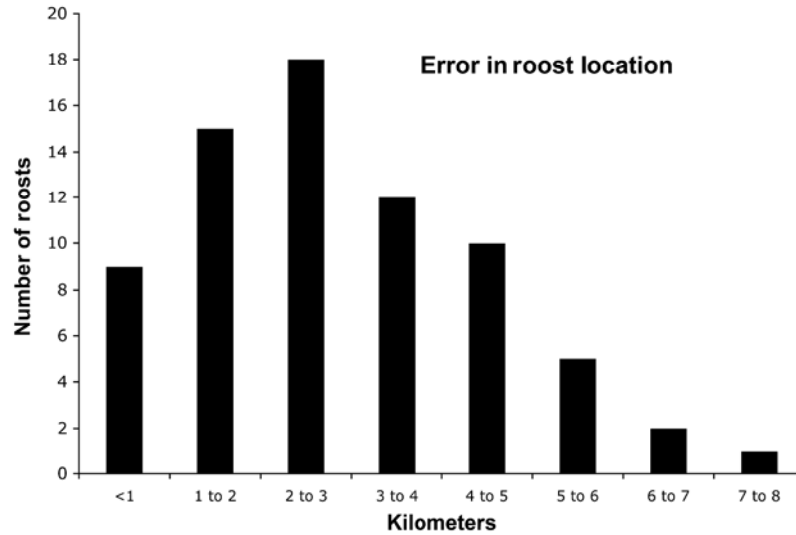


Figure 3. Distribution of magnitude of errors (km) associated with weather surveillance radar-based locations of swallow roosts ($N = 72$ roosts).

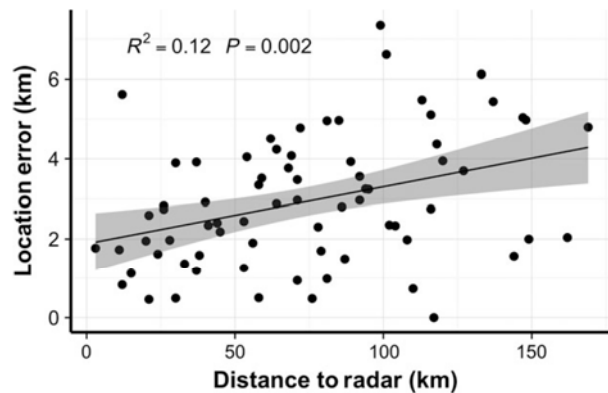


Figure 4. Relationship between error associated with weather surveillance radar (WSR)-based roost locations (y-axis) and distance from those roosts to the nearest WSR (x-axis). The linear regression is significantly positive. (error = $0.14 \times \text{distance to radar} + 1.9$; $R^2 = 0.12$, $P = 0.002$). Gray shading is the standard error of the regression line.

south ($\bar{x} = 180^\circ$, $SD = 1.28$, $N = 64$; Rao's Spacing Test Statistic = 156, $P < 0.01$, Fig. 5), but was not correlated with the direction of the error in roost location ($r = 0.12$, $P = 0.30$).

Discussion

All ground-truth locations were within 10 km of the WSR-based location and the mean of the location errors was <3 km. There was a small, but significant, effect of distance from a WSR on the spatial accuracy of the radar-based location. This pattern suggests a location accuracy of 2 km very close to WSRs (at a range of less

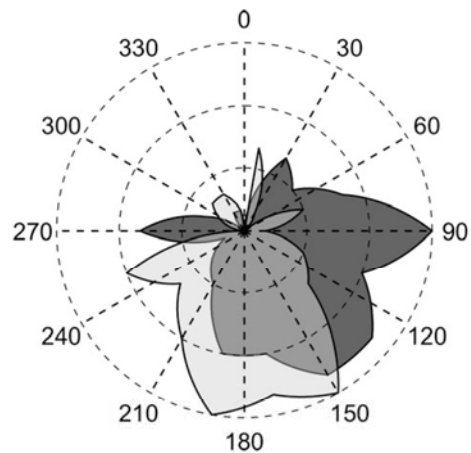


Figure 5. Direction from ground-truth roost location to nearest weather surveillance radar-based roost location (dark grey, $N = 72$) and direction of the prevailing wind (light grey; $N = 64$; 20 degree bins). Concentric dashed rings are 3-roost increments. These distributions tended to be significantly to the southeast and south, respectively.

than 50 km) and 4 km far from WSRs (at a range of 150 km). The shallow slope of this relationship is fortuitous because it limits concerns about uniformity of data across roosts located using WSR images. Surprisingly, wind speed was unrelated to the accuracy of locations assigned using WSR images.

The directions of location errors were non-uniform, suggesting some directional bias in the assignment of locations. This directional tendency was not significantly associated with either the prevailing wind direction or the direction to the nearest WSR. However, the tendency for all of these distributions to be centered in southerly to southeasterly directions leads us to think there may be a

weak association among these factors that would be revealed with larger sample sizes. Overall, our results suggest that it would be efficient to use a WSR-based approach to assign geographic locations to summer roosts of aerial insectivores and to use this method to augment ground observations.

Confirming the species identity of animals that comprise the roost remains the most problematic aspect of a WSR-based approach. Previously, Russell et al. (1998) used WSR images to locate 33 roosts of Purple Martins in the southeastern US between 3 July and 7 August of 1996. They did not collect ground-truth observations for these roosts, but they present several lines of evidence that suggest that these roosts were formed by Purple Martins. Tautin et al. (2005) used similar methods to identify hundreds of Purple Martin roosts throughout the eastern US with ground-truth observations of a small minority of those roosts. Tautin et al. (2005) did not present any information about how often the ground observations of roosts were not primarily martins. Burney (2002) intensively studied a roost in western New York, comprised primarily of Tree Swallows. Ligda (1958) was among the first to report a roost ring detected with radar during summer. He attributed this observation to Red-winged Blackbirds without any direct observation of the roost. These reports suggest uncertainty about the identity of species that create summer roost rings in WSR data in eastern North America.

Ground-truth observations lead us to extend the observations of Burney (2002) who found that in the northeastern US it is likely that summer roosts identified in via radar are formed by a combination to Tree Swallows and Bank Swallows. It also appears that Russell et al. (1998) were justified in concluding that the roosts they located in the Southeastern US using radar were Purple Martins. Throughout the majority of our study area (outside of the northeastern US), all of the roosts we confirmed were created by Purple Martins. Of roosts studied by Bridge et al. (2016), 5 northeastern roosts were dominated by swallow species other than Purple Martins. We did not find any summer roosts attributable to Red-winged Blackbirds, as reported by Ligda (1958). Based on our analysis, we suspect that Ligda's (1958) observations were not Blackbirds, but rather Purple Martins. We think that roosts identified by WSR can be assumed to be Purple Martins if they are within our summer time window (June to September), are morning departures, and not in New York or New England. It is clear that by October most of the roost rings observed are attributable to Tree Swallows and other species (Laughlin et al. 2013). Additional work on location error associated with winter Tree Swallow roosts would be useful. These roosts tend to be less stable in location within a season and would provide a further test of the limits of

WSR-based geographic assignment of roosts. In addition, confirmed roost observations during the summer from Indiana and Illinois would be particularly helpful in understanding the extent of overlap in the summer roosting range of Purple Martins and other swallows.

Regardless of species identity, monitoring swallow roosts with the WSR network has the potential to provide additional ecological insights at large spatial scales. When trying to understand aerial trophic systems and migratory phenologies, the ability to remotely quantify the timing, number, and size of roosts within and among years will be useful macroecological data (Kelly and Horton 2016). Efforts to build a more efficient method of locating and tracking the activity of insectivore roosts using continental scale radar data and images could provide broadly useful ecological data for understanding the response of aerial ecosystems to environmental change.

References

- Bridge, E. S., S. M. Pletschet, T. Fagin, P. B. Chilson, K. G. Horton, K. R. Broadfoot, et al. 2016. Persistence and habitat associations of Purple Martin roosts quantified via weather surveillance radar. *Landscape Ecol.* **31**, 43–53.
- Burney, C. W. 2002. A Study of Swallow Roosts Found in the Eastern United States. MS Thesis, Cornell University.
- Chilson, P. B., W. F. Frick, J. F. Kelly, K. W. Howard, R. P. Larkin, R. H. Diehl, et al. 2011. Partly cloudy with a chance of migration: weather, radars, and aerocology. *Bull. Am. Meteorol. Soc.* **93**, 669–686.
- Crum, T. D., and R. L. Alberty. 1993. The WSR-88D and the WSR-88D operational support facility. *Bull. Am. Meteorol. Soc.* **74**, 1669–1687.
- Eastwood, E., G. A. Isted, and G. C. Rider. 1962. Radar ring angels and the roosting behaviour of starlings. *Proc. R. Soc. Biol. Sci.* **156**, 242–267.
- Fraser, K. C., B. J. Stutchbury, C. Silverio, P. M. Kramer, J. Barrow, D. Newstead, et al. 2012. Continent-wide tracking to determine and tropical habitat associations of a declining aerial insectivore. *Proc. R. Soc. Biol. Sci.* **279**, 4901–4906.
- Frick, W. F., D. S. Reynolds, and T. H. Kunz. 2010. Influence of climate and reproductive timing on demography of little brown myotis (*Myotis lucifugus*). *J. Anim. Ecol.* **79**, 128–136.
- Harper, W. G. 1959. Roosting movements of birds and migration departures as seen by radar. *The Ibis* **101**, 201–208.
- Kelly, J. F., and K. G. Horton. 2016. Toward a predictive macrosystems framework for migration ecology. *Glob. Ecol. Biogeogr.* <https://doi.org/10.1111/geb.12473>.
- Kelly, J., J. Shipley, P. Chilson, K. Howard, W. Frick, and T. Kunz. 2012. Quantifying animal phenology in the aerosphere at a continental scale using NEXRAD weather radars. *Ecosphere* **3**, 16.

- Laughlin, A. J., D. R. Sheldon, D. W. Winkler, and C. M. Taylor. 2014. Behavioral drivers of communal roosting in a songbird: a combined theoretical and empirical approach. *Behav. Ecol.* **25**, 734–743.
- Laughlin, A. J., D. R. Sheldon, D. W. Winkler, and C. M. Taylor. 2016. Quantifying non-breeding season occupancy patterns and the timing and drivers of autumn migration for a migratory songbird using Doppler radar. *Ecography* **39**, 1017–1024.
- Laughlin, A. J., C. M. Taylor, D. W. Bradley, D. Leclair, R. C. Clark, R. D. Dawson, et al. 2013. Integrating information from geolocators, weather radar, and citizen science to uncover a key stopover area of an aerial insectivore. *Auk* **130**, 230–239.
- Larkin, R. P. 1994. *NEXRAD algorithm for bird hazard warning*. Illinois Natural History Survey, Champaign, IL.
- Ligda, M. G. 1958. Radar observations of blackbird flights. *Tex. J. Sci.* **10**, 255–265.
- Michel, N. L., A. C. Smith, R. G. Clark, C. A. Morrissey, and K. A. Hobson. 2015. Differences in spatial synchrony and interspecific concordance inform guild-level population trends for aerial insectivorous birds. *Ecography* **39**, 774–786.
- Nebel, S., A. Mills, J. McCracken, and P. Taylor. 2010. Declines of aerial insectivores in North America follow a geographic gradient. *Avian Conserv. Ecol.* **5**, 1.
- R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. Available at: <http://www.R-project.org/>.
- Robinson, W. D., M. S. Bowlin, I. A. Bisson, I. Shamoun-Baranes, K. Thorup, R. H. Diehl, et al. 2009. Integrating concepts and technologies to advance the study of bird migration. *Front. Ecol. Environ.* <https://doi.org/10.1890/080179>.
- Russell, K. R., and S. A. Gauthreaux. 1998. Use of weather radar to characterize movements of roosting purple martins. *Wildl. Soc. Bull.* **26**, 5–16.
- Russell, K. R., and S. A. Gauthreaux JR. 1999. Spatial and temporal dynamics of a Purple Martin pre-migratory roost. *Wilson Bull.* **111**, 354–362.
- Russell, K. R., D. S. Mizrahi, and S. A. Gauthreaux. 1998. Large-scale mapping of Purple Martin pre-migratory roosts using WSR-88D weather surveillance radar. *J. Field Ornithol.* **69**, 509.
- Shutler, D., D. Hunsell, D. R. Norris, D. W. Winkler, R. J. Robertson, F. Bonier, et al. 2012. Spatiotemporal patterns in nest box occupancy by tree swallows across North America. *Avian Conserv. Ecol.* **7**, 3.
- Sullivan, B. L., J. L. Aycrigg, J. H. Barry, R. E. Bonney, N. Bruns, C. B. Cooper, et al. 2014. The eBird enterprise: an integrated approach to development and application of citizen science. *Biol. Cons.* **169**, 31–40.
- Tarof, S., and C. R. Brown. 2013. Purple Martin (*Progne subis*). In A. Poole, Ed. *The birds of North America online*. Cornell Lab of Ornithology, Ithaca. Available at: <http://bna.irds.cornell.edu/bna/species/287>.
- Tautin, J., P. Karmer, and J. R. Hill. 2005. Project Martin roost: a cooperative program for conserving purple Martin roosts. *Purple Martin Update* **14**, 2–5.
- Van Den Broeke, M. S. 2013. Polarimetric radar observations of biological scatterers in Hurricanes Irene (2011) and Sandy (2012). *J. Atmos. Oceanic Technol.* **30**, 2754–2767.
- Zhang, J., K. W. Howard, C. Langston, S. V. Vasiloff, B. Kaney, A. Aurthur, et al. 2011. *National mosaic and multi-SENSOR QPE (NMQ) system – description*. Bull. Amer. Meteor. Soc. Results and Future Plans. <https://doi.org/10.1175/BAMS-D-11-00047.1>.
- Zhang, J., K. Howard, C. Langston, B. Kaney, and Y. QI. 2016. Multi-radar multi-sensor (MRMS) quantitative precipitation estimation: initial operating capabilities. *Am. Meteorol. Soc.* <https://doi.org/10.1175/BAMS-D-14-00174.1>.