Great Lakes Avian Radar Technical Report

Lake Michigan Lakeshore:

Cook County, IL and Porter County, IN

Spring 2017

U.S. Fish and Wildlife Service, Region 3

Funding Provided by Great Lakes Restoration Initiative

Recommended citation: White, J. D., K. W. Heist, and M. T. Wells. 2020. Great Lakes Avian Radar Technical Report Lake Michigan Lakeshore, Cook County, IL and Porter County, IN, Spring 2017. U.S. Department of Interior, Fish and Wildlife Service.

TABLE of CONTENTS

LIST of TABLES

LIST of FIGURES

INTRODUCTION

The Great Lakes support one of the largest bodies of freshwater on the planet and collectively represent a surface area of nearly 245,000 km^2 with over 17,500 km of shoreline. Global wind patterns help to move millions of migrating birds and bats through the Great Lakes region (Rich 2004, Liechti 2006, France et al. 2012) and lakeshores feature widely recognized Important Bird Areas (Audubon 2013). Migrants passing through the region concentrate near lakeshores (Ewert et al. 2011, Ewert et al. 2012, Peterson and Niemi 2011, Buler and Dawson 2012, France et al. 2012), which provide important stopover habitats – *en route* areas used temporarily for refueling, rest, and protection. These lakeshores offer increased foraging opportunities relative to inland areas (Smith et al. 2004, 2007; Bonter et al. 2007, 2009) and may be used as a visual cue for navigation or for refuge prior to or after crossing open water (Buler and Moore 2011).

Given their location and size, the Great Lakes likely represent a geographic obstacle that migrants choose to cross, or not, based on environmental and physiological conditions at the time of encounter (Faaborg et al. 2010, Schmaljohann et al. 2011). For migrants that rely on powered flight it is more efficient to make several short flights than a long flight due to the cost of carrying high fuel loads (Alerstam 1990). This may cause a migrant to avoid crossing a large body of water even though they have the physiological ability to do so (Alerstam 1990, 2001, Ruth 2007). The decision to cross likely represents a trade-off between minimizing costs (e.g., energy and time) and exposure to risk factors (e.g., predation and fatigue) that are associated with migration (McGuire et al. 2012a). In this trade-off, lakeshores offer refuge when conditions do not favor flights over water.

Migrants challenged by an obstacle may temporarily reverse or deviate from seasonally appropriate flight directions or return to land to delay or recover from a crossing (Bruderer and Liechti 1998, Åkesson 1999, Ewert et al. 2011). Schmaljohann and Naef-Daenzer (2011) found that birds with low fuel loads and/or facing unfavorable weather conditions returned to shoreline habitat rather than continue across open water in a direction appropriate for migration. For bats, migrants varied their choice to circumnavigate or cross lakes and some long-distance migrants used torpor to postpone migration during periods of unfavorable conditions (McGuire et al. 2012a). These behavioral responses as well as the necessity of using stopover habitat during migration likely contribute to the increased use of lakeshores and emphasize the importance of these areas for conservation.

Migrants concentrated along lakeshores can be very mobile. In addition to immediate refueling and rest, migrants make broad scale flights among habitat patches, explore wind conditions, and orient for migration. For example, radio-tagged bird and bat migrants on the north shore of Lake Erie made repeated movements among habitat patches (Taylor et al. 2011). Individuals relocated as far as 18 and 30 km from their capture site (maximum distance tracked for a bat and bird species, respectively) prior to resuming migration (Taylor et al. 2011). Nocturnal migrants such as warblers and other Neotropical migrants regularly engage in morning flights along lakeshores (Wiedner et al. 1992). These flights typically occur within 2 hours of sunrise and are thought to represent reorientation along a geographic obstacle or movements among stopover habitats (Able 1977, Moore 1990, Wiedner et al. 1992). Flights of this nature often occur above tree line (Bingman 1980) but lower than heights associated with nocturnal migration (Harmata et al. 2000, Mabee and Cooper 2004, Newton 2008). Migrants have also been observed initiating nightly exploratory flights at stopover sites (Schmaljohann et al. 2011). These flights are thought to represent normal activity of migrants as they calibrate their internal compass and test wind speed and direction aloft. In addition to these activities while in stopover, migration flights follow north-south oriented lakeshores *en route* to their destination (Buler and Dawson 2012) while east-west oriented lakeshores may be used to circumnavigate open water or find narrow points for crossing (Alerstam 2001, Diehl et al. 2003, France et al. 2012). Cumulatively, these types of activities define a use area near lake shores that include a variety of movements and altitudes for landscape level, exploratory, and migratory flights. These movements in proximity to lakeshores may increase vulnerability to collision risk with a variety of structures, including low-rise buildings which pose collision risk during the day time (Gelb and Delacretaz 2009), and tall structures such as high-rise buildings, communication towers or wind turbines which pose collision risk during nocturnal migration (Longcore et al. 2013).

Migrant populations may experience the greatest mortality pressure during migration (Newton 2006, 2007, Sillett and Holmes 2002, Diehl et al. 2014) and the negative ramifications of compromised stopover habitat to migratory populations are becoming increasingly clear (Sillett and Holmes 2002, Mehlman et al. 2005, Faaborg et al. 2010). Shoreline habitats along the Great Lakes are subject to pressures from urbanization, energy development, land conversion, and environmental contamination that may limit habitat availability and/or reduce habitat quality (France et al. 2012).

We established this project to identify activity patterns, timing, and magnitude of migration along Great Lakes lakeshores to understand and help meet the needs of wildlife conservation. Documenting bird and bat migration is challenging because bats and many bird species migrate at night. In addition, nocturnal movements occur sporadically over the course of a season. To study nocturnal migration we used two avian radar units that operated 24 hours per day and simultaneously scanned horizontal and vertical planes.

METHODS

Study Area

During the spring 2017 season, we deployed radar units at two sites along Lake Michigan. One unit was located within the city of Chicago at Montrose Point, Cook Co. IL, in an urbanized landscape on the southwestern portion of the lake (Table 1, Fig. 1). The second unit was located at Indiana Dunes State Park, Porter Co. IN, in a protected area with minimal urbanization, on the southern tip of Lake Michigan (Table 1, Fig. 1).

Equipment

We used two model SS200DE MERLIN Avian Radar Systems (DeTect Inc., Panama City, FL) to document migration movements, for more details see (Wells et al. 2018). These systems were selected because they are self-contained mobile units specifically designed to detect, track, and count bird and bat targets. Each system employed two marine radars that operated simultaneously, one that scanned the horizontal plane (horizontal surveillance radar, HSR) while the other scanned vertically (vertical scanning radar, VSR; Fig. 2). Additionally, each unit contained four computers for real-time automated data processing and a SQL server for processed data storage and review. The units were configured with a wireless router to allow remote access to the computers and automated status updates.

Table 1. Site names and study locations, for two marine radar units deployed during spring 2017 in Illinois (IL) and Indiana (IN).

Site	Nearby Town	Latitude	Longitude
Montrose Point	Chicago, IL	-87.6401	41.9632
Indiana Dunes	Porter, IN	-87.0651	41.6590

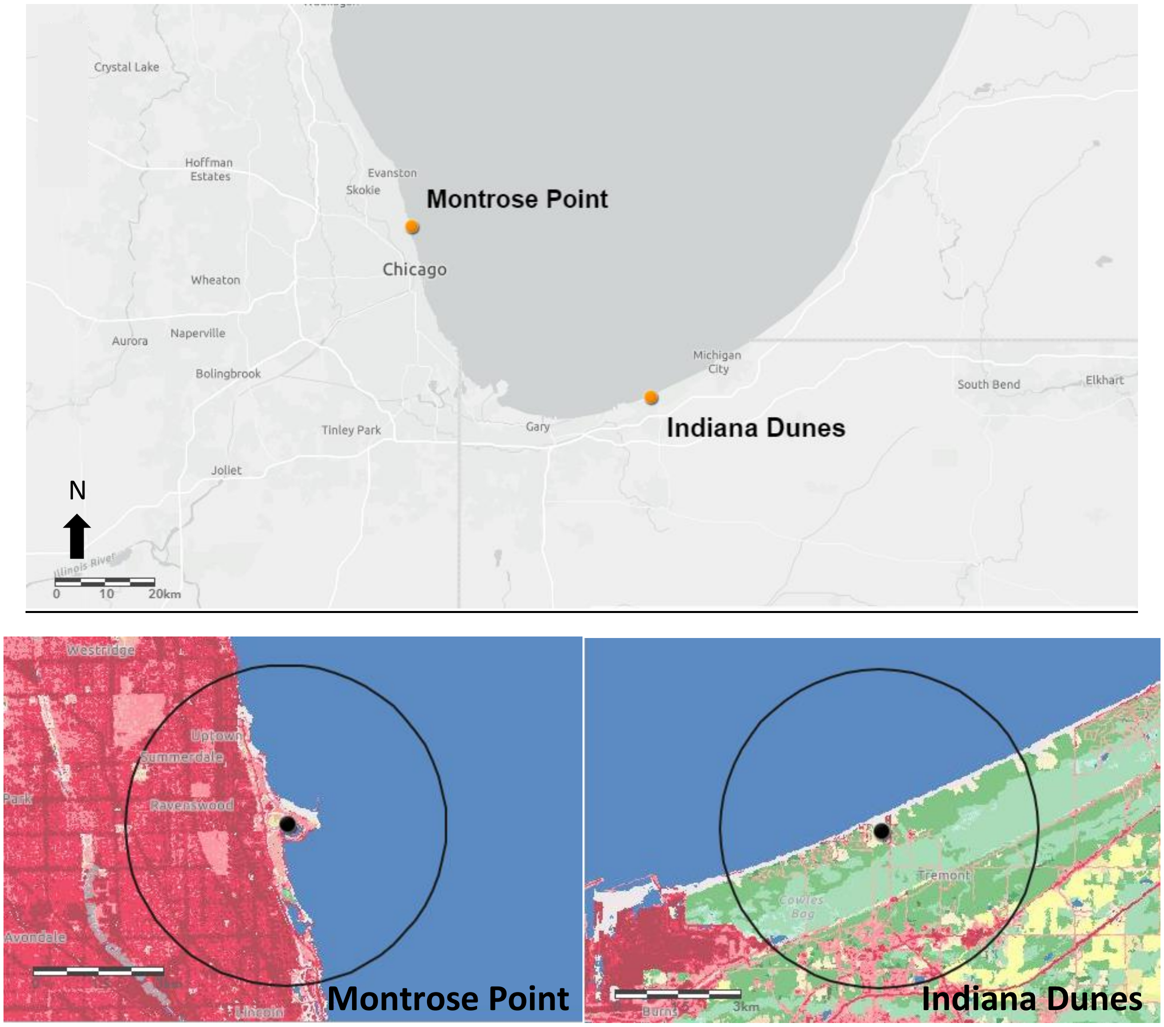


Figure 1. Radar System locations in Cook Co., IL (Montrose Point) and Porter Co., IN (Indiana Dunes). Land cover is indicated with color coding; light pink=developed open space, pink to dark pink=low to high intensity development, medium green=mixed forest, green=deciduous forest, light green=woody wetlands, blue=open water, light blue=emergent herbaceous wetlands, yellow=cultivated crops (Homer et al. 2012). The black circle indicates 3.7 km radius around each radar location.

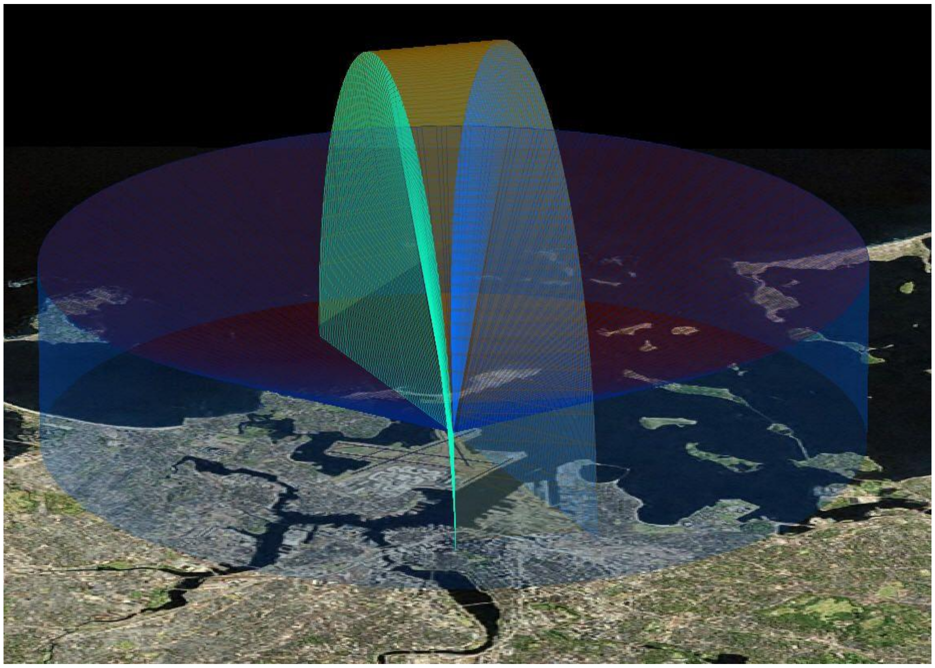


Figure 2. Computer representation of the potential survey volume scanned by horizontal (blue) and vertical (green) radars used by the U.S. Fish and Wildlife Service during spring 2017. Graphic provided by DeTect, Inc.

<u>Radar Set Up and Data Collection</u>

Radar systems were deployed during the first week of April at their respective sites. Each radar system was maintained into the second week of June to capture the anticipated end dates of the migration season. Establishing the radar system at the selected site involved micro-site selection, orienting the VSR, and making adjustments to ensure adequate information was captured and interference from the surrounding landscape was minimized. We anticipated a primarily northbound direction of migration during spring and oriented the VSR to an angle that was slightly off perpendicular to anticipated direction of traffic. This orientation was a compromise between a perpendicular angle that would intercept the greatest number of targets (birds or bats) and a parallel angle that would maximize the amount of travel time within the vertical radar beam.

To improve data collection, clutter maps were generated using 60-scan composite images (Figs. 3 & 4) at time periods with low biological activity. These maps identify areas with static returns (areas that are white). These objects reduced our ability to detect targets in certain regions of the sample volume, and as a result those regions were assigned a reflectivity threshold that prevented the static returns from being included in the data.

Following this initial set up, the MERLIN software from DeTect Inc. was calibrated to site conditions. The MERLIN software provides real-time processing of raw radar data to locate and track targets while excluding non-targets and precipitation. However, parameters used by the tracking software require adjustments to account for site-specific conditions. We established these settings to minimizing inclusion of non-targets while maximizing cohesive tracks of bird and bat targets. We checked these settings periodically during the data collection period to ensure continuous function. We monitored raw (unprocessed analog radar returns) and processed radar outputs and managed data storage. In addition to storing all the processed data, we maintained samples of raw radar data for potential reprocessing.

Data Processing and Quality Control

Prior to data analysis, data processed by MERLIN software was further evaluated for potential contamination by non-targets. We visually reviewed all data in 15-minute time increments and removed time periods that were dominated by rain; data also were reviewed for other forms of transient clutter. Once contaminated time periods were removed, we summarized data for further analysis using database queries provided with the radar system by DeTect Inc.

Data Summary and Trends Analysis

Qualitative Analysis – We used the processed data to assess activity patterns that are associated with migration. Horizontal Trackplots were viewed to identify changes in activity and to investigate migrant behaviors associated with direction of flight, such as reverse migration (Åkesson 1999) and migrants moving toward shore at dawn. Vertical Trackplots were viewed to investigate changes in activity associated with altitudinal distributions, such as dawn ascent (Myres 1964, Diehl et al. 2003). Target counts from the VSR represented an index of abundance and we used these indices to identify temporal trends and overall patterns in migration intensity.

Target Counts & Ground Clutter –The HSR and VSR radars have different strengths that complement one another. For example, the HSR tracks low flying targets in a 360 ̊ span around the radar unit and detection is not affected by the target’s direction of travel. However, the HSR is much more affected by ground clutter (obstacles that block the radar beam) which affects target detection and tracking. Ground clutter is due to topography, vegetation, buildings, and other obstacles. We mapped static clutter for Montrose Point and Indiana Dunes (Figs. 3 & 4, respectively). Errors caused by ground clutter lead to both under- and over-counting; targets blocked by ground clutter may not get counted, and targets that fly in and out of areas with ground clutter may get counted multiple times. This leads to HSR counts that are more influenced by site conditions than VSR counts. However, the HSR better captures targets under certain conditions, such as when targets are primarily at low elevation (Bruderer 1997, Schmaljohann et al. 2008). The HSR also is much more susceptible than the VSR to beam bending (anomalous propagation) from dynamic atmospheric conditions; beam refraction in the VSR is minimal primarily due to its orientation. The VSR was used to track targets captured within the 1-km standard front (defined by a volume of space that extended 500 m to either side of the radar and continued up to the maximum height of data collection (2800 m). The VSR has more consistent detection than HSR as it mostly tracks against clear air, except in the lowest altitude bands. At low altitude bands the VSR is impacted by ground clutter (Figs. 3 & 4). Another strength of the VSR is that it provides altitudinal distribution of the targets. The VSR detection ability is affected by target direction and distance from the radar (Bruderer 1997, Schmaljohann et al. 2008). Plotting these indices together provided a more comprehensive view of changes in target activity over time.

Montrose Point Clutter Maps

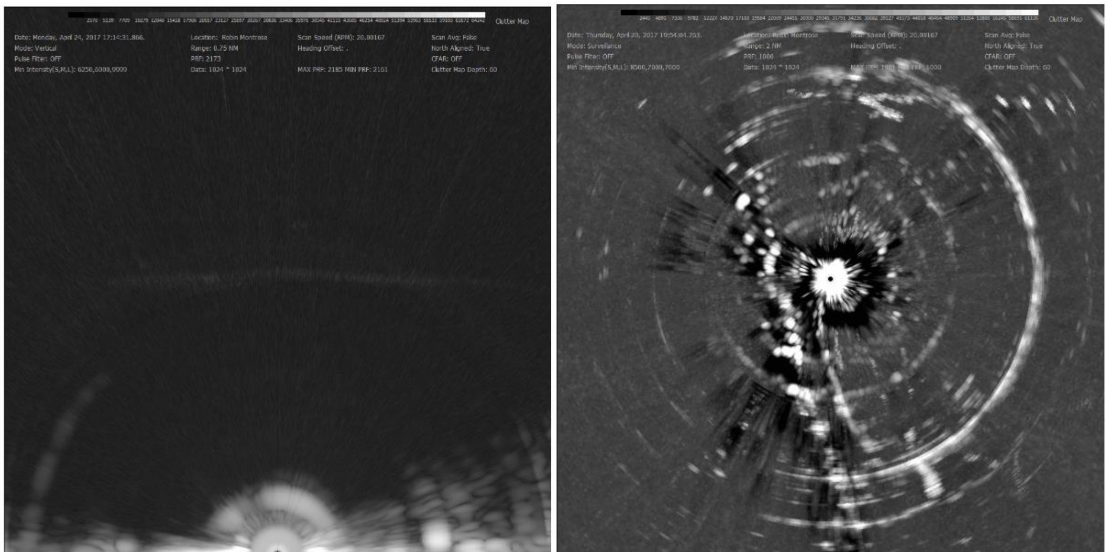


Figure 3. Clutter maps from VSR (left) and HSR (right) during the spring 2017 migration season. Brighter areas represent static returns from stationary objects such as tree lines and buildings or arcs from irregular radar returns. Detection of targets may be reduced or lost in these areas due to obstruction from these objects. In the HSR clutter map, the Chicago skyline can be seen as a line of white dots extending from the bottom center of the image to the left (west) of the radar unit at the center.

Indiana Dunes Clutter Maps

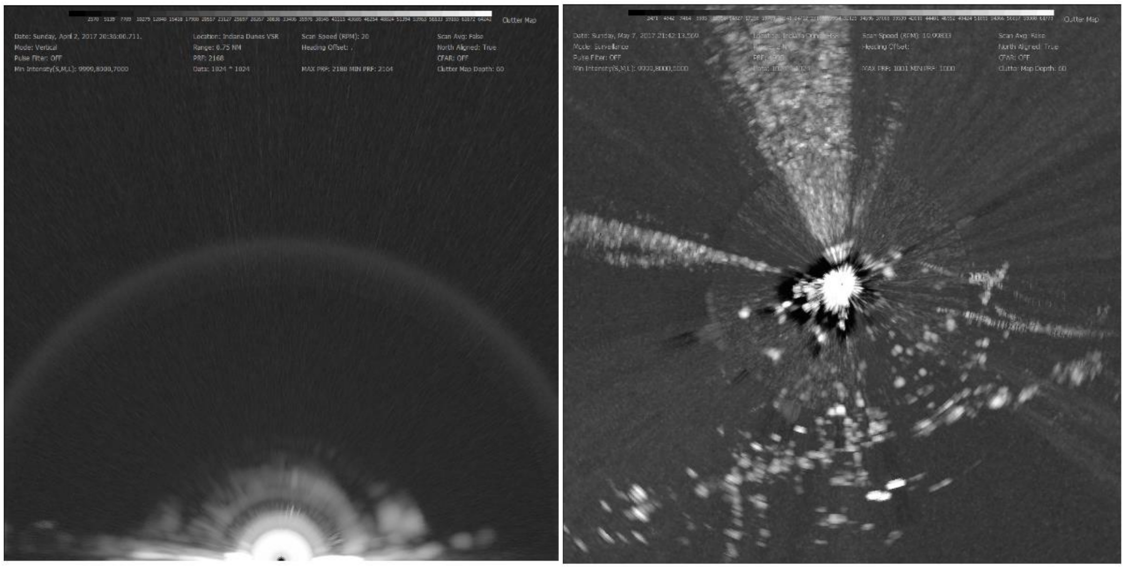


Figure 4. Clutter maps from VSR (left) and HSR (right) during the spring 2017 migration season. Brighter areas represent static returns from stationary objects such as tree lines and buildings or arcs from irregular radar returns. Detection of targets may be reduced or lost in these areas due to obstruction from these objects.

Temporal Trends - We used the VSR index to calculate target passage rate (TPR). We calculated TPR as the number of targets detected in the standard front per hour using DeTect SQL queries. Hours with less than 30 minutes of recording time were omitted from this calculation. For example, after removing all hours with less than 30 minutes of clean data, nocturnal TPR for a given night (biological time period) was calculated by dividing the target count by the number of nighttime minutes and multiplying by 60 to provide the number of targets per hour during that night. We extended this metric to the season and calculated mean TPR for biological time periods and hourly TPR. Mean nocturnal TPR for the season is the sum of nightly TPRs divided by the number of nights sampled. Similarly, mean hourly TPR for the season is the sum of TPRs for an hour period divided by the number of times that hour of the day was sampled.

Directional Trends – Mean angle and concentration (r) of target directions were analyzed following methodology for circular statistics (Zar 1999) provided within DeTect SQL queries. The angular concentration has a value of 1 when all angles are the same (perfect alignment with all targets flying in the same direction) and a value of 0 when there is no alignment. For example, a circular uniform distribution (targets flying in all directions equally) or equal-sized groups flying in opposite directions. We anticipated a generally northward direction of movement from nocturnal targets during spring migration. We used radial graphs to plot the number of targets per 8-cardinal directions (i.e., eight groups centered on N, NE, E, SE, S, SW, W, NW) during four biological time periods (i.e., dawn, day, dusk, night).

In addition, we used the circular mean direction of targets each night to examine potential origins of migrants, plotting the estimated direction of origin as a line with length representing the number of migrants. This measure does not indicate variance of directionality, which can be large, but does provide a visualization of the likely origin direction of many migrants.

Altitudinal Trends – DeTect SQL queries calculated height estimates from the VSR data of targets tracked within the standard front. However, the size and shape of the radar beam changes with altitude, producing a smaller sample volume at low altitudes and a larger sample volume at high altitudes (Fig. 5). To address this we calculated the volume of the radar beam within each 50-m altitude band by Monte Carlo integration (Press et al. 2007). Height estimates were calculated based on the range and bearing of the target location and reported as the height above ground level at the radar unit; this measurement does not take into account changes in topography. We used these estimates to calculate mean altitude of targets above ground level by biological time period and hour and report mean and median altitudes for the season.

RESULTS

During the spring 2017 season data were collected from April 4th to June 9th at Montrose Point, Cook Co. IL and from April 2nd to June 8th at Indiana Dunes, Porter Co. IN (Table 1, Fig. 1). VSR radar units collected data for 1,603 hours at Montrose Point and 1,606 hours at Indiana Dunes. Data were recorded continuously while the radar units were operational. Gaps in analyzed data occurred during rain events (546 and 349 hour gaps at Montrose Point and Indiana Dunes respectively) and when the radar units were not operational due to maintenance or malfunction (radar downtime, 112 and 45 hours at Montrose Point and Indiana Dunes

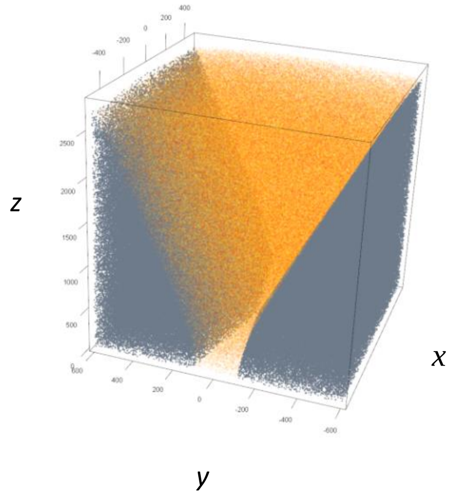


Figure 5. A representation of the structural volume of the vertical scanning radar (VSR) within the standard front. In this graphic the radar unit is located at the origin and the radar beam extends to 500 m on either side of the radar unit (x-axis) and up to a maximum height of 2800 m (z-axis). The y-axis represents the spread of the radar beam as it extends away from the origin. The orange semi-transparent points represent the volume contained by the structure of the radar beam. Dark gray points represent the volume that is within the box but are not included in the volume of the radar beam.

respectively). When correcting for radar downtime and removal of periods with rain, the vertical and horizontal radars collected useable data 59% and 98% respectively at Montrose Point and 75% and 98% respectively at Indiana Dunes.

Qualitative Assessments

Plots of tracked targets show nocturnal migration events at both locations (Figs. 6 & 7). Also apparent on the Trackplots from both sites are areas not well recorded by the radar due to beam blockage from ground clutter (Figs. 4 & 5) resulting in reduced detection in the air space that was within the range of data collection. Rings of decreased detection near the radar unit and where the radar switched from short to medium pulse are also evident in both the horizontal (May 28, 3:00 am, Fig. 6) and vertical (May 28, 8:00 pm, Fig. 6) Trackplots (seen at a range of about 1,400 – 2,000 m).

Temporal Trends

We plotted counts of targets per hour processed by MERLIN software for both HSR and VSR antennas as a time series to identify pulses of nocturnal activity, season duration, and changes in patterns of activity over time (Figs 8 & 9). Hourly target counts provided by horizontal and vertical radars showed nightly pulses of elevated activity with peaks occurring a few hours before midnight at our study sites (Figs 8 & 9). Across our sampling period these events would often occur over a series of 2 to 3 nights at the beginning and end of the season (April and June), and more consistently, for periods of five consecutive days or more, during the middle of the season (May). Peak nighttime pulses occurred at both sites during late May. Nightly pulses in target counts on the vertical radar typically corresponded to pulses on the horizontal radar, though the vertical radar records fewer targets overall.

The pattern of mean and median target passage rate among biological time periods was similar among the two sites with greater target passage at night followed by the dawn time period (Table 2). The mean nighttime TPR also was similar between Montrose Point and Indiana Dunes (Table 2).

Table 2. Seasonal target passage rate at Montrose Point Illinois (IL) and Indiana Dunes Indiana (IN), spring 2017.

	Montrose Point		**Indiana Dunes**	
Biological Period	Mean ± SD	Median	Mean ± SD	Median
Dawn	631 ± 543	401	339 ± 401	252
Day	324 ± 207	335	133 ± 113	127
Dusk	180 ± 208	117	126 ± 148	72
Night	1349 ± 1196	1106	1297 ± 1179	886

<u>Directional Trends</u>

Spring migrants flew primarily in a north/northwesterly direction during nocturnal migration at both sampled locations (Figs. 10 & 11, Table 3). The nighttime northward angular concentration was greater at Montrose Point than Indiana Dunes (r = 0.42 and 0.31, respectively, Table 3).

Movements during other time periods varied at both sites. At Montrose Point dawn movements also were in the north/northwesterly migratory direction (Fig. 10). Daytime movements were in a north/south direction suggesting daytime movements along the shore, the angular concentration for these movements was low (Table 3). Dusk movements were primarily north/south with southerly movements predominating (Fig. 10).

At Indiana Dunes the mean flight direction at dawn was easterly, indicating a reversal of nighttime migratory direction to land along the lakeshore (Fig. 11, Table 3). Daytime movements at Indiana Dunes were in a west/east direction suggesting daytime movements along the shore, these movements had a low level of angular concentration (Table 3). Dusk movements were primarily west/northwesterly and had the highest angular concentration compared to other time periods for this site (Fig. 11).

Table 3. Mean direction (compass degrees with north at 0 degrees, increasing clockwise) and angular concentration (r) of targets during different time periods at Montrose Point and Indiana Dunes, spring 2017.

	Montrose Point		**Indiana Dunes**	
Biological Period	Mean Direction (°)	r	Mean Direction (°)	r
Dawn	320	0.23	95	0.28
Day	147	0.05	303	0.05
Dusk	147	0.12	300	0.42
Night	341	0.42	344	0.31

In addition to studying the flight direction of migrants, we also studied their direction of origin. The mean nightly direction of origin for Montrose Point spanned primarily from the south to southeast direction (Fig. 12a). Flight origin for Montrose Point indicated that a large proportion of targets fly over open water to reach this point, including two nights with the largest target counts recorded over the sampling period (May 26 and 27 with 4445 and 4869 targets per hour respectively). The magnitude of migrant origin also was large from easterly directions but was minimal from westerly directions (Fig. 12a).

Nightly target origin for Indiana Dunes was wide ranging, spanning from southwest to northeasterly and with only one nightly mean indicating over-water flight originating from the northeast (Fig. 12b). The lack of over-water flights at this site is likely due to its location on the southern tip of Lake Michigan and therefore a departing shore for north-bound migrants. This site also had low magnitude of migrants originating from a westerly/west-southwest direction (Fig. 12b).

Altitudinal Trends

At both Montrose Point and Indiana Dunes targets were observed across all sampled altitude bands (Figs. 13 & 14). The highest mean altitude for migrants occurred during the Night (870 ± 582 m) and Dawn (569 ± 472 m) time periods at Montrose Point. Day and Dusk mean altitudes at this site were 444 ± 472 m and 464 ± 547 m respectively. Indiana Dunes also had its highest mean altitude for migrants during the Night and Dawn time periods (716 ± 497 m and 562 ± 439 m, respectively). Day and Dusk mean altitudes were 375 ± 364 m and 409 ± 406 m, respectively at Indiana Dunes.

The corrected density estimates for both Montrose Point and Indiana Dunes show a much higher density of birds within the range of the Rotor-swept Zone (the area through which wind turbine blades sweep, 30-200 m) compared to the uncorrected density estimates (Figs. 13 & 14). The altitude profiles looked similar between these two sites, both sites had high bird densities during each period of the day. Montrose Point had generally higher densities than Indiana Dunes, particularly during daytime. Nighttime for each site had higher densities than the other periods, reflected in the x-axis (Figs. 13 & 14).

The density of migrants at different altitudes by hour throughout the day is presented in Figures 15 & 16, note that the heat scale varies slightly between the two figures. The greatest density of migrants occurred during nocturnal hours, and migrants generally were most dense at less than 550 m altitude at Montrose Point and 600 m at Indiana Dunes, suggesting heavy use of the lower airspace (Figs. 15 & 16). At Montrose Point, there was a moderate density of targets during the daytime (7 am to 7 pm), these targets stayed at lower altitudes (e.g. below 200 m, Fig. 15). Some of these daytime targets may have been waterbirds, for example gulls, which are known to use urban environments where they may supplement their diet with anthropogenic food sources (Laurich et al. 2019) or find nesting sites (Dwyer et al. 1996). Migrant density at Montrose Point increased as migrants rose in altitude with the onset of nighttime migration (9 pm, Fig. 15) and remained at higher altitudes before descending at 4 am (Fig. 15). At Indiana Dunes, there was a low density of targets during the daytime compared to Montrose Point (e.g. at lower altitudes from 9 am to 5 pm, Fig. 16). Migrants at Indiana Dunes began to increase in density and altitude at 8 pm and had their highest altitudes at 9 and 10 pm, after which nighttime migration altitude was lower (Fig. 16). This increase in altitude at the onset of nightly migration may enable migrants to orient as they navigate a water crossing. Targets reduced altitude at 4 am when ending nighttime migration (Fig. 16).

DISCUSSION

This study was undertaken to document migration in the Great Lakes basin. Our findings for the southern tip of Lake Michigan indicate that this area is important for spring migration; the Montrose Point site had a large number of migrants detected, despite being a highly urbanized area. Our research contributes to a growing body of literature that documents various aspects of migration and identifies Great Lakes lakeshores as areas important for conservation of migratory species. Our data provide unique observations about the magnitude and timing of nocturnal migration that could not be observed without the aid of radar.

Migration Patterns

Patterns of movement recorded at these sites were consistent with other observations of migration (Newton 2008) and indicated that nocturnal migratory flights occurred regularly at both locations during spring 2017. Target passage rate was greatest during the nocturnal biological time period at both locations (Figs.13 & 14). Nocturnal activity was typically oriented in a north/northwest direction (Figs. 10 & 11) and occurred in pulses across the season (Figs. 8 & 9). Both sites had peaks in migration on April 24-25th, May 8-17th, and May 26-28th (Figs. 8 & 9). Fluctuations in migrant numbers may be related to broad scale weather fronts, variation in timing among guilds of migrants, or a combination of these and other factors (Newton 2009).

Though nocturnal migration was primarily in the expected direction of migration (i.e. north/northwesterly) movements during other biological time periods varied (Figs. 10 & 11). This may be related to daytime movements along the shore, foraging, or other movements. It also may be related to movements of resident birds (e.g. American Crow), or short-distance migrants on their breeding grounds (e.g. Ring-billed Gull). Changes in flight direction can be observed in the Trackplots; for example, with migrants over water returning to shore at dawn at both sites (Figs. 6 & 7).

Flight Altitude

Altitude profiles indicated that most nocturnal targets passed below 600 m with peak density in the 100-400 m altitude bands (Figs. 15 & 16). We corrected for the approximate shape of the survey volume and included this correction in our density. This correction is based on the manufacturer's estimate of beam geometry, which may not be precise, and beam propagation is not consistent over time. Beam propagation is affected by side lobes, target size and distance, and atmospheric conditions. Nonetheless, we think the correction was an improvement over altitude profiles that ignore beam geometry and sampling effort. We were not able to correct for the loss of detection with distance from the radar (Schmaljohann et al. 2008); in addition, our vertical scanning radars lost detection at a range of about 1,400 – 2,000 m where the radar transitioned from the short to medium pulse. For these reasons, our estimates likely under-represent density as altitude increases. However, densities per altitude band were already decreasing before the 1,400 m band (15 & 16), so any undercount is unlikely to change the overall picture.

Migrants adjust flight altitude with wind direction and speed, visibility, time, and landscape below flight trajectory (Alerstam 1990, Hueppop et al. 2006, Liechti 2006). For example, head winds aloft have resulted in migrants moving *en masse* to lower altitudes where wind speeds were reduced (Gauthreaux 1991). Changes in flight altitude can occur at various times over the course of the night and also are associated with targets ascending from and descending to stopover sites. Depending on location, these altitude changes may place migrants at risk of collision with wind turbines, communication towers and other tall and short-rise human-made structures.

Radar Study and Management Considerations

Whereas radar may be the best tool available for gathering large amounts of data on nocturnal migration, the interpretation of radar data can be challenging. Marine radar is the most common type used to track bird and bat movements (Larkin 2005) and its use to assess risk will likely increase with wind energy development. Despite this growing trend, standardized equipment and methodology for establishing radar settings, ground-truthing biological targets, and data processing have not been adopted. These considerations can substantially affect the quality of data. This presents a challenge that is not easily solved. Without standards, comparisons among studies may be more reflective of differences in equipment, methodology, and site conditions rather than in differences in migration activity among sites.

Additionally, metrics reported in radar surveys can be misleading to someone unfamiliar with avian radar. For example, mean altitude of target passage is often reported to be above the rotor-swept zone and has been interpreted as indication of low risk. However, the mean altitude can be well above the rotor swept zone even when there is a high rate of target passage within the rotor-swept zone. This is due to the long range at which radars collect altitude data, up to 3 km above ground level in our study, where high flying targets inflate the mean altitude. This bias is apparent in our data and can be seen by comparing the mean altitude of nocturnal targets to the most densely populated altitude band (Figs. 13, 14, 15 & 16). It also is misleading to compare the percent of targets below and above the height of the rotor-swept zone without addressing the inherent difference in radar sampling effort at various altitude bands. Within our sampling framework, there are four 50-m altitude bands below 200 m (an estimate for the height of the rotor-swept zone) and 52 altitude bands above 200 m. Based on our model, we estimated that about 1 percent of the potential survey volume is below 200 m. Given that information, we would expect a small percentage of targets to be recorded at or below the rotor-swept zone but this does not necessarily indicate low risk.

When examining general migration patterns, high nighttime migrant activity was documented at both Lake Michigan radar sites. This is evident from the Trackplots (Figs. 6 & 7), time series plots (Figs. 8 & 9), and high target passage rates (Figs. 13 & 14). Density of targets within a 30 – 200 m rotor-swept zone also were high during the dawn, day and dusk time periods (Figs. 13, 14, 15 & 16) and nighttime peak density fell at or just above the rotor-swept zone. Throughout the migration season, nighttime targets were recorded flying both across the lake and along the lakeshores (Figs. 6 & 7). The combination of these behaviors indicates that high numbers of night migrants may be at risk of collision with a wind facility, communication tower or other tall structures placed within the lakeshores of Lake Michigan. These collisions can have detrimental effects on populations; for example, for 13 bird species of conservation concern, communication tower collisions caused mortality of 1-9% of these populations annually (Longcore et al. 2013). Likewise, population models show that wind turbine mortality can drastically reduce migratory bat populations, leading to extinction (Frick et al. 2017).

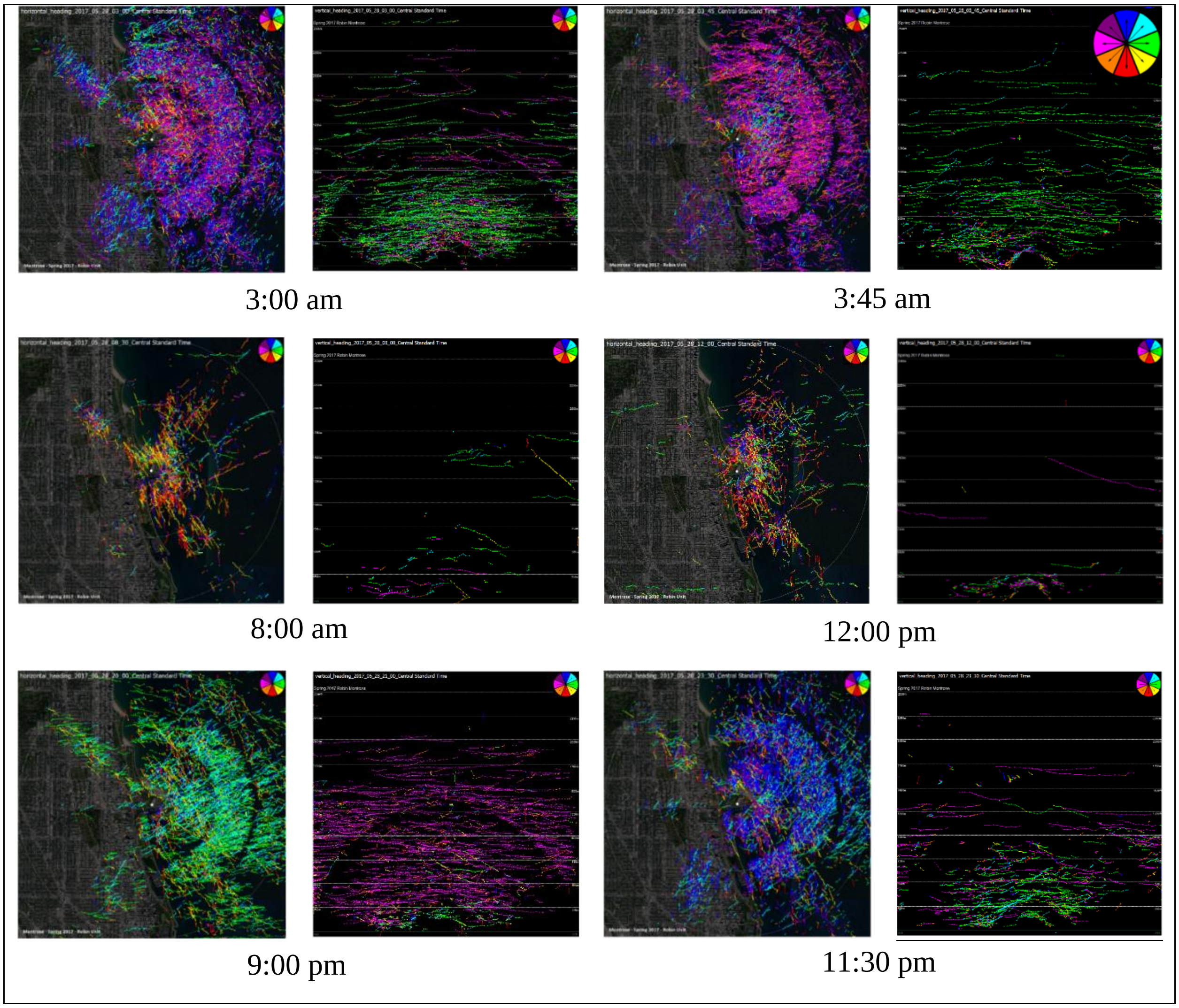
While target passage rate and target density are lower during the dawn, day, and dusk time periods (Figs. 13, 14, 15, & 16), migrants are still active and at risk of collision (Gelb and Delacretaz 2009, Kahle et al. 2016). Targets were recorded flying along the Lake Michigan shoreline during all time periods, indicating the lakeshore provides important migratory pathways and stopover habitat during all times of the day. Therefore, conservation of the entire migration airspace along these lakeshores will be important. This is particularly true at Montrose Point where target density was moderately high from dawn to dusk. Given the high density of targets within the Chicago metropolitan area it will be important to continue identifying and mitigating mortality risks for birds and bats in addition to enhancing stopover habitat. Programs such as Lights out Chicago and the Chicago Urban Bird Treaty are important conservation tools in making built infrastructure and the urban landscape safer for birds.

Conclusion

Overall, we found that radar provided valuable information on movements throughout the day and insight into nocturnal migration that would otherwise be unattainable. We believe continued development and careful interpretation of radar data will result in valuable contributions to the management and conservation of migrating birds and bats.

This study highlights the potential role of radar in implementing recommendations from wind energy guidelines (USFWS 2012) to identify areas where impacts to wildlife would be minimized. We documented clear examples of migrant activity along the southern lakeshores of Lake Michigan at our study sites in Illinois and Indiana, and the density of targets at lower altitudes is a concern. An additional concern is that turbine height and blade length continues to grow, increasing the area of the rotor-swept zone. This increases the altitude range of flight risk for birds and bats migrating through an area. The data we collected may be of interest to public and private entities that are involved with wind energy development or other construction and potential placement of turbines, towers or other structures in the Great Lakes region. Coupling avian radar systems with other forms of research or using radar in conjunction with post-construction fatality searches may broaden the utility of its use in making risk assessments and assessing wind energy development or other projects.

Montrose Point Migration Trackplots



3:00 am

3:45 am

8:00 am

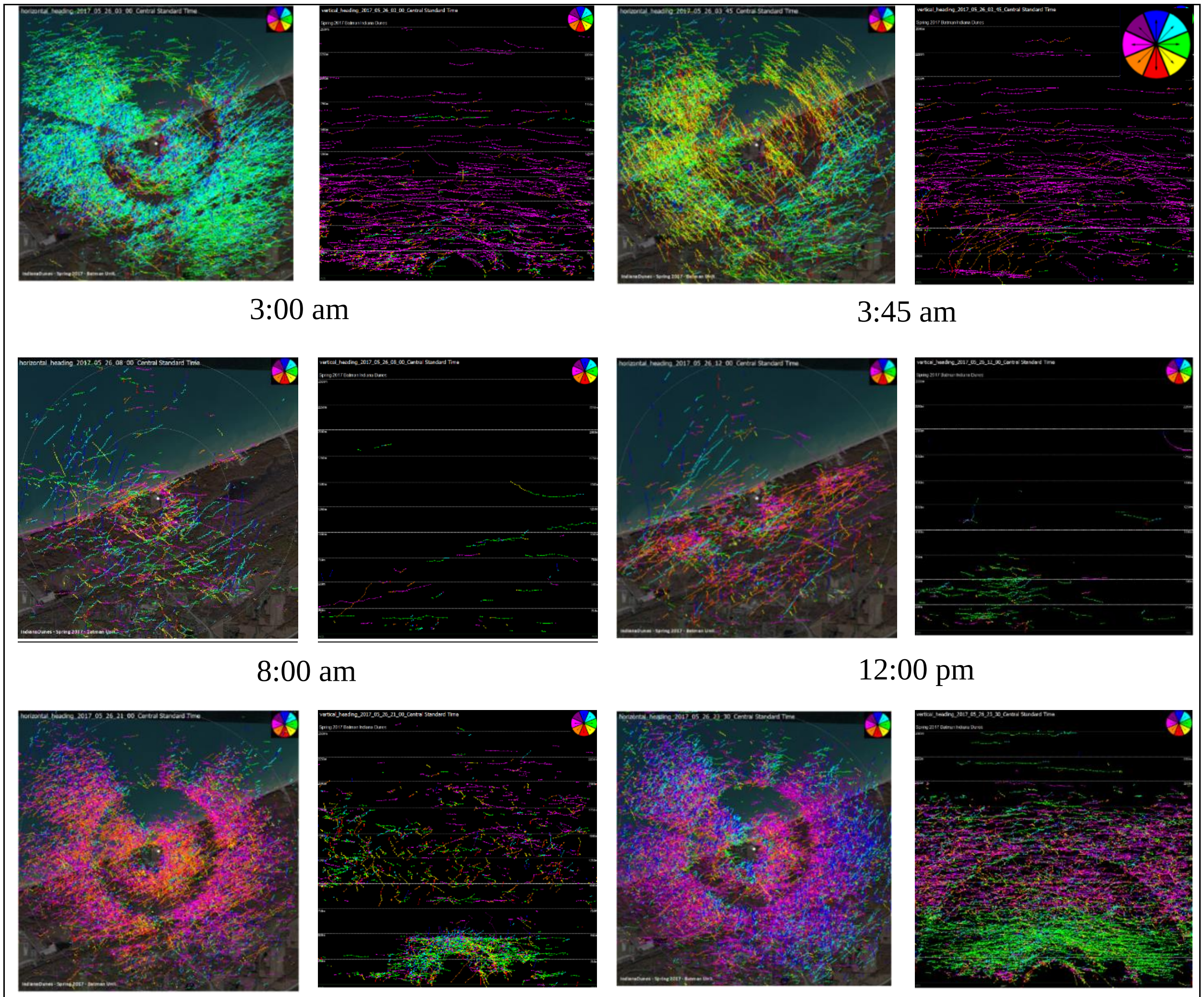
12:00 pm

9:00 pm

11:30 pm

Figure 6. Horizontal (HSR) and vertical (VSR) migration Trackplots, Montrose Point, Cook Co. IL, May 28, 2017. Horizontal radar images show the direction of the targets as indicated by the color wheel. Early morning migration in a northerly direction (3:00 am), a turn to shore for targets over water (flying west, 3:45 am). Targets moving along the shore during daytime (8:00 am and noon). Northeasterly movements as migration begins (9:00 pm) and nighttime migration in a northerly direction (11:30 pm). Vertical radar images show target heights during different time periods. The range of horizontal and vertical radar are 3.7 km and 2.8 km, respectively.

Indiana Dunes Migration Trackplots



3:00 am

3:45 am

8:00 am

12:00 pm

9:00 pm

11:30 pm

Figure 7. Horizontal (HSR) and vertical (VSR) migration Trackplots, Indiana Dunes, Porter Co. IN, May 26, 2017. Horizontal radar images show the direction of the targets as indicated by the color wheel. Early morning migration in the northeast direction (3:00 am), a turn to shore for targets over water (flying south, 3:45 am), a few targets moving along the shore during daytime (8:00 am and noon), westerly movements as migration begins (9:00 pm), nighttime migration in a northerly direction (11:30 pm). Vertical radar images show target heights during different time periods. The bi-colored (purple/green, 11:30 pm) vertical image shows migrants flying different directions at differing altitudes. The range of horizontal and vertical radar are 3.7 km and 2.8 km, respectively.

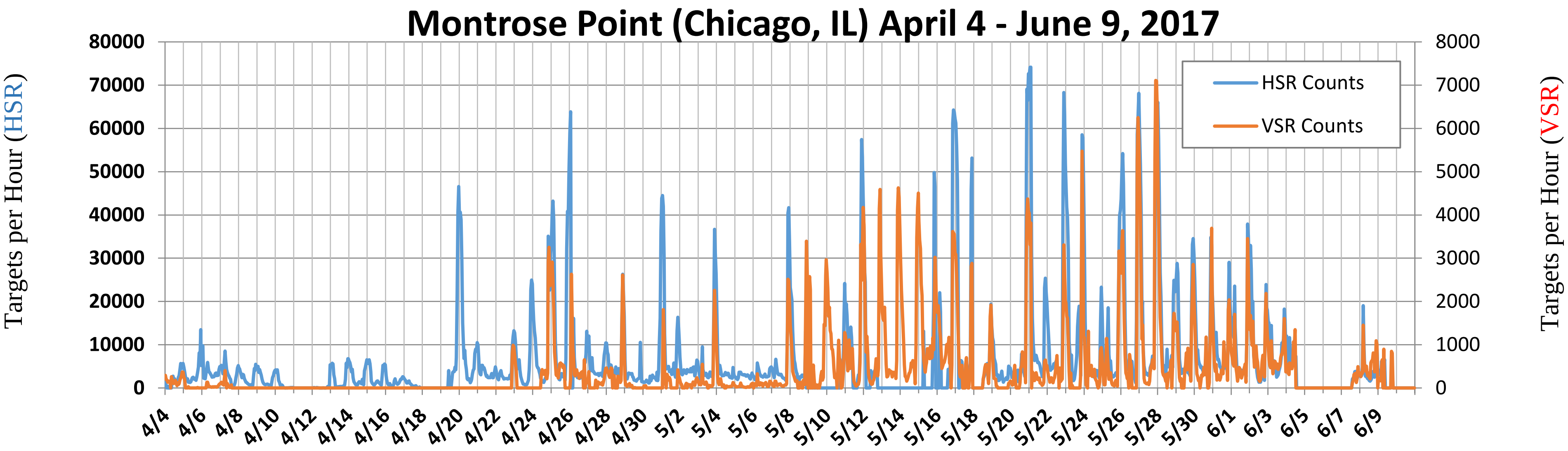


Figure 8. Time series of horizontal (blue) and vertical (red) radar counts for Montrose Point, Cook Co. IL, spring 2017. Note the differing scale between the HSR and VSR counts.

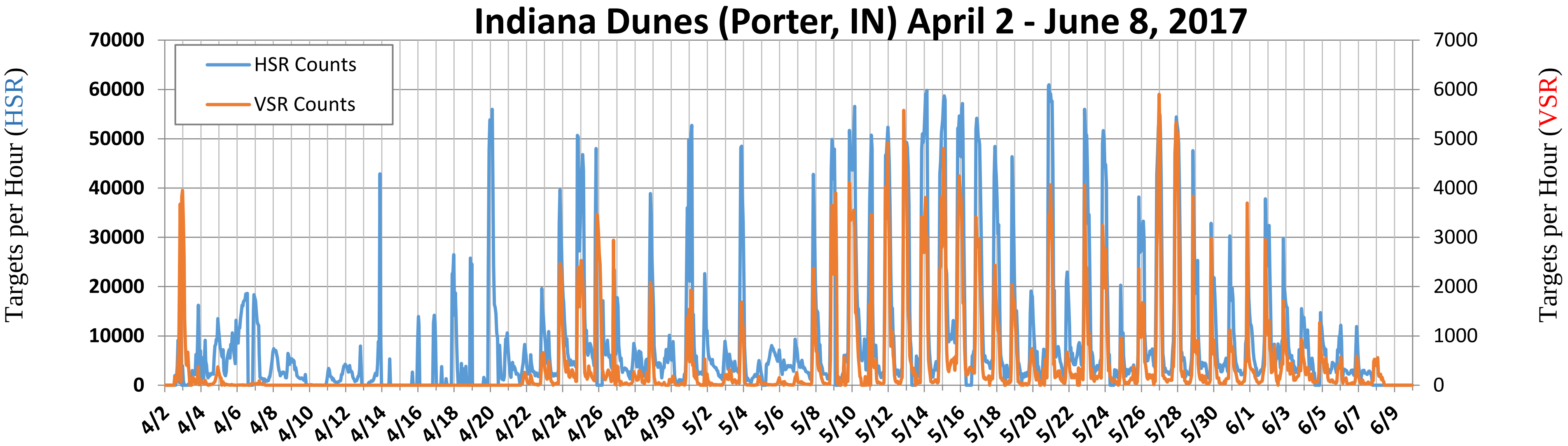
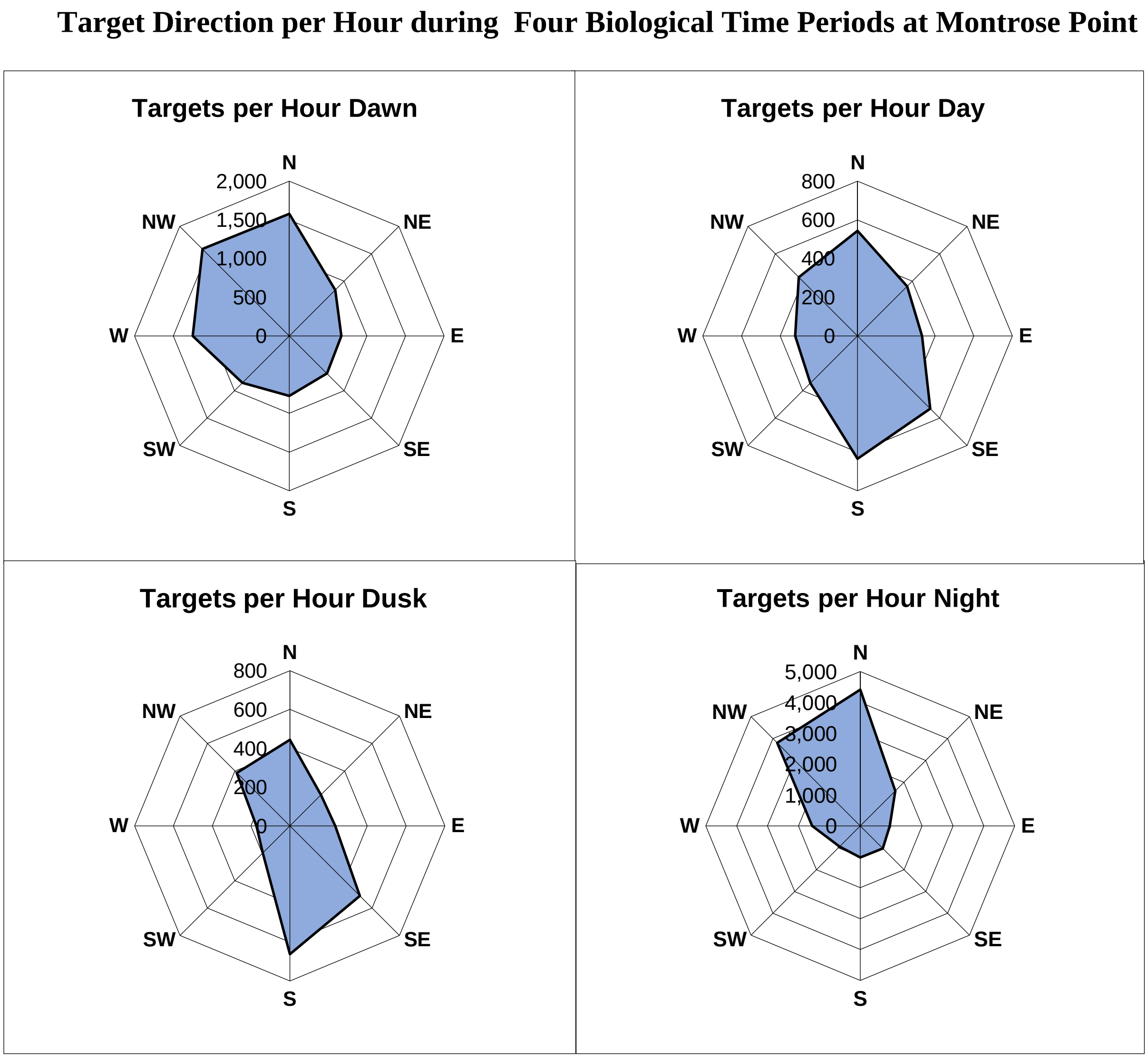


Figure 9. Time series of horizontal (blue) and vertical (red) scanning radar counts for Indiana Dunes, Porter Co. IN, spring 2017. Note the differing scale between the HSR and VSR counts.



Target Direction per Hour during Four Biological Time Periods at Montrose Point

Targets per Hour Dawn

Targets per Hour Day

Targets per Hour Dusk

Targets per Hour Night

Figure 10. Movement direction of targets during four biological periods, Montrose Point, Cook Co. IL, spring 2017. Measures are number of targets per hour, note the difference in targets by time period and marked increase in nighttime targets.

Target Direction per Hour during Four Biological Time Periods at Indiana Dunes

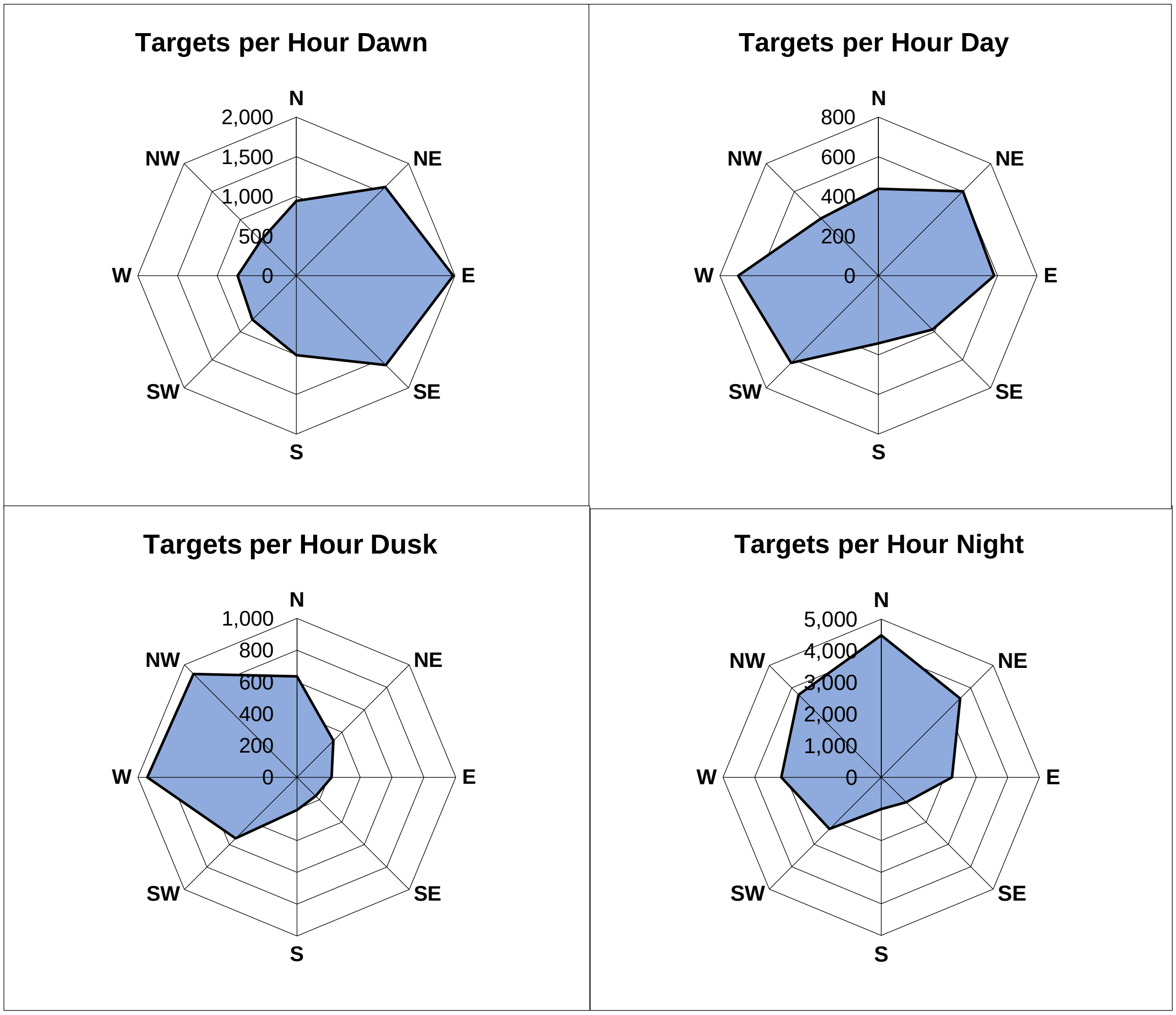
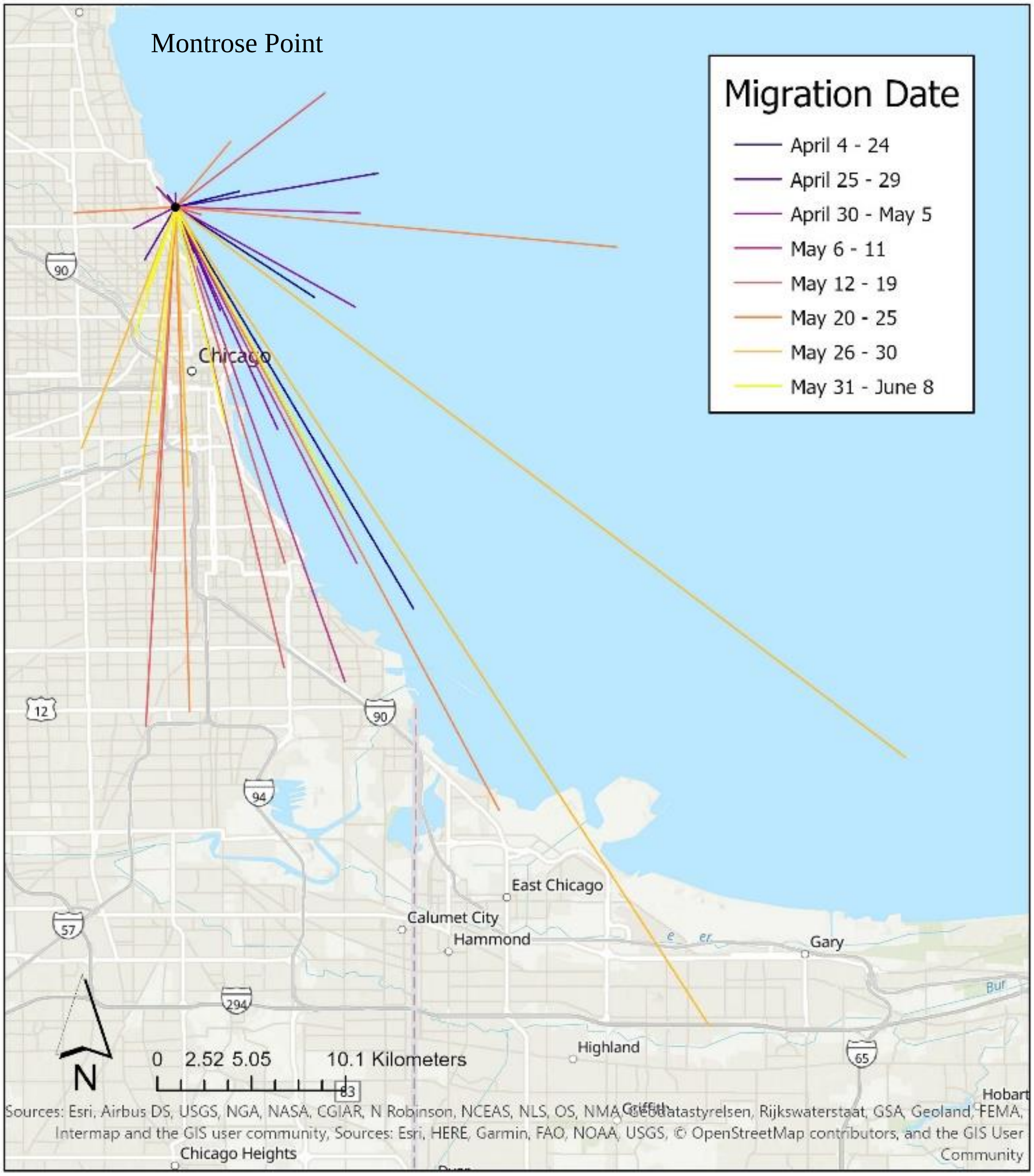


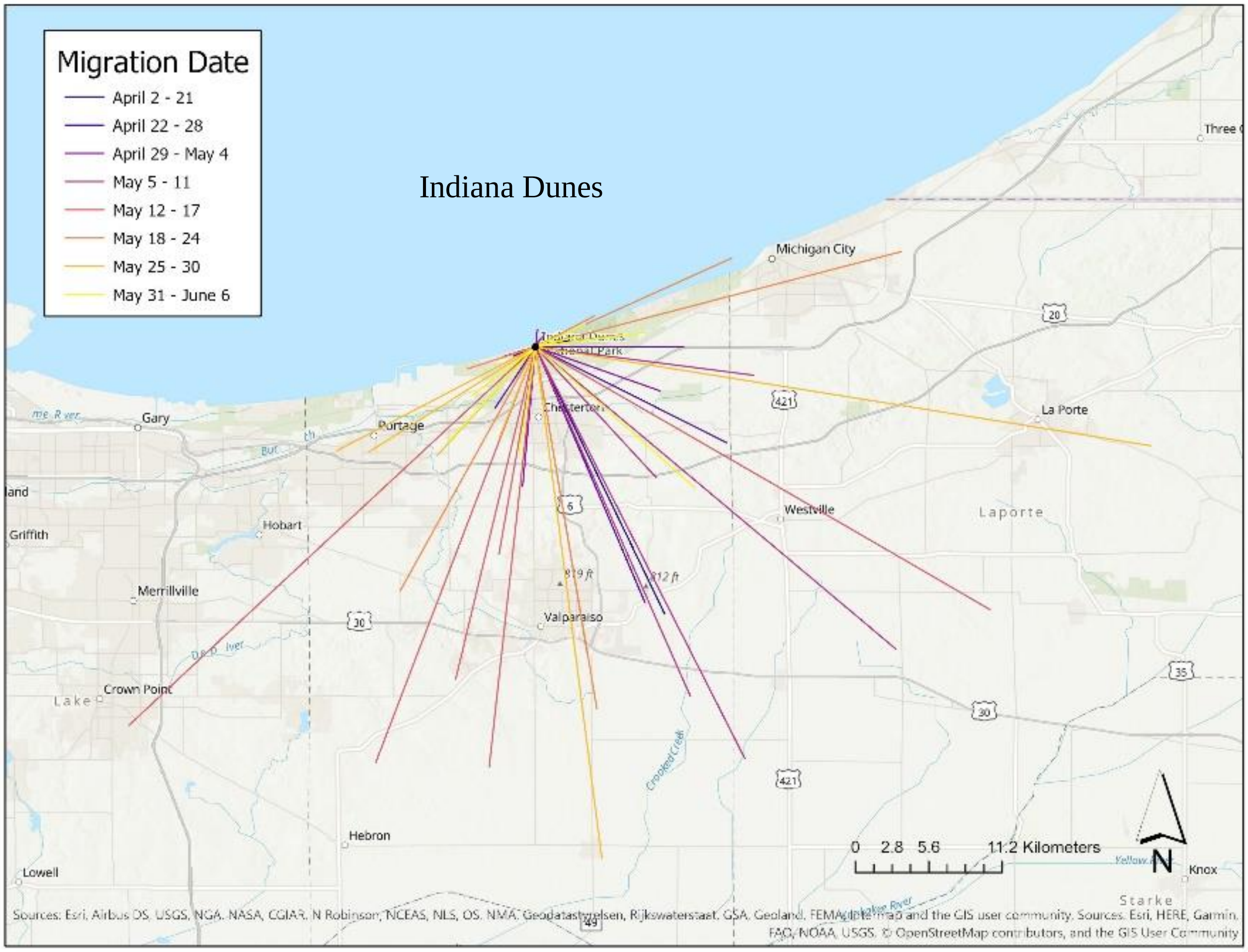
Figure 11. Movement direction of targets during four biological periods, Indiana Dunes, Porter Co. IN, spring 2017. Measures are number of targets per hour, note the difference in targets by time period and marked increase in nighttime targets.

A



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

B



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community. Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 12. Estimated direction of origin, magnitude and timing of migration at each site, Montrose Point (A) and Indiana Dunes (B), during the spring 2017 season. The angle of each line is the circular mean of target headings, represented as movement toward the radar unit. Line length is proportional to the number of targets detected each night. Date is represented by color, with cooler colors earlier and warmer colors later in the season. Note the majority of migrants are following the western shoreline of Lake Michigan north at Montrose Point, whereas at Indiana Dunes migrants arrive from a wide range of directions to a departing shore.

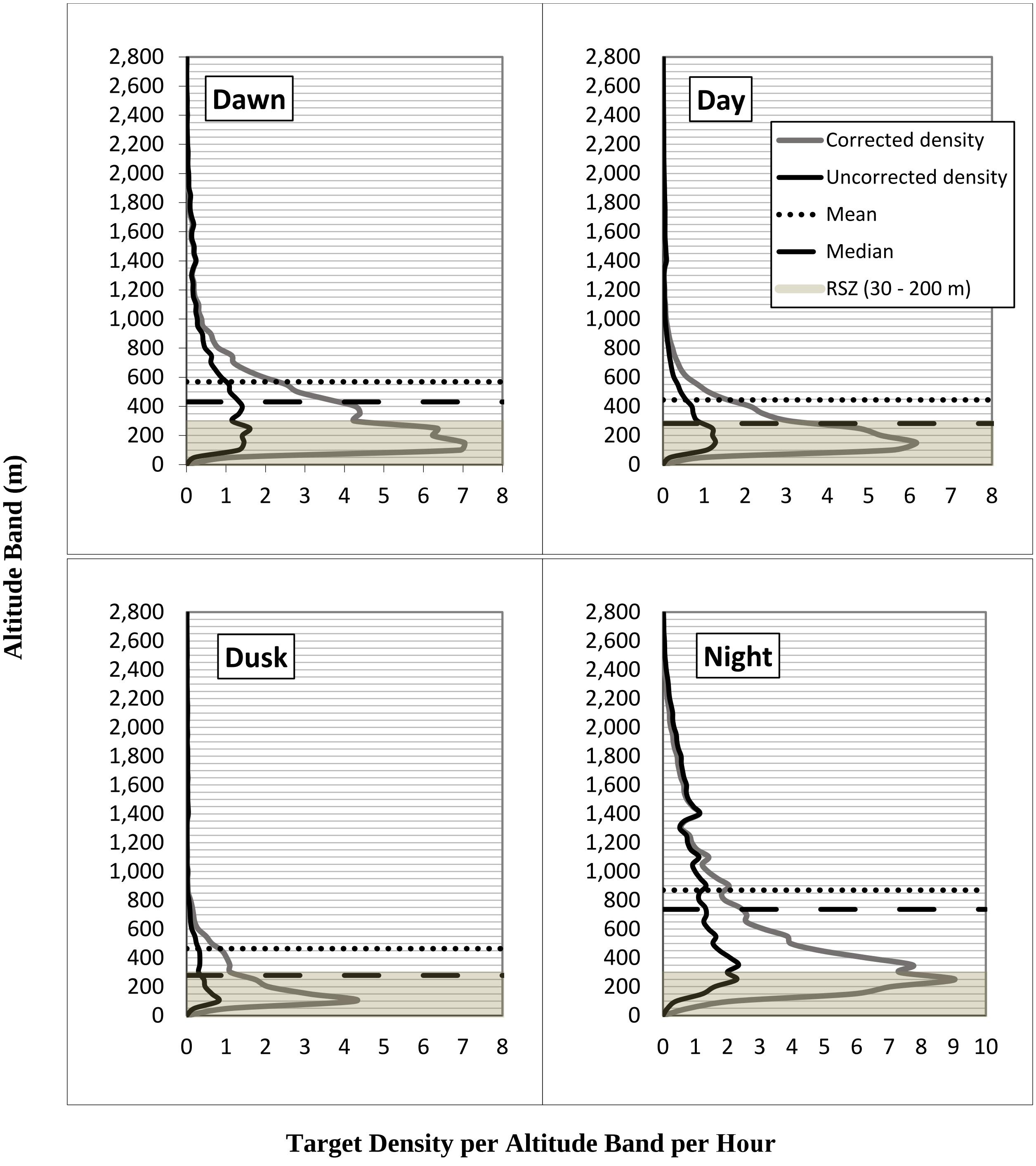


Figure 13. Altitude profile by biological time period for Montrose Point, Cook Co., IL, spring 2017. These graphs show the uncorrected (black) and corrected (gray) density estimates of targets moving on the VSR at different altitudes during four biological time periods. The mean and median heights (dotted and dashed lines respectively) are shown for each time period. The rotor-swept zone (RSZ) is represented by shading at 30-200 m. The x-axis represents target density (targets/1,000,000 m^3) per 50-m altitude band. Note the increased number of nighttime migrants and the increase in the x-axis scale.

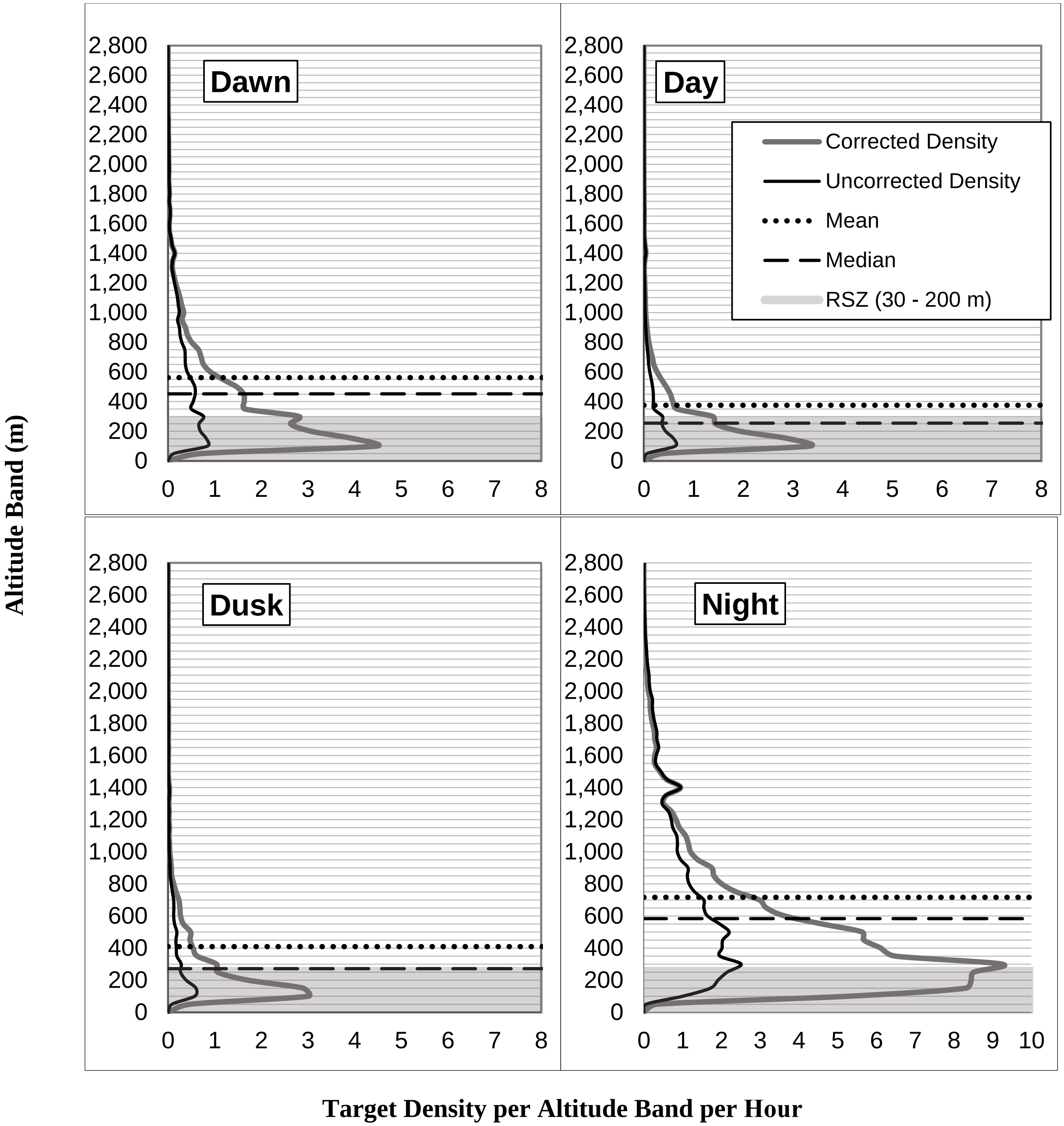


Figure 14. Altitude profile by biological time period for Indiana Dunes, Porter Co., IN, spring 2017. These graphs show the uncorrected (black) and corrected (gray) density estimates of targets moving on the VSR at different altitudes during the four biological time periods. The mean and median heights (dotted and dashed lines respectively) are shown for each time period. The rotor-swept zone (RSZ) is represented by shading at 30-200 m. The x-axis represents target density (targets/1,000,000 m^3) per 50-m altitude band. Note the increased number of nighttime migrants and the increase in the x-axis scale.

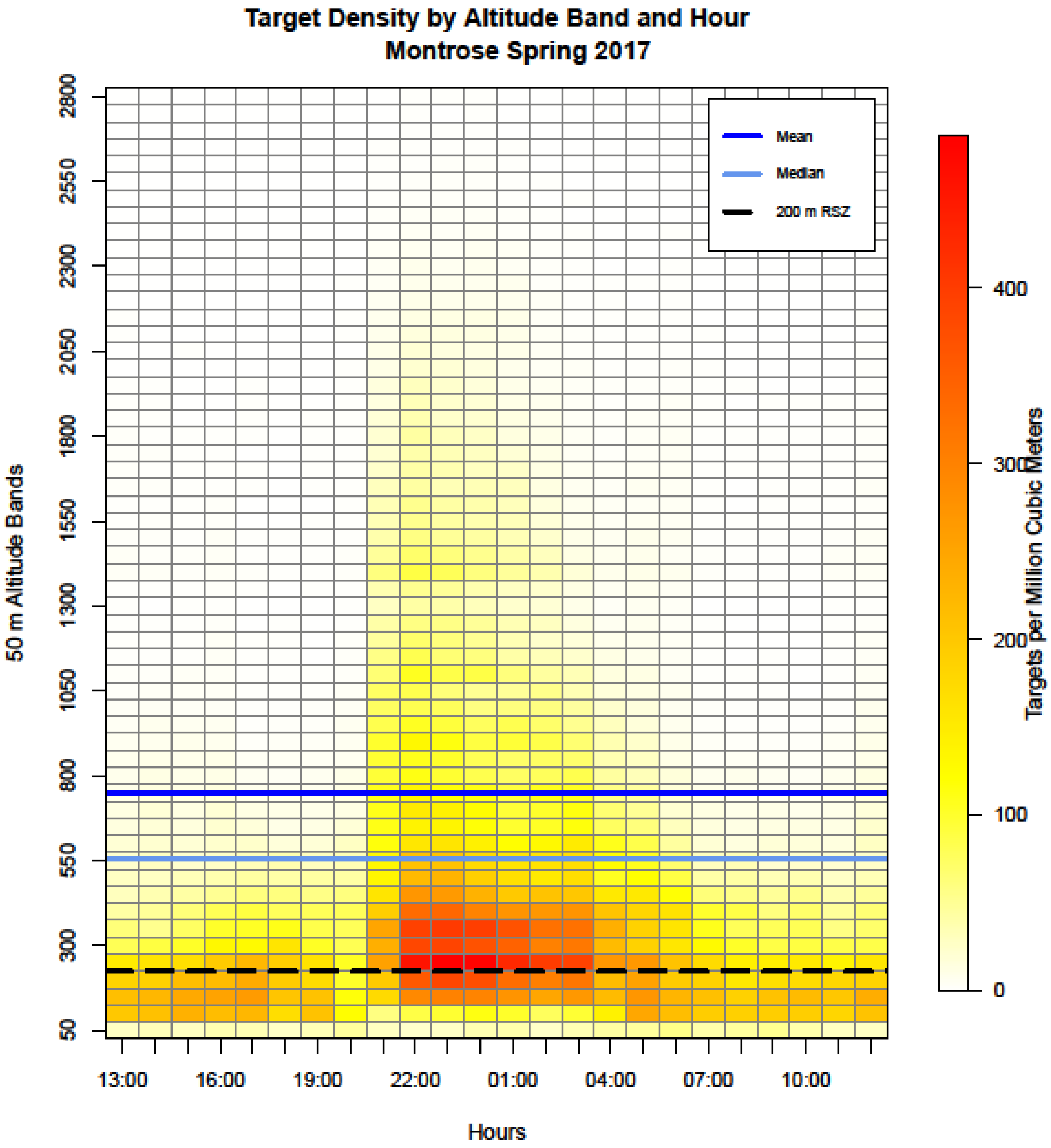


Figure 15. Altitude map for Montrose Point, Cook Co., IL, spring 2017. The y-axis depicts the altitude in 50-meter bands, the x-axis shows hours with midnight (0:00) as the center of the axis. Cell colors show migrant density at different altitude bands, with red and orange indicating higher densities. Uncorrected mean and median altitudes are shown in dark and light blue lines respectively. A 200 m rotor-swept zone is depicted by the dotted black line.

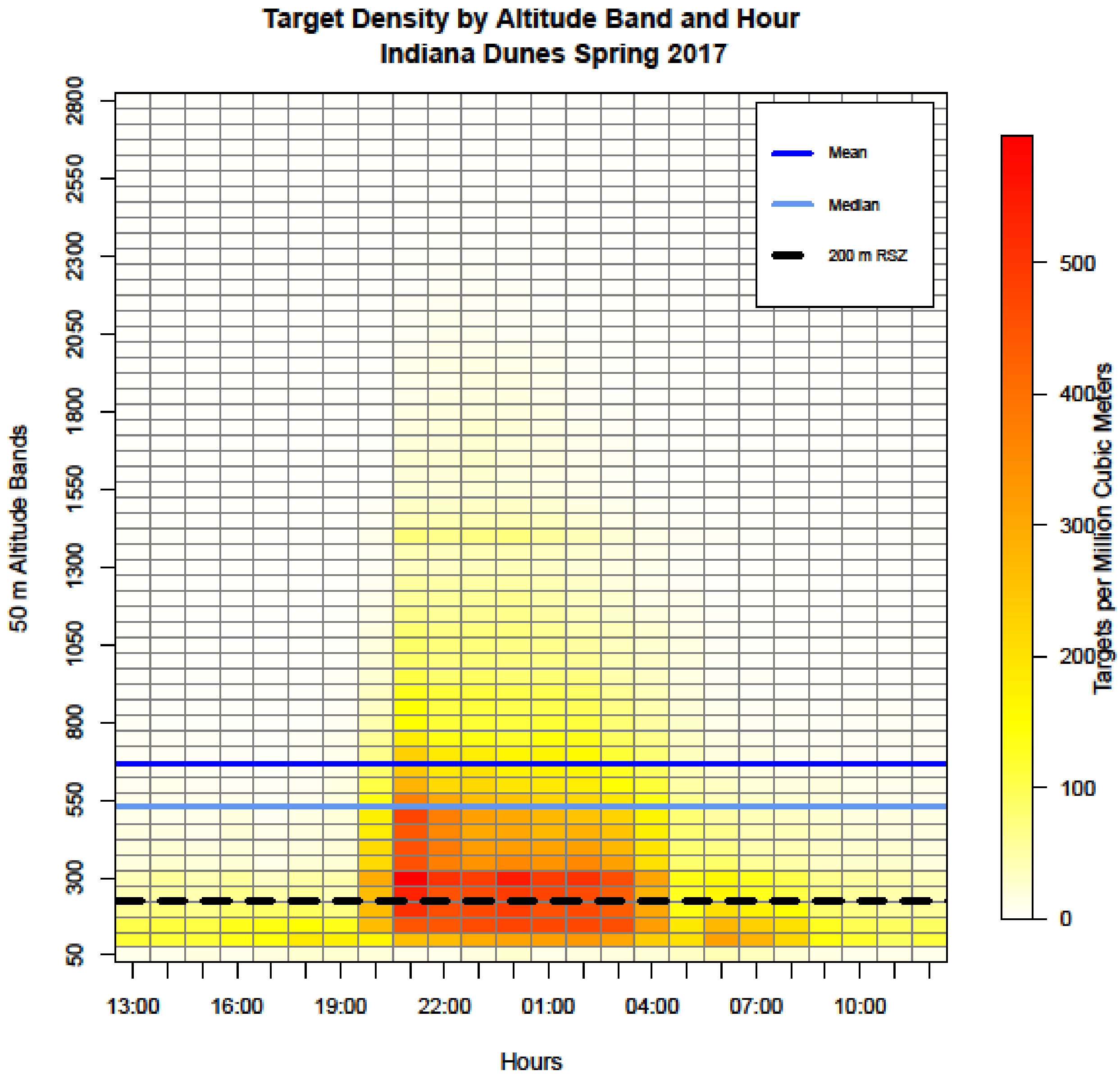


Figure 16. Altitude map for Indiana Dunes, Porter Co., IN, spring 2017. The y-axis depicts the altitude in 50-meter bands, the x-axis shows hours with midnight (0:00) as the center of the axis. Cell colors show migrant density at different altitude bands, with red and orange indicating higher densities. Uncorrected mean and median altitudes are shown in dark and light blue lines respectively. A 200 m rotor-swept zone is depicted by the dotted black line.

LITERATURE CITED

Able, K. P. 1977. The flight behaviour of individual passerine nocturnal migrants: a tracking radar study. Animal Behaviour 25:924–935.

Åkesson, S. 1999. Do passerine migrants captured at an inland site perform temporary reverse migration in autumn? Ardea 87:129-138.

Alerstam, T. 1990. Bird Migration. Cambridge University Press, Cambridge.

Alerstam, T. 2001. Detours in bird migration. Journal of Theoretical Biology 209:319-331.

Arnett, E. B. and E. F. Baerwald. 2013. Impacts of wind energy development on bats: Implications for conservation. Pages 435-456 in R. A. Adams and S. C. Pederson. Editors. Bat Ecology, Evolution and Conservation. Springer Science Press, New York, USA.

Audubon. 2013. Important Bird Areas Program. http://web4.audubon.org/bird/iba/. (last accessed May 2015).

Bingman, V. P. 1980. Inland morning flight behavior of nocturnal passerine migrants in eastern New York. Auk 97: 465-472.

Bonter, D., T. Donovan, and E. Brooks. 2007. Daily mass changes in landbirds during migration stopover on the south shore of Lake Ontario. Auk 124:122–133.

Bonter, D., S. A. Gauthreaux, Jr., and T. M. Donovan. 2009. Characteristics of important stopover locations for migrating birds: remote sensing with radar in the Great Lakes Basin. Conservation Biology 23:440-448.

Bruderer, B. 1997. The study of bird migration by radar, Part 1: The technical basis. Naturwissenschaften 84: 1-8.

Bruderer, B. and F. Liechti. 1998. Flight behaviour of nocturnally migrating birds in coastal areas - crossing or coasting. Journal of Avian Biology 29:499-507.

Buler, J. J. and F. Moore. 2011. Migrant-habitat relationships during stopover along an ecological barrier: extrinsic constraints and conservation implications. Journal of Ornithology 152:101-112.

Buler, J. J. and D. K. Dawson. 2012. Radar analysis of fall bird migration stopover sites in the Northeast U.S. Final Report. Cooperative Agreement USGS and University of Delaware.

DeTect, Inc. 2009. MERLIN avian radar survey for a proposed wind project. Unpublished technical report. Panama City, FL.

Diehl, R. H., R. P. Larkin, and J. E. Black. 2003. Radar observations of bird migration over the Great Lakes. Auk 120:278-290.

Diehl, R. H., J. M. Bates, D. E. Willard, and T. P. Gnoske. 2014. Bird mortality during nocturnal migration over Lake Michigan: a case study. The Wilson Journal of Ornithology 126: 19-29.

Dwyer, C. P., J. L. Belant, and R. A. Dolbeer. 1996. Distribution and abundance of roof-nesting gulls in the Great Lakes Region of the United States. USDA National Wildlife Research Center – Staff Publications. 130.

Ewert, D. N., P. J. Doran, K. R. Hall, A. Froehlich, J. Cannon, J. B. Cole, and K. E. France. 2012. On a wing and a (GIS) layer: Prioritizing migratory bird stopover habitat along Great Lakes Shorelines. Final report to the Upper Midwest/Great Lakes Landscape Conservation Cooperative.

Ewert, D. N., M. J. Hamas, R. J. Smith, M. E. Dallman, and S. W. Jorgensen. 2011. Distribution of migratory landbirds along the northern Lake Huron shoreline. Wilson Journal of

Ornithology 123:536-547.

Faaborg, J., R. T. Holmes, A. D. Anders, K. L. Bildstein, K. M. Dugger, S. A. Gauthreaux, Jr., P. Heglund, K. A. Hobson, A. E. Jahn, D. H. Johnson, S. C. Latta, D. J. Levey, P. P. Marra, C. L. Merkord, E. Nol, S. I. Rothstein, T. W. Sherry, T. S. Sillett, F. R. Thompson, III, and N. Warnock. 2010. Conserving migratory land birds in the New World: Do we know enough? Ecological Applications 20:398-418.

France, K. E., M. Burger, T. G. Howard, M. D. Schlesinger, K. A. Perkins, M. MacNeil, D. Klein, and D. N. Ewert. 2012. Final report for Lake Ontario Migratory Bird Stopover Project. Prepared by The Nature Conservancy for the New York State Department of Environmental Conservation, in fulfillment of a grant from the New York Great Lakes Protection Fund (C303907).

Frick, W. F., E. F. Baerwald, J. F. Pollock, R. M. R. Barclay, J. A. Szymanski, T. J. Weller, A. L. Russell, S. C. Loeb, R. A. Medellin, L. P. McGuire. Fatalities at wind turbines may threaten population viability of a migratory bat. Biological Conservation 209:172-177.

National Land Cover Database for the Conterminous United States.

Gauthreaux, S. A. 1991. The flight behavior of migrating birds in changing wind fields – radar and visual analyses. American Zoologist 31:187-204.

Gelb, Y., and N. Delacretaz. 2009. Windows and vegetation: Primary factors in Manhattan bird collisions. Northeastern Naturalist 16:455-470.

Harmata, A. R., K. M. Podruzny, J. R. Zelenak, and M. L. Morrison. 2000. Passage rates and timing of bird migration in Montana. American Midland Naturalist 143:30-40.

Homer, C. H., J. A. Fry, and C. A. Barnes. 2012. The National Land Cover Database, U. S. Geological Survey Fact Sheet 2012-3020.

Hueppop, O., J. Dierschke, K. M. Exo, E. Fredrich, and R. Hill. 2006. Bird migration studies and potential collision risk with offshore wind turbines. Ibis 148:90-109.

Larkin, R. P. 2005. Radar techniques for wildlife biology. Pages 448-464 In: C. E. Braun, editor Techniques for wildlife investigations and management, 6th Edition. The Wildlife Society, Bethesda, Maryland, USA.

Laurich, B., C. Drake, O. T. Gorman, C. Ivine, J. MacLaurin, C. Chartrand, and C. E. Herbert. 2019. Ecosystem change and population declines in gulls: Shifting baseline considerations for assessing ecological integrity of protected areas. Journal of Great Lakes Research 45:1215-1227.

Liechti, F. 2006. Birds: blowin' by the wind? Journal of Ornithology 147:202-211.

Longcore, T., C. Rich, P. Mineau, B. MacDonald, D. G. Bert, L. M. Sullivan, E. Mutrie, S. A. Gauthreaux Jr., M. L. Avery, R. L. Crawford, A. M. Manville II, E. R. Travis, and D. Drake. 2013. Avian mortality at communication towers in the United States and Canada: which species, how many, and where? Biological Conservation 158:410–419.

Kahle, L. Q., M. E. Flannery, and J. P. Dumbacher. 2016. Bird-window collisions at a west-coast urban park museum: Analysis of bird biology and window attributes from Golden Gate Park, San Francisco. PLoS ONE 11: e0144600. https://doi.org/10.1371/journal.pone.0144600

Mabee, T. J. and B. A. Cooper. 2004. Nocturnal bird migration in northeastern Oregon and southeastern Washington. Northwestern Naturalist 85:39-47.

McGuire, L. P., K. A. Jonasson, and C. G. Guglielmo. 2012a. Torpor-assisted migration in bats. In: The Society for Integrated & Comparative Biology; January 4, 2012; Charleston, SC. Session 20.

McGuire, L. P., C. G. Guglielmo, S. A. Mackenzie, and P. D. Taylor. 2012b. Migratory stopover in the long-distance migrant silver-haired bat, *Lasionycteris noctivagans*. Journal of Animal Ecology 81: 377–385.

Mehlman, D. W., S. E. Mabey, D. N. Ewert, C. Duncan, B. Abel, D. Cimprich, R. D. Sutter, and M. Woodrey. 2005. Conserving stopover sites for forest-dwelling migratory landbirds. Auk 122:1281-1290.

Moore, F. R., P. Kerlinger, T. R. Simons. 1990. Stopover on a Gulf Coast Barrier Island by spring trans-Gulf migrants. Wilson Bulletin. 102: 487-501.

Myres, M. T. 1964. Dawn ascent and reorientation of Scandinavian thrushes (Turdus spp.) migrating at night over the northeastern Atlantic Ocean in autumn. Ibis 106:7–51.

Newton, I. 2006. Can conditions experienced during migration limit the population levels of birds? Journal of Ornithology 147:146-166.

Newton, I. 2007. Weather-related mass-mortality events in migrants. Ibis 149:453-467.

Newton, I. 2008. Migration ecology of birds. Academic Press, Elsevier. UK. 975 pp.

Newton, I. 2009. Moult and plumage. Ringing and Migration 24:220-226.

Peterson, A. and G. J. Niemi. 2011. Development of a comprehensive conservation strategy for the North Shore Highlands Region of Minnesota in the context of future wind development. Final Report. Natural Resources Research Institute technical report: NRRI/TR-2012/13.

Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery. 2007. Numerical Recipes: The Art of Scientific Computing (3rd ed.). New York: Cambridge University Press.

Rich, T. D., C. J. Beardmore, H. Berlanga, P. J. Blancher, M. S. W. Bradstreet, G. S. Butcher, D. W. Demarest, E. H. Dunn, W. C. Hunter, E. E. Iñigo-Elias, J. A. Kennedy, A. M. Martell, A. O. Panjabi, D. N. Pashley, K. V. Rosenberg, C. M. Rustay, J. S. Wendt, T. C. Will. 2004. Partners in Flight North American Landbird Conservation Plan. Cornell Lab of Ornithology. Ithaca, NY.

Ruth, J. M. 2007. Applying radar technology to migratory bird conservation and management: Strengthening and expanding a collaborative. Open-File Report 1361, U.S. Geological Survey, Fort Collins, CO.

Schmaljohann, H., P. J. J. Becker, H. Karaardic, F. Liechti, B. Naef-Daenzer, and C. Grande. 2011. Nocturnal exploratory flights, departure time, and direction in a migratory songbird. Journal of Ornithology 152:439-452.

Schmaljohann, H., F. Liechti, E. Baechler, T. Steuri, and B. Bruderer. 2008. Quantification of bird migration by radar - a detection probability problem. Ibis 150:342-355.

Schmaljohann, H. and B. Naef-Daenzer. 2011. Body condition and wind support initiate the shift of migratory direction and timing of nocturnal departure in a songbird. Journal of Animal Ecology 80:1115-1122.

Sillett, T. S. and R. T. Holmes. 2002. Variation in survivorship of a migratory songbird throughout its annual cycle. Journal of Animal Ecology 71:296-308.

Smith, R. J., M. J. Hamas, D. N. Ewert, and M. E. Dallman. 2004. Spatial foraging differences in American redstarts along the shoreline of northern Lake Huron during spring migration. Wilson Bulletin 116:48-55.

Smith, R. J., F. R. Moore, and C. A. May. 2007. Stopover habitat along the shoreline of northern Lake Huron, Michigan: Emergent aquatic insects as a food resource for spring migrating landbirds. Auk 124:107-121.

Taylor, P. D., S. A. Mackenzie, B. G. Thurber, A. M. Calvert, A. M. Mills, L. P. McGuire, and

C. G. Guglielmo. 2011. Landscape Movements of Migratory Birds and Bats Reveal an Expanded Scale of Stopover. Plos One 6.

USFWS. 2012. U.S. Fish and Wildlife land-based wind energy guidelines. OMB Control No. 1018-0148.

Wells, M. T., T. S. Bowden, K. W. Heist, R. L. Horton, D. C. Nolfi, E. C. Olson, N. A. Rathbun, and J. C. Gosse. 2018. Great Lakes Avian Radar Technical Report Lake Huron Lakeshore: Alcona and Presque Isle, MI, Fall 2015 and Spring 2016. U.S. Department of Interior, Fish and Wildlife Service, Biological Technical Publication FWS/BTB-XXXXX-2018.

Wiedner, D. S., P. Kerlinger, D. A. Sibley, P. Holt, J. Hough, and R. Crossley. 1992. Visible morning flights of neotropical landbird migrants at Cape May, New Jersey. Auk 109 (3): 500-510.

Zar, J.H. 1999. Biostatistical Analysis, 4th ed. Prentice Hall, Upper Saddle River, NJ. 662 pp.