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BEFORE THE OHIO POWER SITING BOARD

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In the Matter of the Application of Icebreaker Windpower Inc. for a Certificate to Construct a Wind-Powered Electric Generation Facility in Cuyahoga County, Ohio. : Case No. 16-1871-EL-BGN

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PROCEEDINGS

before Mr. Nick Walstra and Ms. Megan Addison, Administrative Law Judges, at the Public Utilities Commission of Ohio, 180 East Broad Street, Room 11-A, Columbus, Ohio, called at 9:00 a.m. on Wednesday, September 26, 2018.

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Review

Estimates of bird collision mortality at wind facilities in the contiguous United States

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ABSTRACT

Wind energy has emerged as a promising alternative to fossil fuels, yet the impacts of wind facilities on wildlife remain unclear. Prior studies estimate between 10,000 and 573,000 fatal bird collisions with U.S. wind turbines annually; however, these studies do not differentiate between turbines with a monopole tower and those with a lattice tower, the former of which now comprise the vast majority of all U.S. wind turbines and the latter of which are largely being de-commissioned. We systematically derived an estimate of bird mortality for U.S. monopole turbines by applying inclusion criteria to compiled studies, identifying correlates of mortality, and utilizing a predictive model to estimate mortality along with uncertainty. Despite measures taken to increase analytical rigor, the studies we used may provide a non-random representation of all data; requiring industry reports to be made publicly available would improve understanding of wind energy impacts. Nonetheless, we estimate that between 140,000 and 328,000 (mean = 234,000) birds are killed annually by collisions with monopole turbines in the contiguous U.S. We found support for an increase in mortality with increasing turbine hub height and support for differing mortality rates among regions, with per turbine mortality lowest in the Great Plains. Evaluation of risks to birds is warranted prior to continuing a widespread shift to taller wind turbines. Regional patterns of collision risk, while not obviating the need for species-specific and local-scale assessments, may inform broad-scale decisions about wind facility siting.

Contents

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1. Introduction

Wind energy has emerged globally as a promising alternative to fossil fuels. As of June 2013, more than 270 gigawatts (GW) of power generation capacity were installed across the world's >13,000 wind facilities (The Wind Power, 2013). Roughly 20% of this capacity is installed in the United States (American Wind Energy Association, 2013), providing enough energy to power 18 million households. A continued increase of U.S. wind energy development is expected in response to the Department of Energy's (DOE) goal to have 20% of total energy generated from wind power by 2030 (U.S. DOE, 2008). Conservationists have expressed concern about direct and indirect impacts of wind energy development on wildlife, including bird and bat collisions with wind turbines (Kunz et al., 2007a, 2007b; Kuvlesky et al., 2007), habitat loss, and creation of barriers to wildlife movement (Drewitt and Langston, 2006; Kuvlesky et al., 2007; Pruett et al., 2009; Kiesecker et al., 2011). Despite the decommissioning of many lattice-tower turbines that have caused large numbers of bird collisions, such as those at Altamont Pass in California (California Energy Commission, 1989; Smallwood and Karas, 2009), bird collisions still occur at turbines with solid monopole towers (e.g. Johnson et al., 2002; Kerns and Kerlinger, 2004), which now comprise the vast majority of U.S. turbines.

Wildlife mortality from collisions with wind turbines is the most direct, visible, and well-documented impact of wind energy development. However, conclusions about collision rates and impacts of collisions on bird populations are tentative because most of the mortality data is in industry reports that are not subjected to scientific peer review or available to the public (Piorkowski et al., 2012). The accessible data—which could provide a non-representative sample of all studies—suggests that bird collision rates at turbines are lower than at other structures, such as communication towers, buildings, and power lines (Drewitt and Langston, 2006), and that mass collision events are rare at wind facilities (but see Johnson et al., 2002; Kerns and Kerlinger, 2004; American Bird Conservancy, 2011). Pre-construction assessment of collision risk at proposed wind facilities has been unreliable, with no clear link documented between predicted risk levels and post-construction mortality rates, likely due to substantial variation in collision rates among turbines and a failure to consider risks at individual proposed turbine sites (de Lucas et al., 2012a, 2012b; Ferrer et al., 2012). In addition, most risk assessments focus on the total numbers of birds predicted to be present at a site. A failure to consider species-specific risks may result in relatively high post-construction rates of mortality for some species even if total bird mortality is relatively low (Ferrer et al., 2012).

Mean estimates of annual U.S. mortality from wind turbine collisions range between 20,000 and 573,000 birds (Erickson et al., 2001, 2005; Manville, 2009; Sovacool, 2012; Smallwood, 2013). Earlier estimates were generated by summarizing a small sub-set of industry reports and extrapolating mortality rates across all turbines (Erickson et al., 2001, 2005), by using small samples of preliminary data (Sovacool, 2012), or by using undocumented methods (Manville, 2009). A recent study estimates annual U.S. collision mortality at 573,000 birds and greatly improves upon earlier efforts by using data from a large sample of wind facilities and by accounting for several methodological differences among the studies used (Smallwood, 2013). However, this study did not distinguish between lattice and monopole turbines. Because monopole turbines comprise the vast majority of all installed U.S. wind turbines, it is important to separately estimate mortality and assess correlates of mortality for this turbine type.

We reviewed the wind energy literature, including both peer-reviewed articles and unpublished industry reports, and extracted data to systematically estimate bird collision mortality and mortality correlates at monopole turbines in the contiguous U.S. Specifically, we (1) defined inclusion criteria to ensure a baseline level of rigor for studies used in the estimate, (2) fitted a predictive model that includes correlates of mortality, accounts for differences among studies in the proportion of the year during which collision events were sampled, and includes estimate uncertainty, and (3) implemented the fitted model to estimate bird collision mortality for wind facilities in the contiguous U.S.

2. Material and methods

2.1. Literature search

We searched Google Scholar, the Web of Science database (using the Web of Knowledge search engine), and the National Renewable Energy Laboratory's Wind-Wildlife Impacts Literature Database (http://wild.nrel.gov/) to identify studies documenting bird collisions with wind turbines. We also searched Google because most industry reports are not indexed in databases. We used the search terms "bird AND wind turbine" with "collision," "mortality," "fatality," "carcass," and "post-construction"; all terms with "bird" replaced by "avian" and "wildlife"; and "turbine" replaced by "farm, "facility " and "energy." We checked reference lists and three online bibliographies (National Wind Coordinating Committee, 2005; Johnson and Arnett, 2011; Ellison, 2012) to identify additional studies. In addition to articles we were able to access, we found citations for 47 reports/articles in reference lists that appeared to contain collision mortality data but could not be located using the above search strategy. We requested many of these reports from either the authors that conducted studies or the companies that commissioned studies. However, for some reports we could not find contact information that could be used to request reports, and for some reports that we requested, we received no response to our inquiry. We were therefore only able to acquire 18 (38%) of these additional studies.

Cursory review indicated that studies of collision mortality at wind facilities vary substantially with regard to study design and sampling protocol. These differences must be considered when combining results from multiple studies to estimate mortality (Loss et al., 2012). As described in the following sections, we controlled for much of this variation by implementing inclusion criteria that created a baseline of rigor that studies had to meet to be included in analysis and by accounting for the proportion of the year during which carcass surveys were conducted, the number of turbines in wind facilities, and the size of carcass search plots.

2.2. Inclusion criteria

We only included studies for in-depth review if they were conducted in the U.S. or Canada, provided data on bird collisions with wind turbines, did not repeat findings of earlier studies, and were available as a formal report (i.e. we excluded one legal testimony and one conference presentation). We included Canadian studies to increase the sample of data for the analysis of mortality correlates (Section 2.5), and we thus assume that correlates do not differ between the U.S. and Canada. We only applied our mortality estimation model across wind turbines in the contiguous U.S. (Section 2.6) After in-depth review of remaining studies, we excluded those that focused only on a particular bird group (e.g. raptors), that sampled at fewer than three turbines, and that grouped turbine collisions with collisions from other objects, such as power lines and vehicles. Because raw counts underestimate true mortality (Korner-Nievergelt et al., 2011), we only included studies that corrected counts for searcher detection and scavenger removal rates as estimated in trials at the same facility. All studies that accounted for these factors also adjusted mortality estimates for the proportion of the wind facility's turbines that were not surveyed (or they surveyed all of the facility's turbines), thus resulting in an adjusted mortality estimate for the entire wind facility. Three studies that documented zero fatalities met our inclusion criteria. Because no methods currently exist to adjust zero counts for scavenger removal and imperfect detection, we assumed that zero was the actual number of birds killed at these sites. Finally, studies were included only for turbines with solid monopole towers (i.e., we excluded studies of lattice turbines or of multiple turbine types that did not differentiate among types). We excluded lattice turbines because they have largely been decommissioned in the U.S. and because our objective was to provide a mortality estimate relevant to current and future turbine technology. Our estimate therefore does not incorporate high mortality rates historically recorded at some lattice turbines (e.g., those at Altamont Pass), but we do include data from monopole turbines at some of these same sites. After implementing these inclusion criteria, 68 studies remained from which we extracted data (Appendix A), while 27 studies were excluded from further analysis (Appendix B).

2.3. Data extraction

For each wind facility, we extracted the total estimated amount of mortality across all turbines (after correction for scavenger removal and searcher efficiency). When studies only reported estimated per turbine mortality rates, we multiplied these by the number of turbines in the facility. If the study did not provide the number of turbines, we extracted this information from an online database (Open Energy Info, 2013). Several facilities had more than one study conducted over non-consecutive periods or had a single study that provided data for different periods without providing a collision estimate over the study's entire duration. In these cases, we extracted separate mortality estimates, which resulted in a total of 76 mortality estimates (Appendix A) being extracted from the 68 studies meeting inclusion criteria. However, because of non-independence of separate mortality estimates from the same facility, we only used a single mortality estimate for each wind facility. This resulted in 58 mortality estimates being carried forward for further analysis (see Appendix C for methods describing selection of a single mortality estimate for facilities with more than one estimate).

In addition to extracting total mortality estimates, we extracted data for individual bird species. However, because studies did not provide estimates of species mortality that were corrected for species-specific values of scavenger removal and searcher detection rates (instead, either a single set of adjustments was applied across all birds, or separate adjustments were made, but only for coarse size groupings), we did not generate species-specific mortality estimates. Such estimates would be strongly biased toward larger more detectible species. Nonetheless, we did summarize raw counts to illustrate the species composition of fatalities that have been found at wind facilities in the contiguous U.S. We extracted species data from some studies that were excluded from the total mortality estimate for not adjusting for searcher detection and scavenger removal rates, but we still excluded species records from studies that included lattice turbines, that were from fewer than three turbines, and that did not quantify mortality for all bird groups or distinguish among multiple mortality sources. We also excluded fatalities found incidentally (i.e., not during standardized surveys). The additional included studies are shown in Fig. 1 and Appendix B.

Finally, we also extracted information about wind facilities, including the height of turbine hubs (i.e., the top of the tower where the rotor is mounted; hereafter "hub height"), height to the upper blade tip (hereafter "top height"), and blade-swept area (Appendix A). If hub height was not provided, we calculated this value using one of three approaches: (1) if the turbine model was provided, we looked up hub height online or in a turbine specifications database (The Wind Power, 2013), (2) if the turbine model was not provided but top height and rotor radius were, we calculated hub height as top height minus rotor radius, and (3) if neither the turbine model nor rotor radius were provided but top height was, we used the hub height from turbines with the same top height.

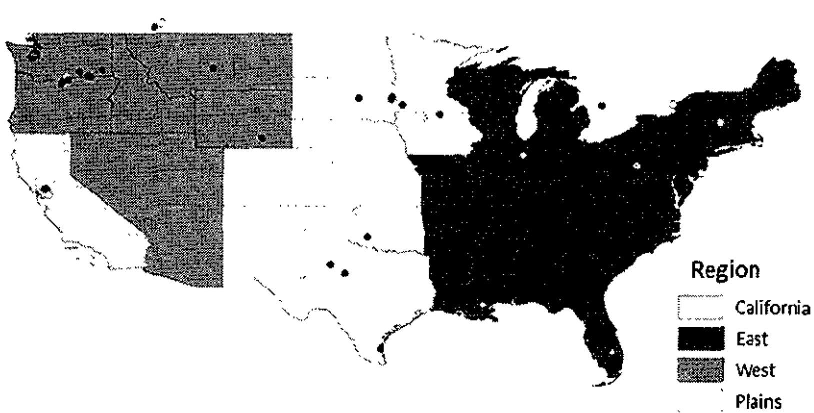

Fig. 1. Regions defined for calculation of annual bird mortality from collisions with monopole turbines in the contiguous U.S. and locations of wind facilities with mortality data used in analysis (solid circles—wind facilities with data used to generate estimates of total mortality *and* with data extracted for species count summary; open circles—wind facilities with data used only for species count summary; open circles with black dot—wind facilities with data used only for total mortality estimates). The two wind facilities on the Texas Gulf Coast were classified as being in the East because of the biological dissimilarity of this region from the rest of the Great Plains.

Table 1
Model selection results for analysis of characteristics related to bird collision mortality at monopole turbines as derived from Akaike's information criteria, corrected for small samples (AIC_c). All candidate models included total mortality estimates for the entire wind facility as the dependent variable (estimates adjusted for scavenger removal, searcher efficiency, and search radius), assumed a Poisson error structure, and included offsets for the number of days out of the year covered by sampling and the number of wind turbines in the facility.

Model	K^a	ΔAIC_c^b	w_i^c
Nacelle height + region	5	0.00	0.521
Nacelle height * region	8	0.73	0.361
Region	4	3.86	0.076
Nacelle height	2	5.06	0.042
Null model	1	16.17	0.000

[a] Number of parameters in the model (including intercept parameter).
[b] Difference in AIC_c value between model and the most strongly supported model.
[c] AIC weight – relative strength of support for model.

2.4. Adjusting mortality estimates for varying search radius

Both turbine height and the radius of carcass search plots influence the proportion of carcasses found out of the total number killed (Smallwood, 2013). Although turbine hub height and search radius co-vary, there is little standardization among studies for the manner in which search radius is selected, and this contributes bias when comparing studies. To account for this among-study variation, Smallwood (2013) calculated the proportion of predicted fatalities found in the maximum search radius for several combinations of hub height and search radius. The proportions were based on a logistic function that predicts a distance asymptote for the cumulative number of fatalities found. We used the hub height and search radius for each mortality estimate in our data set and the proportions in table 3 of Smallwood (2013) to adjust mortality estimates and to account for varying search radius.

For nine of the mortality estimates, hub height information was unavailable; in these cases, we applied the average proportion for the matching search radius across different hub heights in table 3. For estimates with either hub height or radius not exactly matching values in table 3, we used the proportion for the height-radius combination nearest to the non-matching value, or if the non-matching value was equidistant between two values in table 3, we averaged the two proportions. For estimates in our data set with neither the height nor radius matching the values given in table 3, we used the proportion that was the best match that could be derived from the table by first selecting the set of proportions with the nearest search radius and then, among proportions for that radius, selecting the one with the nearest height (e.g. if the mortality estimate came from a study with search radius = 60 m and hub height = 68.5 m, we first referenced all proportions corresponding to a radius of 63 m, the closest value to 60 m, and then, among proportions for that radius, we selected the one for a hub height of 50 m, the closest value to 68.5 m). We took this approach of first referencing radius and then referencing height because Smallwood (2013) found that search radius explains greater variation than height in the predicted distance asymptote.

2.5. Analysis of mortality correlates

We conducted an analysis to identify correlates of collision mortality using previously suggested important variables (Barclay et al., 2007; Kuvlesky et al., 2007; Pearce-Higgins et al., 2012). Because not all variables were available for all mortality estimates, and because we sought to only include variables with sufficient replication to allow rigorous modeling, we only included variables for analysis if they were available for a minimum of 50 mortality estimates. Variables meeting this criterion included: hub height, top height, rotor diameter, and geographical region. We defined four geographical regions, including California, the West (excluding California), the Great Plains, and the East (Fig. 1). Hub height, top height, and rotor diameter were all strongly correlated with each other ($r \geqslant 0.81$). Because hub height was the most commonly reported variable in the studies we reviewed, we removed top height and rotor diameter from further analysis, thus avoiding multicollinearity in the following model selection exercise. Thus, the remaining variables included hub height and region. From the 58 mortality estimate replicates, we removed five records that lacked information about one of these predictor variables because the following model selection approach required that the same number of replicates and the same set of response variable data be used for each candidate model. Thus, we used 53 mortality estimates for the following model selection exercise (Appendix A). For a full description and rationale for every decision made prior to reaching this final data set used for analysis, see Appendix C.

All analyses were conducted in Program R. We used an information theoretic approach for model selection. In a preliminary analysis that assumed a normal distribution of errors (R function lm), visual assessment of the response variable residuals indicated unequal variance of residuals. We therefore used a generalized linear modeling approach (R function glm) for all candidate models, and we assumed a Poisson error distribution because the response variable was based on count data.

A common assumption for studies that do not sample throughout the year is that mortality is negligible during the un-sampled time period—typically the months outside of migration seasons. However, collision mortality can be substantial during summer (Osborn et al., 2000; Gritski et al., 2010; Stantec, 2011) and winter (Kerlinger et al., 2007; Young et al., 2007). Furthermore, in a preliminary analysis of all mortality estimates that met our inclusion criteria, estimated mortality increased significantly with an increasing proportion of the year sampled ($\beta = 0.081$, ±95% $CI = 0.013–0.149$, $df = 76$, $p = 0.020$). Annual mortality estimates derived from a partial year of sampling may therefore substantially underestimate mortality. To account for sampling of varying proportions of the year and to generate a mortality estimate that includes the potential for mortality in un-sampled periods, we specified an offset term in all candidate models that was the log

Table 2
Estimates of bird mortality from collisions with monopole wind turbines in the contiguous United States.

Region	Total # of turbines	Total MW capacity	Total mortality			Mortality per turbine			Mortality per MW		
			Mean	LCI[a]	UCI[b]	Mean	LCI[a]	UCI[b]	Mean	LCI[a]	UCI[b]
California	13,851	5796	108,715	56,095	161,335	7.85	4.05	11.65	18.76	9.68	27.84
East	6418	11,390	44,006	34,749	53,262	6.86	5.41	8.30	3.86	3.05	4.68
West	5757	9590	27,177	19,671	34,682	4.72	3.42	6.02	2.83	2.05	3.62
Great Plains	18,551	29,896	54,115	29,923	78,307	2.92	1.61	4.22	1.81	1.00	2.62
Total U.S.	44,577	56,852	234,012	140,438	327,586	5.25	3.15	7.35	4.12	2.47	5.76

[a] Lower bounds of estimate 95% confidence interval.
[b] Upper bounds of estimate 95% confidence interval.

Table 3
Comparison of characteristics of wind facilities in the data set used to generate estimates of contiguous U.S bird mortality from collisions with monopole wind turbines and in larger database of U.S. onshore wind facilities (The Wind Power, 2013).

Region	Data analyzed (53 facilities)				All U.S. facilities in database		
	# Of facilities	Ave. # of turbines in facility	# Of turbines surveyed	Ave. hub height	# Of facilities	Ave. # of turbines in facility	Ave. hub height (m)
California	4	74.00	246	64.6	154	89.94	81.0
East	22	57.77	569	77.1	228	28.15	76.5
West	17	85.41	721	67.1	149	38.64	78.2
Great Plains	10	81.80	271	63.7	469	39.55	75.6
Total U.S.	53	72.40	1807	70.4	1000	44.577	76.7

of the count duration (number of days of the year sampled with maximum = 365 for year-round studies). In addition, because the number of turbines in the wind facility influences the total number of carcasses found, and therefore the total estimated amount of mortality at the wind facility, we also specified an offset term that was the log of the number of turbines in the wind facility.

Within this generalized linear model structure (assumption of a Poisson error distribution, specification of offsets for sampling duration and number of turbines in the facility, and response variable = fatality count adjusted for scavenger removal, searcher efficiency, and search radius), we defined a candidate set of models, including a null model, single-variable region and hub height models, a 2-variable additive model including both region and height and a 2-variable region-height multiplicative model (i.e. the global model). We used Akaike's Information Criteria corrected for small sample sizes and the residual deviance from each candidate model to compare relative support for each model. We considered models to be strongly supported if they had ΔAIC values <2.0 (Burnham and Anderson, 2002).

2.6. Model used for estimation of collision mortality

We used the additive 2-variable model that included hub height and region—the most strongly supported model from the above model selection procedure (see details of AIC analysis results in Section 3.1)—to predict mortality across all U.S. wind turbines with location data available as of May 2013 (R function predict). We used a database that included entries for 1000 onshore wind facilities in the contiguous U.S. (i.e. excluding Alaska and Hawaii) either in production or currently under construction (i.e., facilities that will be in production within two years) that also referenced the number of turbines in the wind facility (44,577 total turbines; 56,852 total MW capacity; The Wind Power, 2013). We could not determine whether each individual wind turbine was a lattice or monopole model. Our mortality estimates, which are based only on collision data from monopole turbines, therefore represent the amount of expected mortality if all current U.S. wind turbines were updated to monopole models. We excluded wind facilities in Alaska and Hawaii because we found no mortality data for these states, and it is unclear whether mortality data from the contiguous U.S. can be reliably extrapolated to these regions. We also found no data for the southwestern U.S.; we assumed that the amount of mortality per turbine in Arizona, Nevada, and Utah was the same as the rest of the West (excluding California) and that mortality in New Mexico was similar to mortality in the Great Plains due to proximity of this state to two western Texas facilities with data. We also classified two facilities on the Texas Gulf Coast as being in the East because of the biological dissimilarity of this region from the Great Plains. For 29% of the 1000 wind facilities in the database, the hub height or turbine model was listed. Turbine model information was used to cross-reference another portion of the same database that included specifications, including average hub height, for different types of wind turbines. For the remaining 71% of turbines, we used the average height of other turbines in the same region. We provide a discussion of the assumptions made for the mortality estimate in Section 4.4.

3. Results

3.1. Correlates of mortality

The additive 2-variable model that included turbine hub height and region was the most strongly supported model in our analysis, followed by the multiplicative height-region model. Because the relative strength of support was greater for the additive model (Table 1), we used this model for mortality prediction. The univariate region and hub height models each received less support than the 2-variable models; however, because both variables were included in the best-supported model, we compared estimated mortality across turbine heights and among regions. Bird collision mortality was modeled to increase significantly with increasing hub height (univariate hub height model: $\beta = 0.039$ [95% $CI = 0.037–0.40$], $z = 51.5$, $df = 52$, $p < 0.001$) (raw data back-calculated to per turbine mortality rates in Fig. 2A). Across the range of hub heights in our data set (36–80 m), and when accounting for varying proportions of the year being surveyed, annual model-predicted mortality increased nearly ten-fold (from 0.64 to 6.20 birds per turbine). After accounting for varying proportions of the year being sampled, annual per turbine mortality was modeled to be highest in the East (median = 8.16 birds), followed by California (median = 4.82 birds), the West excluding California (median = 3.64 birds), and the Great Plains (median = 2.43 birds) (raw data back-calculated to per turbine mortality rates in Fig. 2B).

3.2. Estimates of total bird collision mortality

Using the top model from the previous analysis and incorporating region and height data for the 1000 onshore wind facilities generated a mean estimate of 234,012 birds (95% $CI = 140,438–327,586$) killed annually by collisions with monopole wind turbines in the contiguous U.S. Mortality estimates varied geographically due to variation in both numbers of turbines and mortality rates. There was no statistically significant difference among regions in turbine hub height ($F = 2.278$, $df = 285$, $p = 0.080$); therefore, this factor was unlikely to explain substantial regional variation in mortality estimates. We estimate that 46.4% of total mortality at monopole wind turbines occurs in California, 23.1% occurs in the Great Plains, 18.8% occurs in the East, and 11.6% occurs in the West (Table 2).

Regional rankings changed when estimated mortality was evaluated on a per turbine or per MW basis. California still ranked above all regions with a mean annual collision rate of 7.85

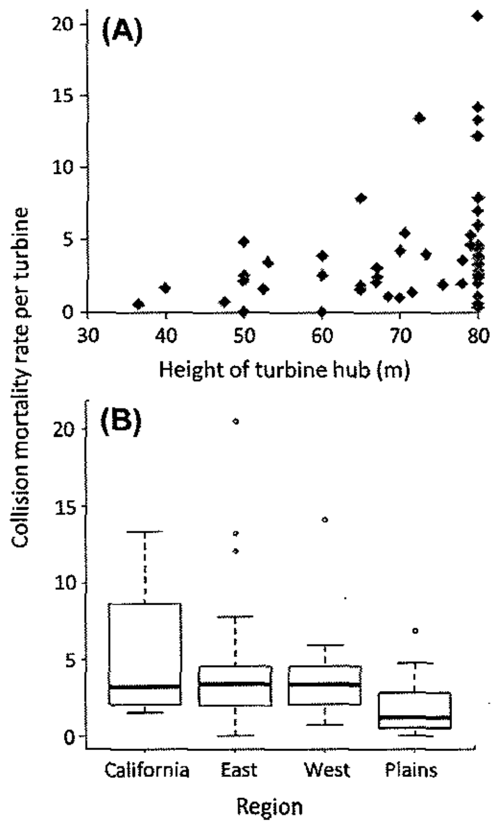

Fig. 2. Univariate relationships between annual per turbine bird mortality at monopole turbines (adjusted for scavenger removal, searcher efficiency, and search radius) and variables appearing in the top model selected in the AIC_c analysis: (A) turbine hub height (i.e. height to the hub where the rotor is mounted) and (B) geographic region.

birds/per turbine (95% CI = 4.05–11.65), followed by the East (6.86 birds/turbine; 95% CI = 5.41–8.30), the West (4.72 birds/turbine; 95% CI = 3.42–6.02), and the Great Plains (2.92 birds/turbine; 95% CI = 1.61–4.22). On a per MW basis, California had a mean collision rate of 18.76 birds per MW (95% CI = 9.68–27.84), followed by the East (3.86 birds/MW; 95% CI = 3.05–4.68), the West (2.83 birds/MW; 95% CI = 2.05–3.62), and the Great Plains (1.81 birds/MW; 1.00–2.62). Regional differences based on the additive region-height model are different from those based on the univariate region model (Section 3.1) because the latter were calculated independently of turbine height data.

The wind facilities for which we compiled mortality data may not be representative of all wind facilities (see Table 3 for comparisons between wind facilities with and without bird mortality data). For example, California data came from facilities that had fewer turbines than average for wind facilities in this state, and data from the East, West, and Great Plains came from facilities that had more turbines than average for these regions. Mortality data also came from wind facilities with turbine hub heights that were shorter than average for California, the West, and the Great Plains. For the East, facilities with mortality data had turbine heights that were characteristic of average heights for this region.

For the species count summary, we found 3605 fatality records representing at least 218 bird species from 73 studies (raw counts in Appendix D). As mentioned in Section 2.3 and further discussed in Section 4.4, these counts may be non-representative of species-specific mortality because counts are influenced by rates of scavenger removal and searcher detection.

4. Discussion

4.1. Comparison to other mortality estimates

Our mean projected estimate of 234,012 annual bird collisions in the contiguous U.S. – and even our low-end estimate (140,438) – is greater than most previous estimates, including ~20,000 birds/yr (Sovacool, 2012), 10,000–40,000 birds/yr (Erickson et al., 2001; Manville, 2005), and 20,000–40,000 birds/yr (Erickson et al., 2005). Two recently published annual estimates exceed our upper estimate of 327,586 birds: 440,000 (Manville, 2009) and 573,000 (Smallwood, 2013). We provide the first mortality estimate specific to monopole turbines. Our focus on this turbine type could explain why our estimate is lower than the estimate of Smallwood (2013) that also includes data from lattice turbines. Lattice turbines can kill relatively large numbers of birds (Smallwood and Karas, 2009), but they are largely being decommissioned in the U.S. Our modeling approach, including data extraction from 68 studies and prediction of mortality based on turbine height and geographic region, provides a more systematic approach than most previous estimates (but see Smallwood, 2013). Furthermore, we accounted for variable sampling coverage among studies (by defining an offset term in our model for the number of days out of the year sampled). This approach improves upon the assumption that mortality is negligible during periods of the year that are not surveyed.

4.2. Correlates of mortality

Bird collision rates at communication towers are known to increase with increasing tower height (Longcore et al., 2008, 2012). Meta-analyses of collision mortality at wind turbines have found either an increase in mortality with height, but only for bats (Barclay et al., 2007), or a decrease in mortality with turbine size for birds (Smallwood, 2013). Our finding of support for a positive relationship between bird collision mortality and turbine hub height may be a result of: (1) using a mortality data set that is larger and more comprehensive than those used in previous studies (but see Smallwood, 2013), (2) accounting for variation among studies in the proportion of the year sampled, and/or (3) only including data from solid monopole turbines.

Our finding of a positive relationship between turbine height and bird mortality appears to be the opposite of the Smallwood (2013) finding of reduced mortality rates with increasing turbine size for raptors (nationwide) and for all birds (within the Altamont Pass Wind Resource Area). However, we used a different metric for turbine size (hub height) than the previous study (MW of energy generation capacity), and this difference in approaches could explain our apparently contradictory result. In addition, our analysis only included wind turbines with solid monopole towers, whereas previous authors have included both monopole and lattice-towered turbines, including lattice turbines from the Altamont Pass Wind Resource Area (APWRA). Lattice turbines in the APWRA are relatively small (with total height between roughly 18 and 45 m; Orloff and Flannery, 1992) and characterized by relatively high per turbine mortality rates. This mortality likely occurs due to a combination of turbine design (lattice turbines provide perches that attract raptors near spinning blades) and turbine placement near areas of high bird movement (mountain ridgelines) (Smallwood and Thelander, 2008; Smallwood and Karas, 2009). Thus, our exclusion of lattice turbines could contribute to the unique finding of a positive relationship between turbine height and mortality.

The average hub height of U.S. wind turbines has increased 50% between 1998 and 2012, and further up-scaling in both hub height and rotor size is expected in the future (U.S. DOE, 2013). Because we found a strong correlation between turbine hub height and rotor diameter, it is important to note that increased bird mortality may be a result of both increased turbine height and increased rotor diameter. As turbines get taller, greater mortality may occur due to turbines extending further into altitudes that contain large numbers of flying birds. As rotor diameter increases, a greater area of airspace is swept by the turbine blade and therefore exposed to collision risk. Recent well-publicized research indicates that larger wind turbines may provide more efficient energy generation (Caduff et al., 2012; National Geographic, 2012). Given that we found evidence for increased bird mortality with increasing height of monopole turbines along with a move toward increasing turbine size, we argue that wildlife collision risk should be incorporated with energy efficiency considerations when evaluating the "greenness" of alternative wind energy development options.

Our finding of some evidence for mortality rates differing among geographic regions (both when based on our mortality predictions and model selection results) suggests that coarse-scale decisions about siting of wind facilities may benefit from information about bird collision risk. Because average per turbine collision rates in the Great Plains may be relatively low, wind energy development in this region could potentially result in comparatively lower collision risk for wildlife. Previous research illustrates that the development potential for wind energy in the Great Plains is sufficient to meet the output capacity of the DOE's 20% goal, even if development occurs only on lands that are already disturbed (Kiesecker et al., 2011). However, precaution must be taken when making broad-scale siting decisions, especially in regions where no publicly available mortality data exists, including many Great Plains states (North Dakota, Kansas, Nebraska, and Colorado) and the U.S. Southwest. Furthermore, little is known about the potential for indirect impacts of wind energy development in both disturbed and undisturbed areas (Kuvlesky et al., 2007; Kiesecker et al., 2011; Piorkowski et al., 2012). Finally, the cumulative effects of wind energy must still be considered because a large number of turbines that each cause a small number of collisions can still result in a large overall amount of mortality.

4.3. Data biases and model limitations

Study design and sampling methods varied among the studies we used in our analysis, and it is unclear how this variation influenced our mortality estimates. Although we were unable to account for all sources of variation, we accounted for variation in seasonal coverage of surveys, and our inclusion criteria and adjustments accounted for searcher efficiency, scavenger removal, and varying search plot radius. Other methodological differences could not be accounted for. For example, whereas some studies clearly distinguished between fatalities found during scheduled searches and those found incidentally, others combined all fatality observations without differentiating among types of records. Some studies corrected for incomplete searching of survey plots (e.g., due to obstructions, dense vegetation, or safety concerns), while others did not make these corrections or did not present information to determine whether corrections were made or even necessary. Furthermore, different statistical estimators were used to generate mortality estimates, and some of these consistently under-estimate mortality (Huso, 2010). Standardization of methods for carcass searches, searcher efficiency trials, scavenger removal trials, and statistical estimators will reduce biases in comparisons of multiple studies (for further discussion of biases affecting mortality estimates, see Kunz et al., 2007b; Smallwood, 2007; Smallwood et al., 2010; Loss et al., 2012).

Extrapolation of data from the western U.S. and Great Plains to the southwestern U.S. may influence our mortality estimates. Further research at wind facilities in these areas is needed to estimate regional mortality rates and identify species and locations that are at elevated risk of bird mortality from wind energy development. We collected data from wind turbines with hub heights ranging from 36 to 80 m, but we applied our predictive model to turbines with hub heights up to 100 m. The accuracy of extrapolating our model to taller turbines remains untested because there are no publicly available studies of mortality for U.S. turbines taller than 80 m. Notably, 8.2% of U.S. wind facilities with turbine hub height data available (24 of 290 facilities) included turbines in excess of 80 m in height.

Because we were unable to determine the specific turbine type for every wind turbine in the database to which we extrapolated the fitted model, we assumed that all turbines had monopole towers. This assumption assumption is likely valid given that all U.S. facilities for which we found mortality data—except for three facilities in California—solely use monopole turbines. Nonetheless, given that a small number of the turbines to which we extrapolated our model were lattice turbines, our estimates represent the amount of mortality expected if all U.S. turbines were updated to monopole models. Additional estimate bias may have occurred due to uncertainty about hub heights for some turbines to which we extrapolated the fitted model. However, we are unaware of a wind turbine data set that includes hub height information for every U.S. wind turbine; development and use of such a database would improve future mortality estimates and assessments of mortality correlates.

Finally, as illustrated in Table 3, the wind facilities from which we extracted mortality data may be of non-representative size and have non-representative turbine heights for their respective region. In addition, it is unclear whether the mortality estimates that we used provide a representative sample of all collision mortality data that has been collected at U.S. wind facilities. Despite numerous calls for an increase in the transparent reporting of study results and availability of reports to the public and scientists (Kunz et al., 2007b; Stewart et al., 2007; Piorkowski et al., 2012), collision data largely remains confidential and/or offline. Furthermore, reports that have been released to the public (e.g. on the internet) are often difficult to locate. We join previous authors in calling for increased transparency in data reporting. Requiring industry reports to be made publicly available would greatly improve understanding of wind energy impacts to wildlife.

4.4. Study design improvements and research needs

Our findings do not obviate the need for pre-construction risk assessments for proposed wind facilities and post-construction studies at existing facilities. Even within regions predicted to have relatively low risk, local mortality rates may be substantially higher along or near migratory routes, such as rivers and ridgelines, or in areas with high bird abundance or sensitive species. Ideally, pre-construction studies should be conducted for at least one entire year prior to wind facility siting decisions. As suggested by Ferrer et al. (2012), these risk assessments are likely be effective only when based on investigation of species-specific risks and locations of individual proposed turbines, as opposed to assessment of risks to all birds combined and for locations of entire wind facilities. Post-construction studies ideally should extend for at least three years with sampling conducted throughout the year. If year-round sampling is not possible, inferences about site-specific mortality rates should not be extended beyond the period of sampling coverage. Post-construction studies should identify the age and sex of carcasses when possible because this information can be used to inform understanding of population dynamics relative to mortality at wind turbines. (For a thorough discussion of needed protocol improvements, see also Smallwood (2013)).

Determining whether individual bird species are vulnerable to population declines as a result of wind turbine collisions is a major conservation objective. However, little evidence exists to infer whether turbine collisions cause population declines (Stewart et al., 2007). In the wind energy literature that we reviewed, we found a relatively small sample of mortality data with species information available. Furthermore, these mortality counts are likely influenced by detectability and scavenger removal rates that vary by species, with larger species more likely to be detected and less likely to be removed by scavengers than smaller species (Smallwood, 2007). Most studies do not provide the species-level detectability and scavenger removal information that is needed to calculate bias-adjusted estimates for individual species. Thus, any mortality estimates for large species would be inflated relative to those of small species. Further research is needed to increase the sample size of species-specific mortality data at U.S. wind facilities and to clarify how species-specific biases influence estimation of mortality and assessment of population impacts. In addition, intensive research of local and regional-scale population impacts to raptors and other slow-reproducing, long-lived species (e.g., waterbirds) is needed. As illustrated by studies in Europe, even low rates of turbine collision mortality have the potential to be associated with significant population declines for raptors in some localities (Carrete et al., 2009; Dahl et al., 2012).

Wind facility siting decisions should also incorporate risks to bats, which experience high collision rates, primarily along forested mountain ridgetops in the eastern U.S. but also in isolated portions of western North America (Kunz et al., 2007a). Post-construction mortality studies have often focused on bird collisions with only incidental reporting of bat fatalities. Study designs and sampling protocols for investigating bird fatalities may be inadequate for quantifying bat collision rates because factors that affect collision rates (e.g., time of day, season, weather, and turbine and wind facility characteristics) may differ between the two taxa. With increased quantity and rigor of bat studies (Arnett et al., 2008), our approach can be applied to generate total and region-specific estimates of bat mortality.

4.5. Conclusions

Development and production of U.S. wind energy represents a promising opportunity to decrease global carbon emissions and increase energy independence. However, our results suggest that the amount of U.S. bird mortality caused by collisions at monopole wind turbines is non-trivial. Furthermore, the projected trend for a continued increase in turbine size coupled with our finding of greater bird collision mortality at taller turbines suggests that precaution must be taken to reduce adverse impacts to wildlife populations when making decisions about the type of wind turbines to install. Despite an apparent lower magnitude of bird mortality at wind turbines compared to other anthropogenic mortality sources (e.g., windows/buildings, Klem, 2009; Loss et al., 2014; communication towers, Longcore et al., 2012, 2013; feral and pet cats, Loss et al., 2013), mortality at wind facilities should not be dismissed offhand. Instead, we stress the importance of considering species-specific and location-specific risks and the potential for cumulative impacts of multiple wind facilities and multiple mortality threats.

The total amount of bird collision mortality at U.S. wind facilities will likely increase with increased wind energy development in the coming decades. Scaling our estimates to the scenario projected to meet the DOE's 20% goal (a six-fold increase from current generation capacity, U.S. DOE, 2008) produces a mean annual mortality estimate of roughly 1.4 million birds. This estimate assumes that average wind turbine height will not increase. Installation of increasingly larger turbines could result in a greater amount of mortality. Multi-scale decisions about where to site wind facilities and individual wind turbines in the context of risks to individual bird species will be crucial to minimizing this mortality. Mortality estimates can be updated using our approach as more wind facilities are constructed, more regions are studied, and additional mortality data is compiled and made publicly available.

Role of the funding source

The funder had no role in study design; collection, analysis, and interpretation of data; in writing the report; and in the decision to submit the paper for publication.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2013.10.007.

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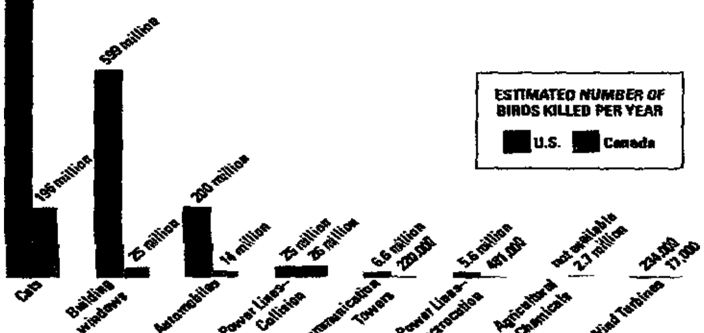
Attachment CEG-12

ADDITIONAL DRIVERS OF BIRD DECLINES

Habitat loss is by far the greatest cause of bird population declines. *Humans also kill billions of birds in the U.S. annually through more direct actions, such as allowing outdoor cats to prey upon birds. Canadian bird mortality estimates show remarkably similar patterns. Data-driven assessments of how different human-caused sources of bird mortality contribute to population declines are essential for developing strategic conservation objectives and science-based policies.*

Reducing or eliminating direct sources of mortality could save millions, if not billions, of birds annually. The best ways to reduce *bird mortality include:*

- ***CATS:*** *Keeping pet cats indoors* and implementing policies to eliminate feral cat colonies.
- **COLLISIONS:** Following bird-friendly window practices, reducing *night lighting in* and on tall buildings, warning auto drivers in high-collision areas, installing flashing rather than steady-burning lights on communication towers, *and locating wind turbines* away from areas of high bird concentrations (especially areas that pose threats to particular species such as eagles).
- ***CHEMICALS:*** *Limiting* the broadcast spraying of pesticides and insecticides and introducing integrated pest management practices (which reduce or eliminate chemical applications) *in agricultural areas.*



Bar chart based on independent assessments of direct human-caused mortality in the United States and Canada. This data is adapted from Loss SR, Will T, Marra PP. Direct human-caused mortality of birds. Annual Review of Ecology, Evolution, and Systematics In prep

The Cornell Lab of Ornithology
nabci
Rocky Mountain Bird Observatory
The Nature Conservancy
Protecting nature. Preserving life.
USGS
science for a changing world
Ducks Unlimited
Smithsonian Institution
Audubon
University of Idaho
Association of Fish & Wildlife Agencies
North American Waterfowl Management Plan
American Bird Conservancy
Point Blue Conservation Science
Environment Canada
Environnement Canada

Referenced as CEG-2 in testimony

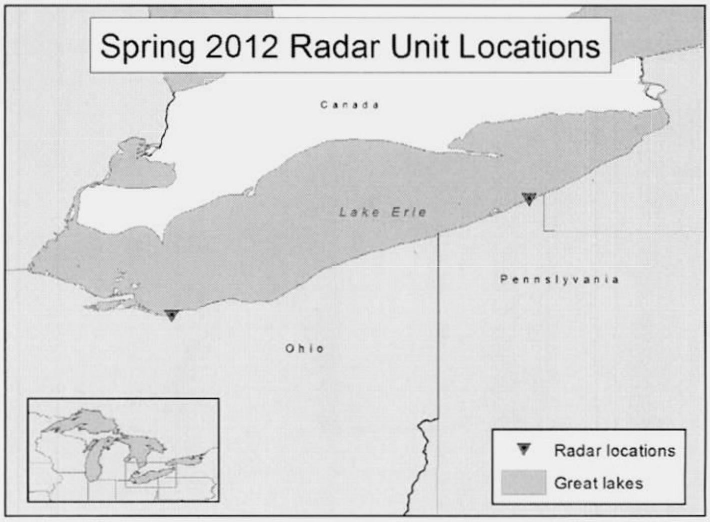
Attachment WE-7

Great Lakes RESTORATION

U.S. Fish & Wildlife Service

Great Lakes Avian Radar Technical Report Lake Erie Shoreline: Erie County, Ohio and Erie County, Pennsylvania

Spring 2012



U.S. Fish & Wildlife Service, Region 3

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Executive Summary

Global wind patterns help move millions of migrating birds and bats through the Great Lakes region, where the shorelines provide important stopover habitat. Shorelines are thought to concentrate migrants because they offer a last refuge prior to crossing a geographic obstacle, and they are likely used for navigation. However, shorelines are also attractive for wind energy development, which is a known cause of mortality in birds and bats. Due to this this potential for conflicting land use interests, more information on the aeroecology of the shorelines of the Great Lakes region is required. Therefore, we used two avian radar systems to identify the activity, temporal patterns, and duration of migration in birds and bats that occurred along shorelines of the Great Lakes.

We placed avian radar systems on opposite ends of the south shore of Lake Erie, and the automated systems continuously tracked and recorded the movements of targets (birds and bats) from early April to mid-June 2012. We determined the direction of movement, target passage rates, and altitude profiles for the air space above our study areas, and we developed a model of the vertical sample volume that allowed us to estimate the target density according to the altitude band.

Migration appeared to be strong along the southern shoreline of Lake Erie, and at both of our locations, the mean target passage rates at night were greater than those at dawn, day, and dusk combined. The nocturnal movements were typically oriented in a northerly direction, although we also recorded other behaviors associated with migrants, such as reverse migration, dawn ascent, and migrants over water returning to land at dawn. After applying a correction, the peak density was found to occur between 50 – 150 m above ground level, although the density at higher and lower altitudes may have been underestimated.

The results of our research highlight the potential role of radar in implementing the Land-Based Wind Energy Guidelines and help to identify areas where the impacts to wildlife from wind energy could be minimized. We documented migration activity in the air space above our study areas, and the results indicate that the high target density at low altitudes may present conservation concerns. Our data revealed the ebb and flow of migration activities throughout the sampling period and documented the occurrence of nocturnal peaks through late May. Given the amount of time during which migration occurred in the sampled sites, curtailing wind energy operations to minimize bird and bat mortality during nocturnal pulses could severely limit energy production time along shorelines during the migration season. Combining the results of radar studies with fatality searches would greatly improve risk assessments and assist with the interpretation of standardized radar studies.

Avian radar is often used to perform surveys for pre-construction risk analyses, and although it is an important tool, few regulatory agencies have experience implementing avian radar or recognizing the strengths and limitations of the technology. This report highlights a number of considerations in the use of avian radar, and it reviews certain potentially confusing metrics and introduces new metrics for reporting radar data. In addition to providing information relevant for wildlife conservation in the Great Lakes region, this report presents concepts that are widely relevant for reviews of avian radar studies and describes methods for identifying critical components of migration, such as the following:

- Nocturnal pulses
- Season length
- Estimated density per altitude band
- Migrant behavior near a geographical obstacle

Given the rapid growth of the wind energy sector, our most effective conservation strategy might be identifying and avoiding locations where migrants concentrate when choosing sites for energy development. Our use of commercial-grade avian radar to document migration is a broad-scale effort toward this end, and to our knowledge, this effort is the first of its type by the U.S. Fish and Wildlife Service.

Spring 2012

Great Lakes
RESTORATION

Introduction

Collectively, the Great Lakes are one of the largest bodies of freshwater on the planet, and they have a surface area of nearly 245,000 km^2 and over 17,500 km of shoreline. Global wind patterns help move millions of migrating birds and bats through the Great Lakes region (Rich 2004, Liechti 2006, France et al. 2012), and globally recognized Important Bird Areas are often located on lake shorelines (Audubon 2013). Migrants passing through the region concentrate near shorelines (Ewert et al. 2011, Peterson and Niemi 2011, Buler and Dawson 2012, France et al. 2012), which provide important stopover habitats, or areas that are used temporarily for refueling, rest, and protection while en route to their breeding grounds. Compared with inland areas, these shorelines offer increased foraging opportunities relative to inland areas (Smith et al. 2004, 2007, Bonter et al. 2007, 2009) and may serve as visual cues for navigation or as refuges for migrants before or after they cross open water (Buler and Moore 2011).

Due to their location and size, the Great Lakes likely represent a geographic obstacle that migrants must cross or avoid based on the environmental and physiological conditions at the time of they encounter the obstacle (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 single long flight because of the cost of carrying high fuel loads (Alerstam 1990), and this may be one reason why migrants partially circumnavigate the Great Lakes despite being physiologically capable of crossing them (Alerstam 1990, 2001, Ruth 2007). Thus, 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) associated with migration (McGuire et al. 2012a). Shorelines offer refuge when conditions do not favor flights over water.

When challenged by an obstacle, migrants 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, Akesson 1999, Ewert et al. 2011). Schmaljohann and Naef-Daenzer (2011) found that birds managing low fuel loads and/or unfavorable weather conditions returned to the shoreline habitat rather than continue across open water in the direction of migration. For bats, the migrants varied in their choice to cross over or circumnavigate lakes above the shorelines, and a number of long distance migrants use torpor to postpone migration in unfavorable conditions (McGuire et al. 2012b). These behavioral responses as well as the need to use stopover habitat during migration likely contribute to the increased use of shorelines and demonstrate the importance of these areas for conservation.

Migrants concentrated along shorelines can be very mobile. In addition to using the shoreline habitats for immediate refueling and rest, migrants make broad-scale flights between 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 between habitat patches, with individual birds and bats relocating as far as 18 and 30 km from their capture site, respectively, prior to resuming migration (Taylor et al. 2011). Nocturnal migrants, such as warblers and other Neotropical species, regularly engage in morning flights along shorelines (Wiedner et al. 1992). These flights typically occur within 2 hours of sunrise and likely represent reorientation along a geographic obstacle or movements between stopover habitats (Able 1977, Moore 1990, Wiedner et al. 1992). Flights of this nature often occur above the tree line (Bingman 1980) but at heights lower than those 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), and these flights are considered normal activities aimed at calibrating internal compasses and testing the wind speed and direction aloft. Migrants also follow north-south oriented shorelines en route to their destination (Buler and Dawson 2012), whereas east-west oriented shorelines 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 activities define an area of use near lake shores and include a variety of movements and altitudes for landscape-level, exploratory, and migratory flights. However, these activities may increase the risk of collision with tall structures, such as buildings, communication towers or wind turbines.

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 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 urban and energy development, land conversion, and environmental contamination, which may limit habitat availability and/or reduce habitat quality (France et al. 2012).

Of further concern is the devastation of hibernating bat populations by white-nose syndrome, which has increased the need for identifying conservation areas as several of these species face extirpation in the Great Lakes region (Turner et al. 2011). The increased number of wind energy installations within the U.S. is further devastating bat populations by causing high numbers of fatalities to long-distance migratory tree bats (Kunz et al. 2007a, Cryan 2011, Arnett and Bearwald 2013, Hayes 2013, Smallwood 2013). In response to such factors, substantial efforts are being made to identify and protect stopover habitat along the shorelines of the Great Lakes (Buler and Dawson 2012, Ewert et al. 2012, France et al. 2012, Johnson, 2013), although careful planning is needed to balance the demands between increased renewable energy development to mitigate climate change and the conservation of migratory species.

There is a national movement towards supplying 20% of the end-use electricity in the U.S. market by wind power by 2030 (US DOE 2008, 2015) and 35% by 2050 (US DOE 2015). As of 2012, wind energy installations were on target to achieve the 2030 goal (AWEA 2015), which would represent a nearly five-fold increase in wind energy capacity over the next 15 years (Loss et al. 2013). Coinciding with this national effort, wind energy development is increasing within the Great Lakes region, where windy shorelines are attractive areas for turbine placement (Mageau et al. 2008, Great Lakes Commission 2011). However, utility-grade wind facilities have been associated with mortality events in migrating vertebrates (Newton 2007, Arnett et al. 2008, Smallwood and Thelander 2008), and chronic fatalities across the US, particularly in bats, have become a concern (Timm 1989, Johnson 2005, Arnett and Bearwald 2013, Hayes 2013, Smallwood 2013). For example, approximately 75% of all bat mortalities occur in three species of long-distance migratory bats that are impacted by wind energy facilities (Cryan 2011, Kunz et al. 2007a, Arnett and Baerwald 2013), and these migrants, the hoary bat (Lasiurus cinereus), eastern red bat (Lasiurus borealis), and silver-haired bat (Lasionycteris noctivagans), typically account for the majority of *bat fatalities at wind facilities in the Upper Midwest* (Arnett et al. 2008). Three Wisconsin studies found high fatality rates for these same migrant species as well as substantial fatalities in the little brown bat (Myotis lucifugus) and big brown bat (Eptesicus fuscus) (Gruver et al. 2009, BHE Environmental 2010, Grodsky et al. 2012), although the presence of major hibernacula in the vicinity of wind facilities may have influenced the results. Additionally, low reproductive rates inhibit the ability of bats to rebound from population declines (Racey and Entwistle 2000), which have already begun in several species (Kunz et al. 2007a, Cryan 2011). The cumulative impacts on migratory birds and bats are a concern that will increase with the growth of wind energy if methods to avoid or minimize mortality events are not implemented. A number of promising conservation measures have been proposed to reduce mortality levels, but the greatest benefit to the conservation of migrants might lie in our ability to identify and avoid future growth in locations where migrants concentrate.

To help meet the needs of both renewable energy development and wildlife conservation, we established this project to identify the activity, temporal patterns, and magnitude of migration that occurs along the shorelines of the Great Lakes. Since bats and many bird species migrate during the night throughout the spring and fall, documenting migration is challenging because observing sporadic nocturnal movements is difficult. We used a combination of techniques to address this problem. We primarily used two avian radar units that simultaneously scanned the horizontal and vertical planes 24 hours per day, and we used nearly 40 automated ultrasonic/acoustic monitors to record bird and bat calls. Finally, we collected incidental bird observations in the areas near the monitoring equipment. We are reporting only on the avian radar portion of the overall study, and our objectives include the following:

- Monitor locations along the shorelines of Lake Erie using a consistent methodology;
- Maintain an archive of continuously recorded *radar data during the spring migration season;*
- Identify the activity patterns captured by radar that are diagnostic of migration;
- Estimate the duration of the migration season.
- Document changes in the behavior of migrants under varying conditions and during different parts of the season.

Methods

Study Area and Site Selection

In spring 2012, we selected two sites along Lake Erie for radar placement, with one site located towards the western end of the lake in Ohio and the other site located towards the eastern end of the lake in Pennsylvania (Figure 1). We located sites within 1.5 km of the Lake Erie shoreline to monitor the airspace above inland, shoreline and lake areas. The western site, which is located in Erie County, Ohio, at 41.3798° N, -82.4376° W, was approximately 1.5 km from the shoreline and 177 m above sea level. Here, the radar unit was placed in the middle of an agricultural field in an area where cultivated crops and deciduous forest were the predominant land cover types within the range of the radar unit according to our analysis using Esri ArcGIS software and the 2006 National Land Cover Database (Fry et al. 2011) (Table 1, Figure 2, Appendix 2). Cultivation in this area of Ohio predominately consists of row crops, such as corn and soybeans. The eastern site, which is located in Erie County, Pennsylvania, at 42.2213° N, -79.8683 W, was approximately 1 km from the shoreline and 222 m above sea level. This radar was also placed in an agricultural field although in an area where cultivated crops and open water are the primary land cover types within range of the radar unit (Table 1, Figure 2, and Appendix 2). The crops in this area of Pennsylvania are predominately vineyards and fruit orchards.

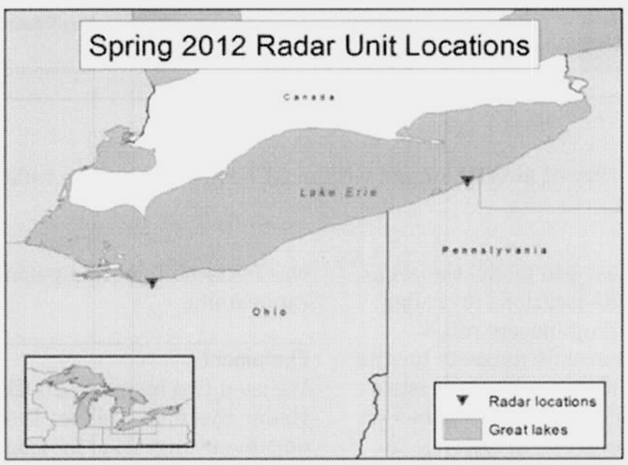


Figure 1. Locations where MERLIN Avian Radar Systems were deployed during the spring 2012 migration season.

National Land Cover Class	Ohio % of Land Cover	Pennsylvania % of Land Cover
Cultivated Crops, Hay/Pasture	35.83%	36.44%
Developed[1]	10.96%	16.23%
Forest[2]	28.52%	5.50%
Open Water	24.40%	35.79%
Other[3]	0.28%	6.03%

[1]Includes low-, medium- and high-intensity development and developed open space.

[2]Includes deciduous, evergreen and mixed forests.

[3]Includes barren land, herbaceous, shrub/scrub and woody and emergent herbaceous wetlands.

Table 1. Predominant land cover types found within a 3.7-km radius of the radar locations in Ohio and Pennsylvania in spring 2012.

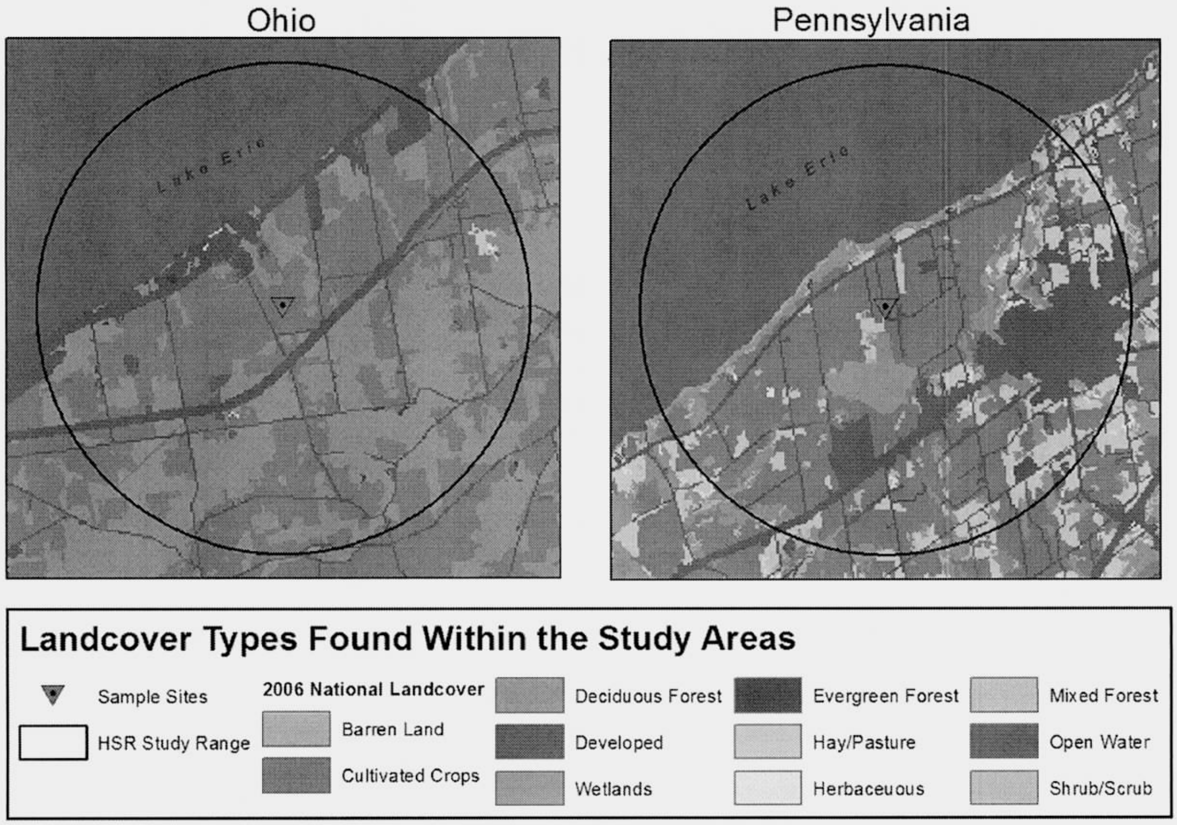


Figure 2. Land cover types (Fry et al. 2011) found within a 3.7-km radius of the radar units in Ohio and Pennsylvania in spring 2012.

Esri ArcGIS software was used to model the areas of interest to identify suitable locations for radar siting. This suitability modeling incorporated elevation, land cover, and shoreline datasets for the Great Lakes. Additional landscape characteristics were derived from these datasets (elevation below the local maximum, percent forested, distance to forest, distance from shoreline, etc.) and ranked to create a continuous raster surface within the area of interest with estimated suitability values. Contiguous areas with high suitability were identified through the GIS modeling process and targeted for on-site assessment.

Biologists were dispatched to the areas of interest to more thoroughly evaluate the potential sites identified by the modeling effort, and this assessment included determining the land use, line of sight to shorelines, and accessibility for the placement of the radar units. Additional suitable locations not identified through modeling were frequently discovered through this process and evaluated. When the field biologists determined that a location was highly suitable relative to the other locations visited, contact with the property owners was initiated to obtain permission to set up the radar units.

Equipment

We used two model SS200DE MERLIN Avian Radar Systems (DeTect Inc., Panama City, FL) to document migration movements, and 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, with one scanning the horizontal plane and the other scanning the vertical plane (Figure 3). Additionally, each unit contained four computers for real-time automated data processing and a SQL server for the storage and review of processed data. The units were configured with a wireless router to allow remote access to the computers and automated status updates.

Description of radar. The solid-state marine radar antennas (Kelvin Hughes, London, UK) employed by our systems were 3.9 m in length and had a peak power of 170 W, wavelength in the S-band (10 cm), and frequency range of 2.92 – 3.08 GHz, and they were configured to operate with both short and medium pulses (0.1 and 5 μs, respectively). The horizontal radar was also equipped with Doppler to help filter the stationary targets. The radars emanated a fan-shaped beam that had an approximately 1° horizontal and 25° vertical span when operated in the horizontal plane. The S-band radar was selected because it uses longer wavelengths that are less sensitive to insect and weather contamination compared with the X-band (3 cm wavelength) antenna (Bruderer 1997), and it is also less sensitive to signal attenuation from ground clutter, such as vegetation and structures (DeTect Inc., unpublished data, 2009). The radars spin perpendicular to each other at a rate of 20 RPM and were synchronized so that they did not emit over one another. The horizontal scanning radar (HSR) was affixed to a telescoping base that was raised to approximately 7 m above the ground for operation; this radar rotated in the x-y plane with a 7° tilt to reduce the amount of ground clutter within its view. Although the radar was capable of scanning large distances, we selected a 3.7-km range setting to collect higher resolution data and identify smaller targets, such as passerines and bats. The HSR was primarily used to provide information on target movement direction. The vertical scanning radar (VSR) rotated in the x-z plane and scanned a 1° x 25° span of the atmosphere. We selected a 2.8 km range setting for this radar to collect data with increased resolution and used the VSR to provide information on the number and height of the targets.

Weather Station. Each system was equipped with a weather station (Davis Vantage Pro 2, Hayward, CA, USA) that recorded wind speed and direction, humidity, temperature, precipitation, and barometric pressure. The weather data were summarized and stored every 5 minutes. An anemometer was attached to the radar unit, and it measured wind speed at a height of approximately 6 m above the ground.

Radar Set Up and Data Collection

The radar systems were deployed at their respective sites during the third week of March; however, data collection did not start until the first week of April because of the need for adjustments at each unit and a malfunction with the vertical scanning radar in Ohio. Each radar system was maintained into the second week of June to capture the anticipated end dates of the migration season.

Establishing a radar system at a site involved several steps, including orienting the VSR, micro-site selection, and performing adjustments to ensure that adequate information was captured. We anticipated a primarily northbound direction of migration along the Lake Erie shoreline during spring and oriented the vertical scanning radars to an angle that was slightly off-perpendicular to the 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

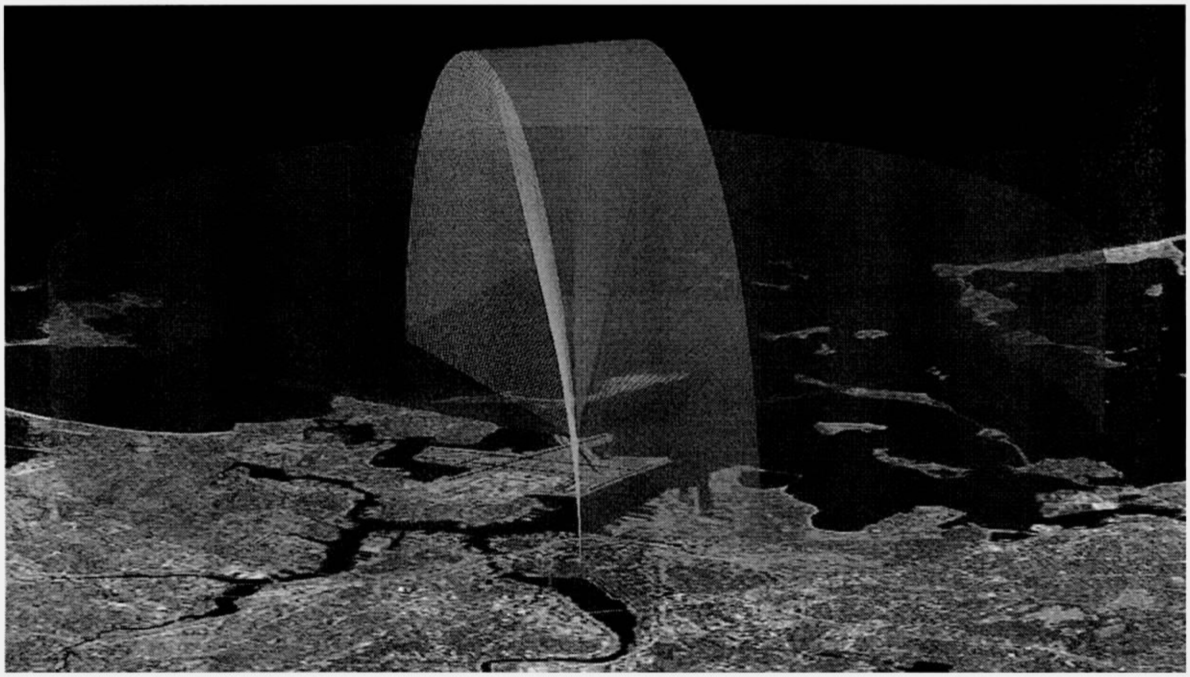


Figure 3. Computer representation of the potential survey volume scanned by the horizontal and vertical radars used by the U.S. Fish and Wildlife Service in spring 2012. Graphic provided by DeTect, Inc.

radar beam, and it was also influenced by micro-site selection, which is important because the position of the radar can affect the amount of interference from ground clutter or other sources. If large areas were obstructed from the radar view or if substantial amounts of clutter impeded data collection, then the systems were incrementally rotated to improve the view and/or reduce interference.

Once a position was established, clear-air thresholds and the radar's built-in sensitivity time control (STC) filters were employed to reduce small non-target returns and improve the tracking of distant targets. These settings are necessary because an object reflects more energy at close range than it does when it is further from the radar. For example, an object within a range of 50 m will return approximately 16-times more energy compared with an object at 100 m (Bruderer 1997, Schmaljohann et al. 2008). To further improve the data collection, clutter maps were generated using 60-scan composite images (Figure 4) during time periods with low biological activity to identify areas with constant returns (white areas) that were not biological targets, such as tree lines, fencerows and buildings. These areas were assigned a reflectivity threshold that precluded the constant returns from being included in the data, thus reducing our ability to detect targets in these areas.

Following this initial set up, MERLIN software was customized for the conditions at the sites. The MERLIN software provides real-time processing of raw radar data to locate and track targets while excluding non-targets and rain events, although the parameters used by the tracking software require adjustments to account for site-specific conditions. DeTect personnel trained our biologists to establish these settings with the goals of minimizing the inclusion of non-targets and maximizing cohesive target tracking. The processed data were stored in an Access database and then transferred each day to a SQL database, where they were stored and later queried for data analysis.

Despite the radar system's ability to be operated remotely for extended periods of time, biologists remained on site during the data collection period to ensure continuous functioning, monitor raw (unprocessed analog radar returns) and processed radar outputs, provide routine maintenance (such as re-fueling and oil changes), and manage data storage. In addition to the processed data, we maintained all of the raw radar data for potential reprocessing. The raw radar data were temporarily stored in the field on 2 TB external hard drives and regularly transported on ruggedized external drives back to the U.S. Fish and Wildlife Service Regional Office (Region 3), where the data were transferred to long-term tape storage.

Radar System Outputs

The MERLIN software generates more than 30 measurements to describe the target size, shape, location, speed, and direction of movement. These data are of the same type used by biologists when identifying biological targets on a radar screen (DeTect Inc., unpublished data, 2009), and this information was stored in the database for later analysis. To reduce potential false tracking, the MERLIN tracking algorithm removed tracks with less than five observations and an automated filter was used to remove sectors of the sample volume that were dominated by rain.

In addition to storing the target attribute data, the DeTect software outputs a two-dimensional digital display of targets being tracked in real-time and static images of tracked targets over a specified period of time (Trackplots) for both the vertical and horizontal radars. During each site check, we viewed the real-time digital display to ensure that it was consistent with the raw radar display, and we later viewed 15-minute and 1-hour Trackplots to assess the target direction and height during the previous day's activity.

Data Processing and Quality Control

Prior to the data analysis, the data processed by MERLIN software were further evaluated for potential contamination by non-targets. Although an automated rain filter was used, it did not remove all of the rain from the recorded outputs during certain time periods. Additionally, insects and other forms of transient clutter may have been recorded during data collection. Therefore, biologists reviewed all of the data in 15-minute time increments and removed the time periods that were dominated by rain, although there were no time periods dominated by other forms of transient clutter that needed to be removed.

We relied on visual inspections of the track patterns to discern contamination events. Rain and insect events form diagnostic patterns (Detect Inc., personal communication, 2011), and time periods with these types of track patterns can be removed. Unknown contamination that mimicked the patterns of desired targets was not removed from the database and contributed to the error associated with the indices. In addition, we evaluated initial counts by generating a time series of the variation in the number of targets per hour throughout the season for the HSR and VSR radars. In general, the HSR and VSR hourly counts were positively correlated with higher HSR counts, and in situations where the VSR counts were higher than the HSR counts or where the peak counts appeared to be outliers, the data were further investigated for evidence of contamination or potential issues with

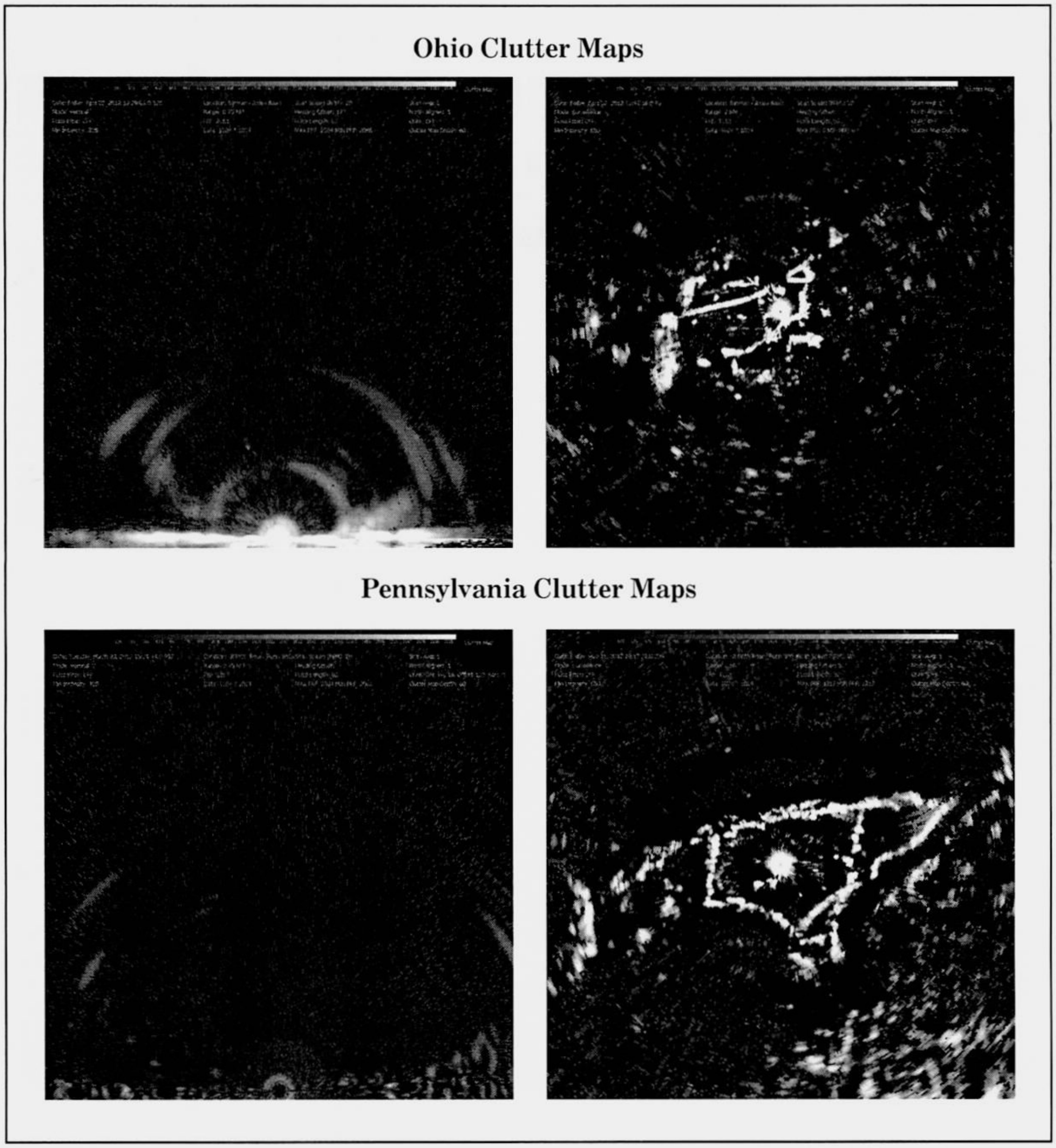


Figure 4. Clutter maps from vertical (left) and horizontal (right) scanning radars at study sites in Ohio and Pennsylvania during the spring 2012 migration season. Brighter areas represent static returns from stationary objects, such as tree lines and fencerows. Target detection may be obscured in these areas because of obstructions from the objects.

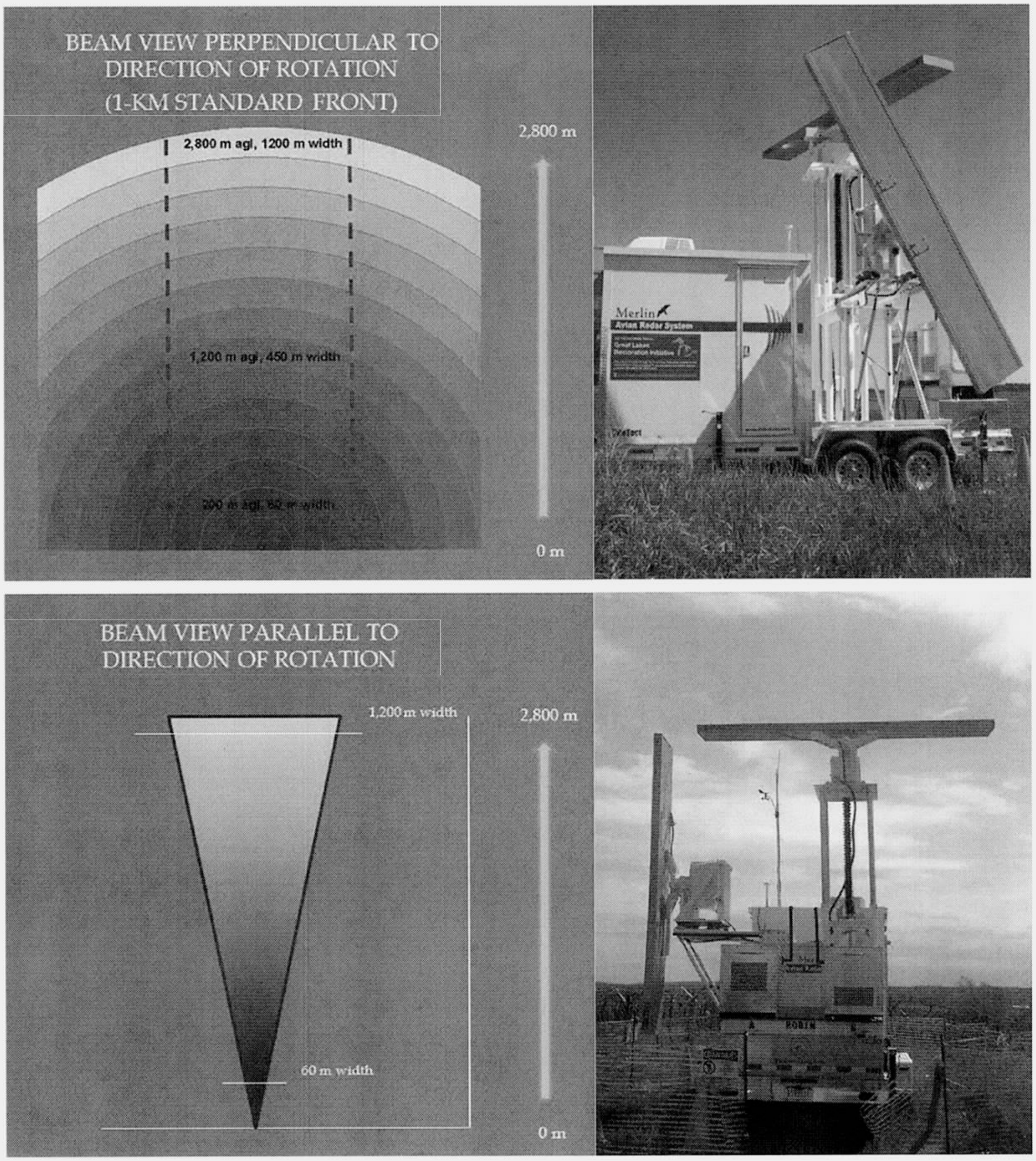


Figure 5. Schematic depicting the vertical scanning radar beam from two different views and pictures of the radar unit associated with those views. The top left graphic identifies the standard front used for data analysis, which extends to 500 m on either side of the radar and up to a height of 2800 m. In this graphic, the radar is situated at the bottom center and the red dashed lines represent the lateral limits of the standard front. In the bottom graphic, the radar rotation is suspended so that the beam is emitting directly upward; this view is an approximation of the beam dispersion as it travels away from the radar unit (schematic not drawn to scale).

radar performance. On the rare occasions when time periods with anomalies appeared to represent artifacts that were unrelated to target movement (e.g., rain events, insects or data processing errors), these periods were removed from further analysis.

Once the contaminated time periods were removed, we summarized the data using SQL queries provided with the MERLIN radar system. Data from the HSR were used to calculate the hourly counts and target direction, and all of the targets within 3.7 km of the radar unit were included in the analysis. Data from the VSR were used to calculate the hourly counts and height estimates, and these data were truncated to a 1-km or "standard front". We adopted this sampling technique because it is the method used by the manufacturer of the MERLIN units and has also been used by other researchers (Lowery 1951, Liechti et al. 1995, Kunz et al. 2007b). The standard front was defined by a volume of space that extended 500 m to either side of the radar and continued to the maximum data collection height (2800 m) (Figure 5). For each site location, the time at sunrise and sunset was calculated, and target counts were further segregated into four biological time periods: dawn, day, dusk, and night. Dawn represented 30 minutes before sunrise to 30 minutes after sunrise; day represented 30 minutes after sunrise to 30 minutes before sunset; dusk represented 30 minutes before sunset to 30 minutes after sunset, and night represented 30 minutes after sunset to 30 minutes before sunrise.

Data Summary and Trends Analysis

We used the processed data to assess the activity patterns associated with migration. Horizontal Trackplots were viewed to identify changes in activity and investigate the behaviors of the migrants, such as reverse migration (Akesson 1999) and migrants moving toward the shore at dawn, and vertical Trackplots were viewed to investigate changes in activity, such as dawn ascent (Myres 1964, Diehl et al. 2003). Target counts represented abundance, and we used these indices to identify directional, temporal, and altitudinal trends.

Directional Trends. The mean angle and concentration (r) of the target movement directions were analyzed following the methodology for circular statistics (Zar 1999) included in the DeTect SQL queries. The angular concentration value has a value of 1 when all of the angles are the same and a value of 0 when all of the angles cancel each other out, indicating that there is no predominant direction of travel (e.g., if 50% of the vectors are 180° and 50% are 360°, then no direction is predominant because there were as many targets heading south as there were heading north). We anticipated a generally northward direction of movement by the nocturnal targets during the spring migration season and reported the mean direction and the percent of nocturnal targets that traveled in a direction between northwest and northeast (292.5° – 67.5°). 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, and NW) during the four biological time periods (i.e., dawn, day, dusk, and night).

Temporal Trends. We plotted the counts of targets per hour processed by the MERLIN software for both the HSR and VSR antennas as a time series to identify pulses of nocturnal activity, the duration of the season, and changes in activity patterns over time. The HSR and VSR radars have different strengths that complement one another and were plotted together. The HSR index tracks low flying targets in a 360° span around the radar unit, and compared with the VSR, detection is not affected by the target's direction of travel, although the HSR index is much more affected by ground clutter, which impacts target detection and tracking, and errors caused by ground clutter lead to both under and over counting. Targets blocked by ground clutter may not be counted, and targets that fly in and out of areas with ground clutter may be counted multiple times. Such issues lead to HSR counts that are more influenced by site characteristics relative to the VSR counts; however, the HSR index better captures targets under certain conditions, such as when targets are primarily at low elevations and/or traveling parallel to the VSR. The HSR is also more susceptible to beam-bending from dynamic atmospheric conditions relative to the VSR, which presents minimal beam refraction primarily because of its orientation. The VSR index was used to track targets captured within the standard front, and it exhibits more consistent detection than the HSR because it mostly tracks against clear air except in the lowest altitude bands. Detection by the VSR index is affected by target direction and distance from the radar (Bruderer 1997, Schmaljohann et al. 2008), and it is impacted by ground clutter, particularly at low elevations. Plotting these indices together provided a more comprehensive understanding of changes in target activity over time.

We used the VSR index to calculate the target passage rate (TPR), which is the number of targets per standard front per hour, using the DeTect SQL queries, and hour intervals with less than 30 minutes of recording time were omitted from this calculation. For example, after removing all of the hours with less than 30 minutes of clean data, the nocturnal TPR for a given night (biological time period) was calculated by dividing the target count by the number of nighttime minutes and multiplying the value by 60 to yield the number of targets per hour during that night. We extended this metric to the season and calculated the mean TPR for the four biological time periods and hours of the season. The mean nocturnal TPR for the season is the sum of the night TPRs divided by the number of nights sampled. Similarly, the mean hourly TPR for the season is the sum of the TPRs for an hour-long period divided by the number times that hour was sampled. We also calculated mean nocturnal (night biological period) and diurnal (day biological period) TPR weekly during the sampling period using two methods. First, to demonstrate the variability among the sampled weeks, we divided the sum of the TPRs for a week (nocturnal or diurnal) by seven and reported the weekly mean TPR and its standard deviation.

Altitudinal Trends. The DeTect SQL queries were used to estimate the height of the targets tracked within the standard front from the VSR data. The height estimates were calculated based on the range and bearing of the target location with the largest radar echo and reported as the height above the ground as measured at the radar unit; this measurement does not consider changes in topography across the landscape. We used these estimates to calculate the mean altitude of the targets above the ground according to biological time period and hour, and we reported the mean and median altitudes for the season.

Density per Altitude Band. To provide information on the density of targets per 50-m altitude band per hour within the standard front, we first estimated the volume of the radar beam's approximate geometric shape. The width of the radar beam expands as it travels from the radar, resulting in increased survey volume with distance from the origin. The shape of the survey volume represents the space in which targets have the potential of being detected and is one of several factors that define the realized or actual survey volume (Bruderer 1997, Schmaljohann et al. 2008). We calculated the volume contained by the shape of the radar beam and reported the target density (targets per 1,000,000 m^3) per 50-m altitude band per hour for each biological period. This was calculated by dividing the number of targets per volume of an altitude band by the number of minutes with clean data during the biological time period of interest and multiplying the result by 60.

To estimate the volume of the 50-m altitude bands that are constrained by the standard front, we used Monte Carlo integration (Press et al. 2007), which is described in detail elsewhere (manuscript in preparation) and summarized here. The volume contained by the shape of the radar beam can be calculated using spherical coordinates and multiple integration. However, subjecting this volume to Cartesian constraints (i.e., the standard front and the altitude bands) complicates the calculation, so the volume bands are more easily estimated using Monte Carlo integration, which is a method used to calculate an unknown volume by enclosing it in a known volume and saturating the space with random points. Monte Carlo integration requires rules that determine whether the randomly drawn points are inside or outside of the unknown volume, and the proportion of points that fall within these constraints multiplied by the volume of the known space is approximately equal to the unknown volume. In Monte Carlo integration, the estimate approaches the true value as the number of random points approaches infinity.

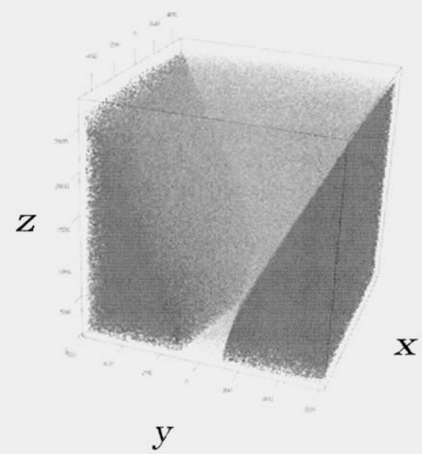


Figure 6. Graphical representation of the structural volume of the vertical scanning radar within the standard front. In this graphic, the radar unit is located at the origin and the radar beam extends to 500 m on either side of the radar unit (x-axis) up to a maximum height of 2800 m (z-axis). The y-axis 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 radar beam. Dark gray points represent the volume within the box but not included in the radar beam.

We used R software (R Core Team 2012) to describe a box of known volume that was large enough to enclose the radar beam and saturated this space with 10 million random points, and we determined two simple rules that defined whether a point was in the survey volume. The first rule was that the distance of the randomly drawn point from the origin had to be less than 2.8 km, and the second rule was that the angle between a randomly drawn point and the vertical plane (the x-z axis in Figure

6) had to be less than 12.5° (i.e., half the angle of the width of the beam). The volume of a full sweep of the radar beam, which was estimated by Monte Carlo integration, was within 5% of the analytical solution using spherical coordinates; therefore, the number of random points that we used provided a reasonable approximation of the volume. By determining the volume of a full sweep of the radar beam, we were able to further constrain the Monte Carlo integration to describe the structural volume of the radar beam within a standard front (Figure 6) and within altitude bands (Figure 7).

The number of targets per altitude band has often been reported by other researchers, although volume corrections are seldom reported. We wanted to compare our correction to the uncorrected method; however, the count data and volume data were on different scales. Therefore, we compared our density estimate to a density estimate based on the number of targets per 50-m altitude band per hour while assuming an equal amount of volume within each altitude band (the volume of each altitude band is equal to the total volume divided by the number of altitude bands). An assumption implicit to reporting the number of targets per altitude band is that comparisons among bands can be made directly (i.e., altitude bands are equal); for our comparison metric, we made this assumption explicit (see Appendix 4).

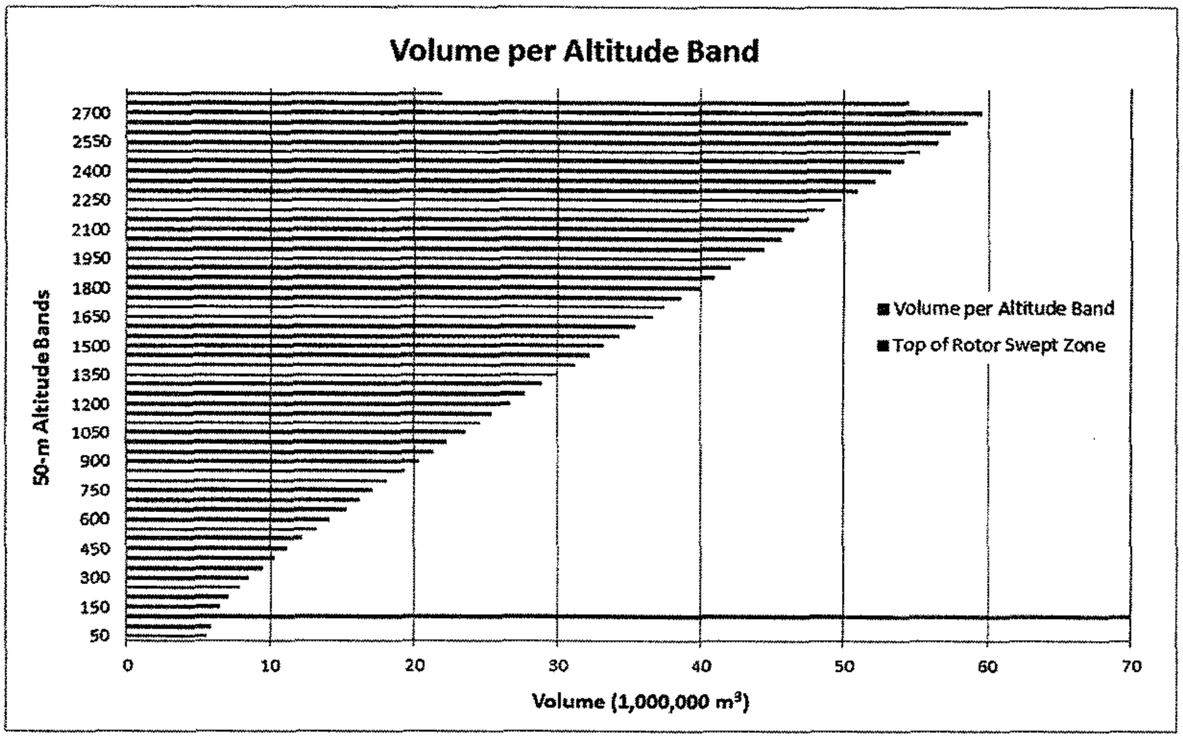


Figure 7. Volume of 50-m altitude bands within the standard front as estimated by Monte Carlo integration. Altitude band intervals represent the upper band limit, and the target counts provided by the vertical scanning radar are limited to the structure of the standard front. The red line represents the top of the rotor-swept zone at 130 m.

Results

Data collection began in the spring 2012 season on April 1 and 3 at the Ohio and Pennsylvania sites, respectively, and it ended on June 11, 2012 at both sites, which produced a survey period of 1,727 hours at the Ohio site and 1,679 hours at the Pennsylvania site (Table 2). Data were recorded continuously while the radar units were operational, although gaps in the data occurred during rain events and when the radar units were not operational due to maintenance or malfunction (radar downtime). The horizontal radar at the Ohio site malfunctioned and did not collect data from May 7 through mid-day on May 10 because of water intrusion and a corrosion issue in an electrical pin. The vertical radar at the Pennsylvania site malfunctioned from April 21 through mid-day on May 10 because of the STC filter reverting to a default setting, which resulted in a loss of target detection during this time. When correcting for radar downtime and removing the periods with rain, the vertical and horizontal radars collected usable data 92% and 99% of the season in Ohio and 66% and 98% of the season in Pennsylvania, respectively.

Table 2. Survey effort (hours) by vertical and horizontal scanning radars during spring 2012 at the radar sites in Ohio (OH) and Pennsylvania (PA).

Site	Radar	Survey Period	Radar Downtime	Time Radar Collected Data	Radar Data w/Rain	Usable Radar Data	% Usable Data
OH	VSR[1]	1727	28	1699	107	1592	92%
OH	HSR	1727	19	1708	0	1707	99%
PA	VSR[2]	1679	502	1177	76	1101	66%
PA	HSR	1679	34	1645	4	1641	98%

[1]Vertical and horizontal radars are not equally impacted by rain events or downtime.

[2]Vertical radar malfunctioned and did not collect data for approximately 3 weeks of the survey period.

Qualitative Assessments

Plots of the tracked targets showed images of nocturnal migration events at both locations (Figure 8 and 9). For example, on May 19 at the Ohio site, the horizontal radar recorded scattered activity, and the vertical radar recorded a low number of targets from 12:00 – 18:00 (Eastern Standard Time). During the 18:00 hour, directional movement began, and biologists observed that these targets were blackbirds flying west towards their nighttime roosts. During this time, the vertical radar showed low target counts because of the low altitude at which these targets flew as well as the direction and position of the radar unit, which was oriented for optimum data collection for targets moving north. During the 20:00 hour, directional movement to the north/northwest began, and vertical radar detection increased with more targets at higher altitudes. At approximately 23:00, northern movement continued, although the targets began to move northeast as well, and vertical detection continued to increase. By 04:00 on May 20, the target flight direction shifted from predominantly north/northeast to northeast/east, and the target counts began to decline on both the horizontal and vertical radars. By 05:00, the target directions shifted again, with certain scattered directional activity as well as movement towards the land from out over the water. The horizontal and vertical radars detected a continued decrease in activity, and the target height began to decrease as well. By 12:00, diurnal activity appeared to be similar to that of the proceeding day at 12:00 (Figure 8). This pattern of target movement and changes in altitude were indicative of a pulse of migratory activity.

A similar pattern of low target activity and flight heights during the day and increased directional activity and higher flight heights at night was also observed at the Pennsylvania site. Figure 9 shows targets moving north towards the shoreline at dusk (with certain western movement as well) and a shift in the direction of target movement to the northeast at approximately 23:00. By 04:00 the next morning, the target direction had shifted again, moving south to the shore and east along the lakeshore rather than north across the lake. This pattern continues until after dawn when the activity begins to return to the normal non-directional diurnal movement.

Also apparent on the Trackplots from both sites are areas that are not well recorded by the radar because of beam blockage from ground clutter (i.e., topography, vegetation, buildings, etc.) (Figure 4), thus resulting in reduced detection in the air space within the data collection range (e.g., west of the radar unit at the Ohio site and in the center and eastern areas of the Pennsylvania radar site, as observed in the horizontal Trackplots in Figures 8 and 9). Rings of decreased detection near the radar unit and where the radar switched from short to medium pulses are also evident in both the horizontal (May 19, 20:00) and vertical (May 19, 23:00) Trackplots (observed at a range of approximately 1,400 – 2,000 m).

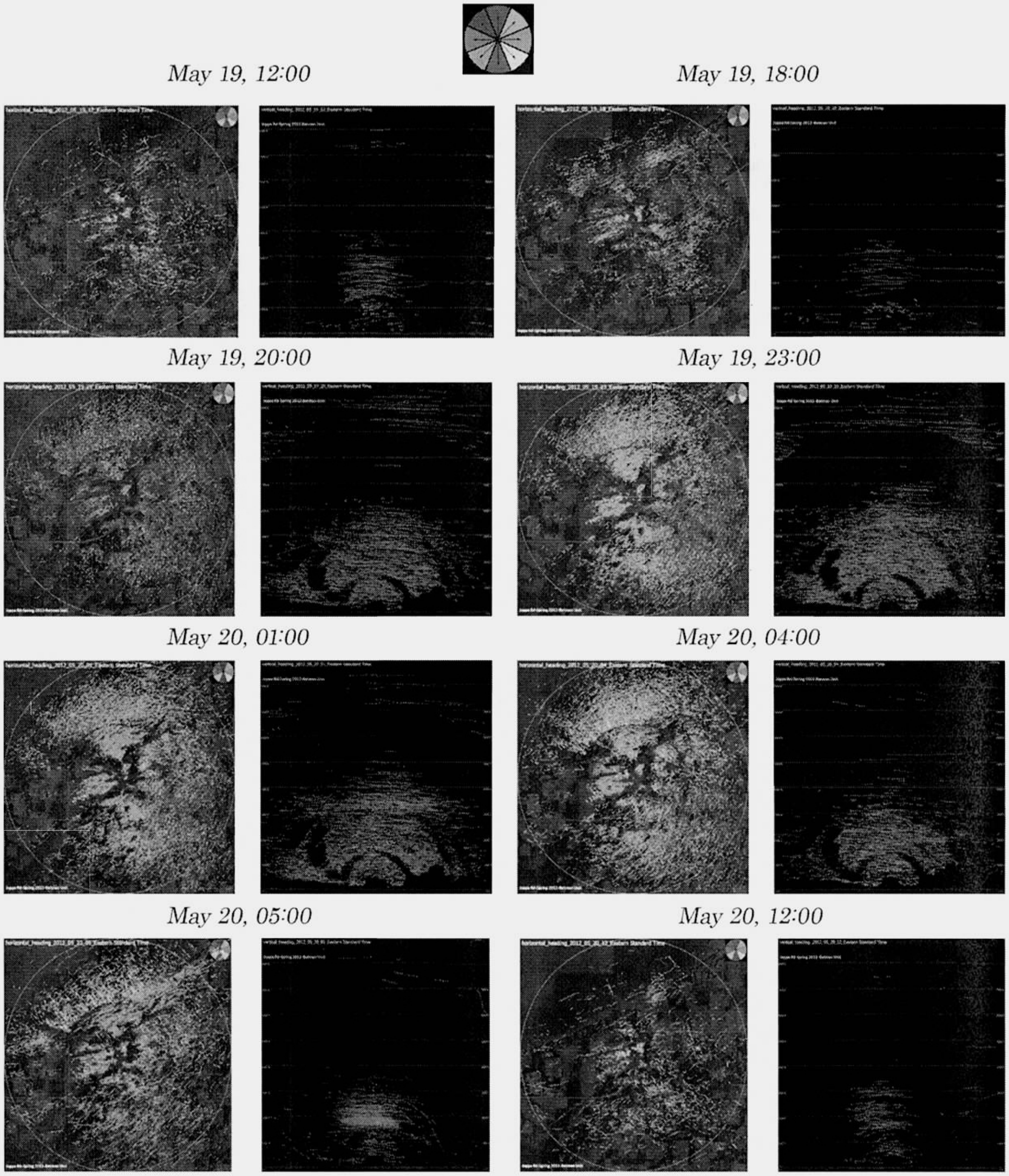


Figure 8. Images of the tracks during 1-hour increments recorded by horizontal and vertical scanning radars during a migration event at our radar site in Ohio. Horizontal radar images (columns 1 and 3) show the directions of targets as indicated by the color wheel (dark blue indicates travel to the north and red indicates travel to the south). Vertical radar images (columns 2 and 4) show the target heights.

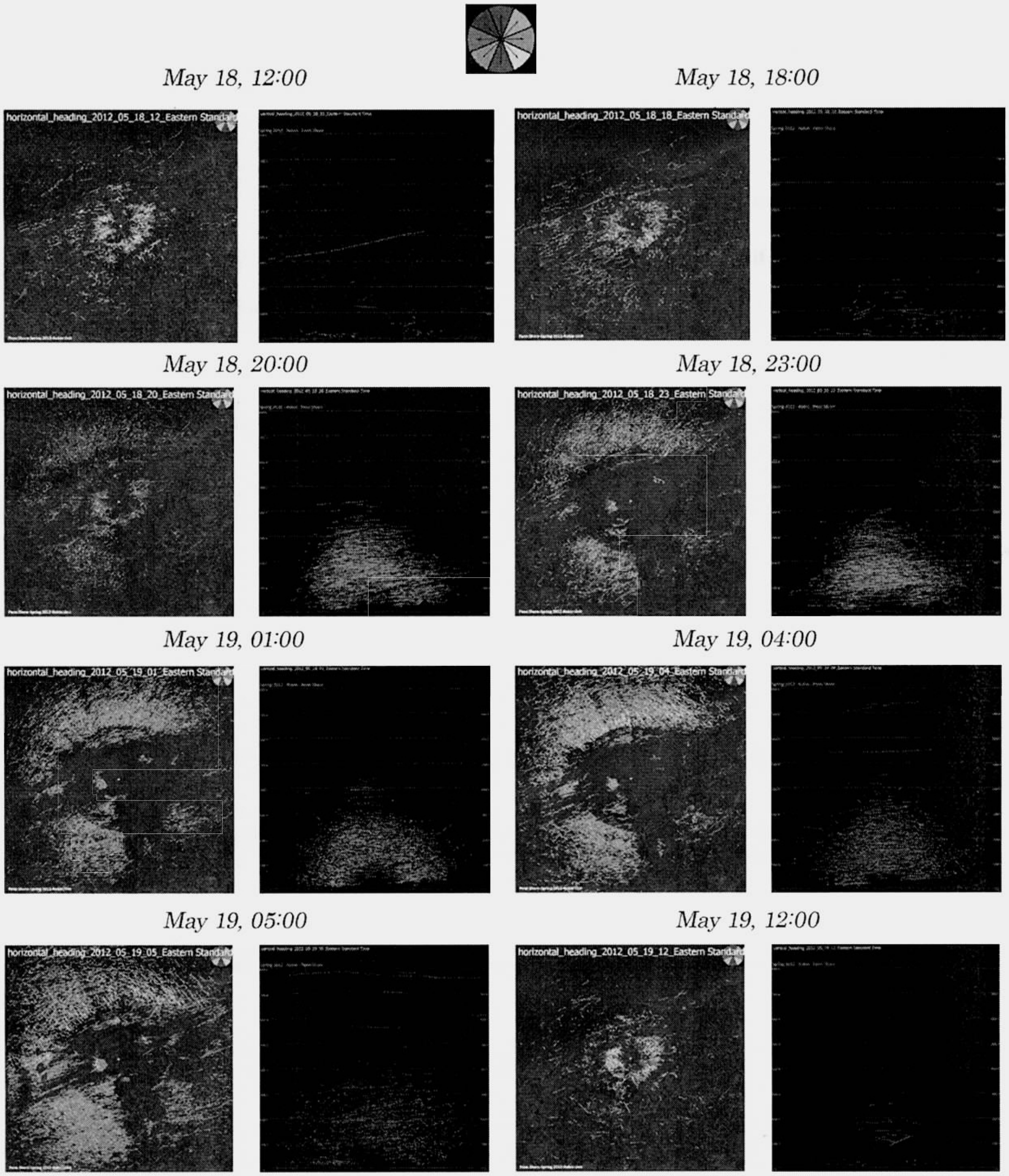


Figure 9. Images of tracks during 1-hour increments recorded by horizontal and vertical scanning radars during a migration event at our radar site in Pennsylvania. Horizontal radar images (columns 1 and 3) show the directions of targets as indicated by the color wheel (dark blue indicates travel to the north and red indicates travel to the south). Vertical radar images (columns 2 and 4) show the target heights.

Directional Trends

During the spring 2012 season, the nocturnal target direction was generally north/northeast at both of the sampled locations (Figure 10). At the Ohio site, the mean nocturnal direction was 23°, and it had an angular concentration (r) of 0.43 (n = 3,078,229 targets). In addition, on 76% of the nights, the mean target direction was between northwest and northeast (292.5° – 67.5°). The Pennsylvania site had a mean nocturnal direction of 45° (r = 0.56, n = 2,874,773) with 68% of nights presenting a mean direction between northwest and northeast. Onshore movement to the east at dawn was visible at both locations (Figure 10), and uniform directionality at night was slightly stronger at our Pennsylvania site compared with the Ohio site (Table 3).

Target Direction per Hour during Four Biological Time Periods

Ohio **Pennsylvania**

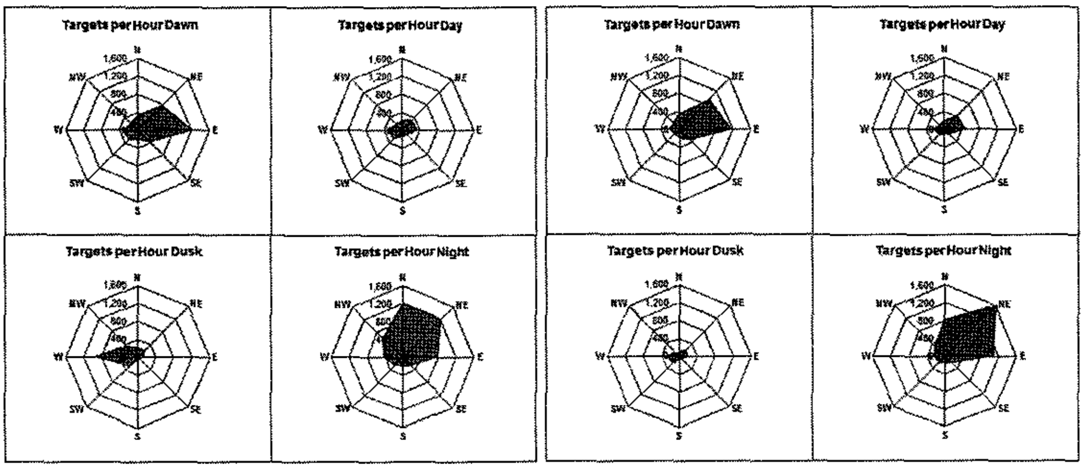


Figure 10. Target direction per hour during four biological periods in spring 2012 at our sites in Ohio (left) and Pennsylvania (right).

Table 3. Mean direction, angular concentration (r), and percent of biological time periods with strong target directionality (r ≥ 0.5) at our sites in Ohio and Pennsylvania.

	Ohio				Pennsylvania			
Biological Period	Mean Direction (degrees)	r	% Time r ≥ 0.5	n	Mean Direction (degrees)	r	% Time r ≥ 0.5	n
Dawn	75	0.39	49.2%	262,766	69	0.49	56.5%	251,484
Day	12	0.09	3.1%	1,810,464	59	0.28	21.7%	1,765,471
Dusk	287	0.52	71.2%	164,532	299	0.13	23.2%	92,224
Night	23	0.43	62.9%	3,078,229	45	0.56	66.7%	2,874,773

Temporal Trends

Time Series Plots. Hourly target counts provided by the horizontal and vertical radars showed pulses of elevated nocturnal activity at our study sites with peaks occurring a few hours before midnight. Throughout our sampling period, these events were often clustered into groups of several nights, and they were first observed on April 3 and 8 at the Ohio and Pennsylvania sites, respectively (Figures 11 and 12). At both sites, the occurrence and magnitude of nocturnal pulses decreased substantially after June 1.

Different activity patterns were apparent at our study sites as the season progresses. For example, activity patterns were dominated by nocturnal pulses, which were observed with the horizontal and vertical radars beginning in late April in Ohio. This pattern was apparent on the horizontal radar for Pennsylvania as well (the vertical radar at our unit in Pennsylvania malfunctioned at this time), and it continued until late May when the activity levels began to decrease overall.

Differences in the detection capability of the vertical and horizontal scanning radars were also apparent. As noted earlier, on May 16 at 18:00 at the Ohio site, the westward flight path of blackbirds was well captured by the horizontal radar, although the higher degree of target movement was not captured by the vertical radar because of the flight path and lower altitude of these targets (note the red arrow pointing to this time period in Figure 11). At midnight on April 30, many targets passed at high elevations above the HSR range of detection, which brought the count indices of the two antennas much closer together. The record from May 20 provides an example of targets above the study area moving in a direction and at an altitude distribution that could be detected by both radars.

Hourly Counts by Horizontal and Vertical Radars: Ohio

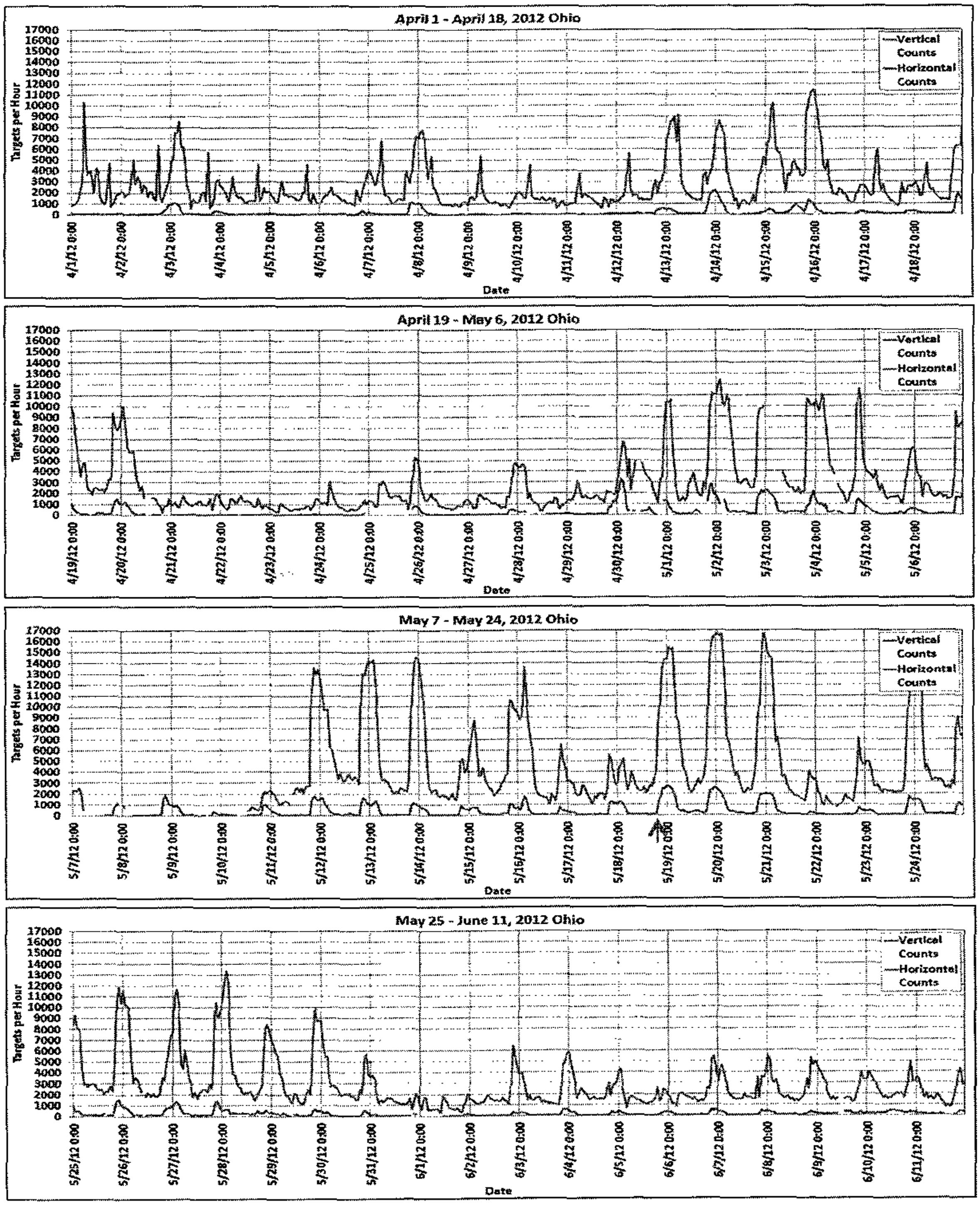


Figure 11. Hourly counts by the horizontal and vertical radars from April 1 – June 11, 2012 in Ohio. Light gray vertical lines indicate midnight.

Hourly Counts by Horizontal and Vertical Radars: Pennsylvania

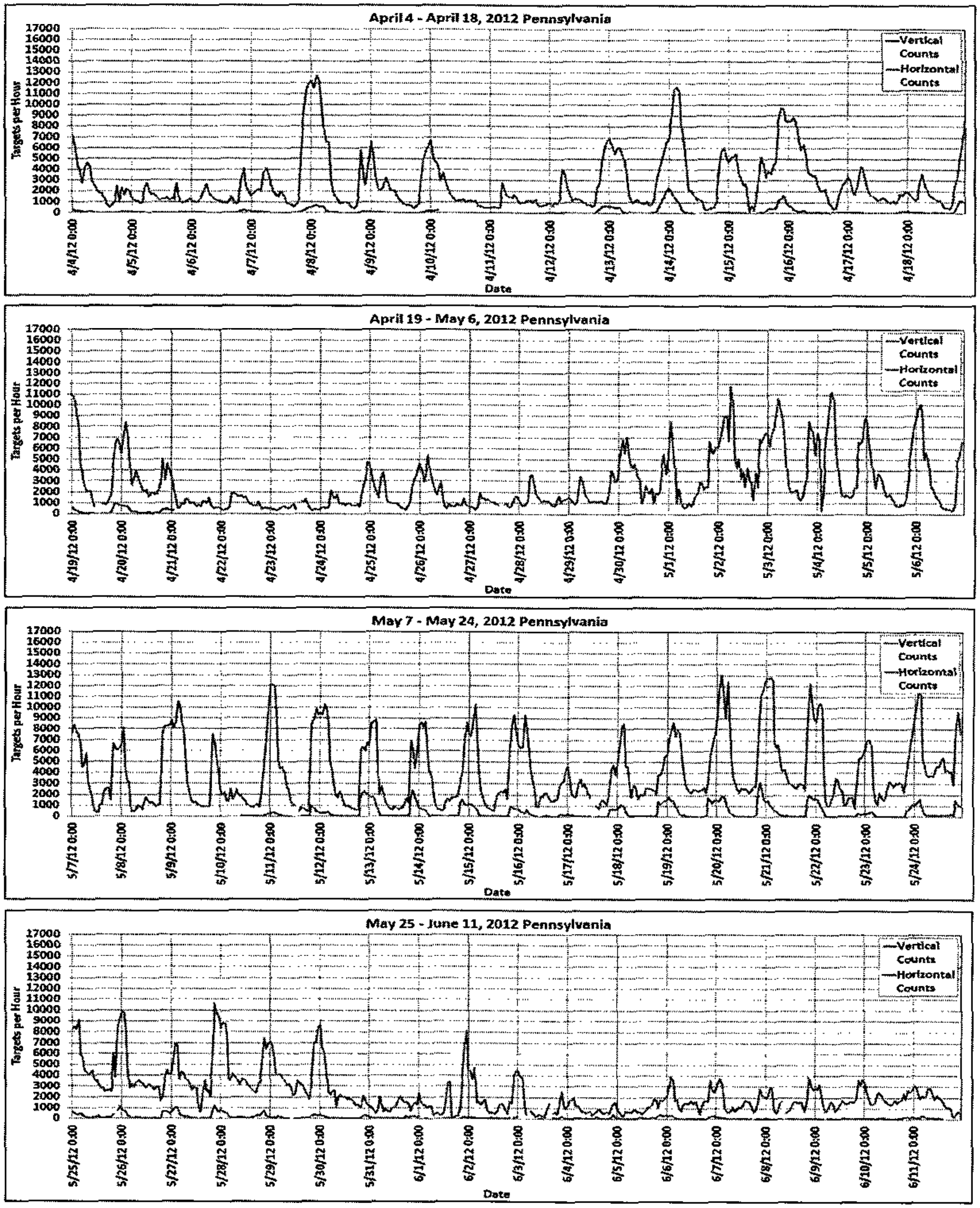


Figure 12. Hourly counts by the horizontal and vertical radars from April 4 – June 11, 2012 in Pennsylvania. Light gray vertical lines indicate midnight, and the gap in the vertical data from April 21 - May 11 was because of a radar software malfunction.

Target Passage Rate. The pattern of mean TPR among the four biological time periods was similar between the two study sites (Figure 13), and the mean TPR at night was greater than the combined means of the other three biological time periods (Table 4). The mean nocturnal TPR was 640 ± 601 SD (n = 68 nights) and 514 ± 518 SD (n = 49 nights) at the Ohio and Pennsylvania sites, respectively. The mean TPR varied by hour and presented peak numbers between 21:00 and 22:00 hours (approximately dusk through an hour after sunset) at both sites. At both locations, the mean TPR gradually decreased as the night progressed, with the most drastic decline occurring from approximately 04:00 to 05:00, which corresponded to dawn (Figure 14).

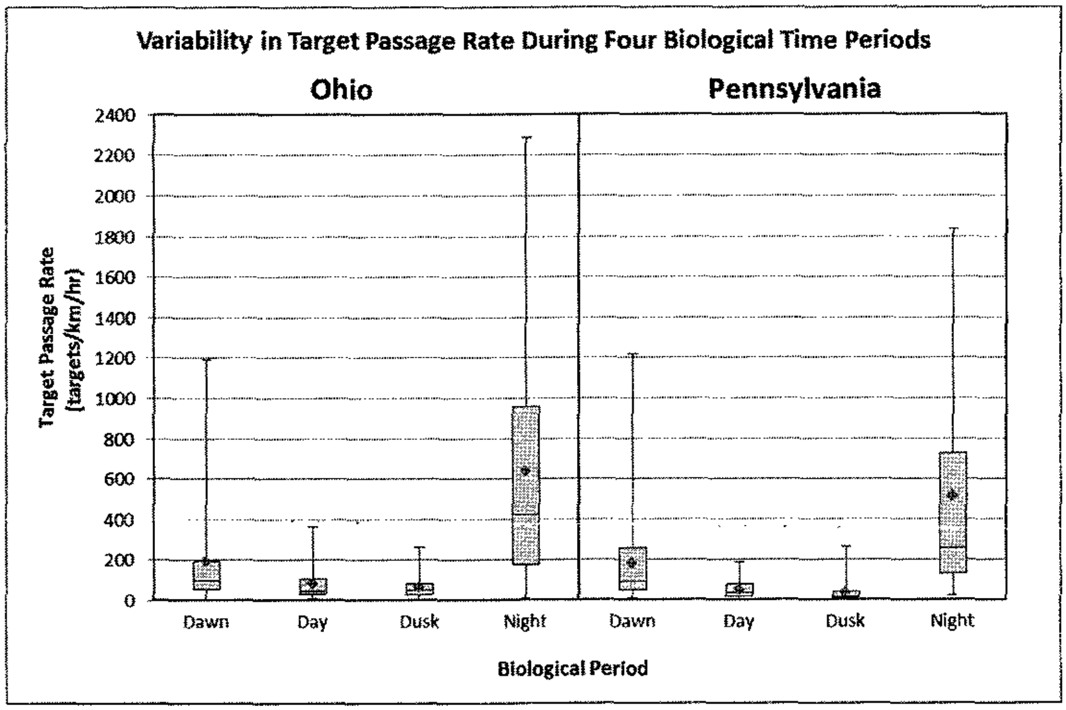


Figure 13. Box plots showing the variability in target passage rate (targets/km/hour) during the four biological periods in spring 2012 in Ohio and Pennsylvania. Whiskers represent the 1st and 4th quartiles; boxes represent the 2nd and 3rd quartiles (with the line between indicating the median); and blue diamonds represent the seasonal mean for the time period.

Table 4. Mean target passage rate (TPR) with standard deviations during the four biological periods in Ohio and Pennsylvania in Spring 2012.

Biological Period	Ohio Mean TPR	Pennsylvania Mean TPR
Dawn	192 ± 244	183 ± 223
Day	83 ± 83	52 ± 43
Dusk	66 ± 56	37 ± 55
Night	640 ± 601	513 ± 518

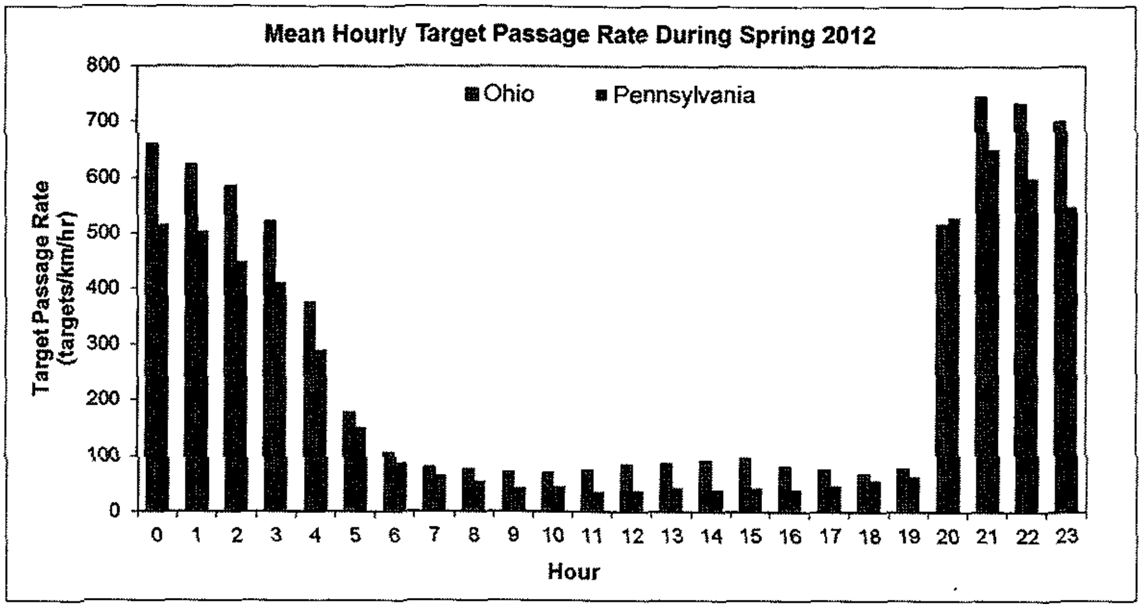


Figure 14. Mean hourly target passage rate (targets/km/hour) in spring 2012 at sites in Ohio and Pennsylvania.

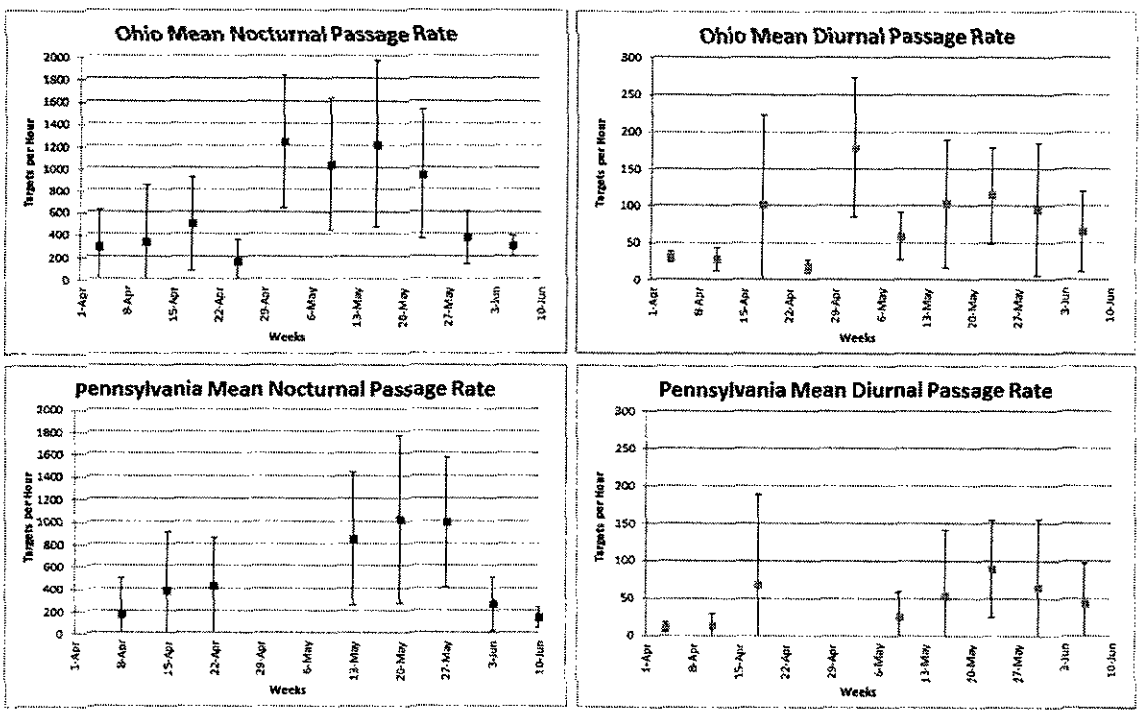


Figure 15. . Weekly mean nocturnal and diurnal target passage rates (targets/km/hour) in Ohio (top row) and Pennsylvania (bottom row) from April 1 – June 10, 2012. Error bars represent one standard deviation. Note the different scales on the nocturnal and diurnal plots.

Weekly Mean of Target Passage Rates. At both sites, the weekly mean nocturnal target passage rates were relatively high compared with the diurnal target passage rates, and both sites showed a general increase in the means throughout the season. In mid-to-late May, the mean nocturnal TPRs began to decrease (Figure 15), and the lower TPR during the last week of April was likely due to a change in weather conditions bringing lower temperatures and a mix of sleet and snow. This shift in weather likely resulted in fewer migrants moving through the area during this time period in Ohio. The weekly mean nocturnal TPR was consistently higher than the weekly mean diurnal TPR (Figures 15), and as the migration season subsided, less of a difference was observed between the nocturnal and diurnal target passage rates (Figures 15 and 16). Trends in both the nocturnal and diurnal TPRs (7-day moving means) were similar at both sites (Figure 17).

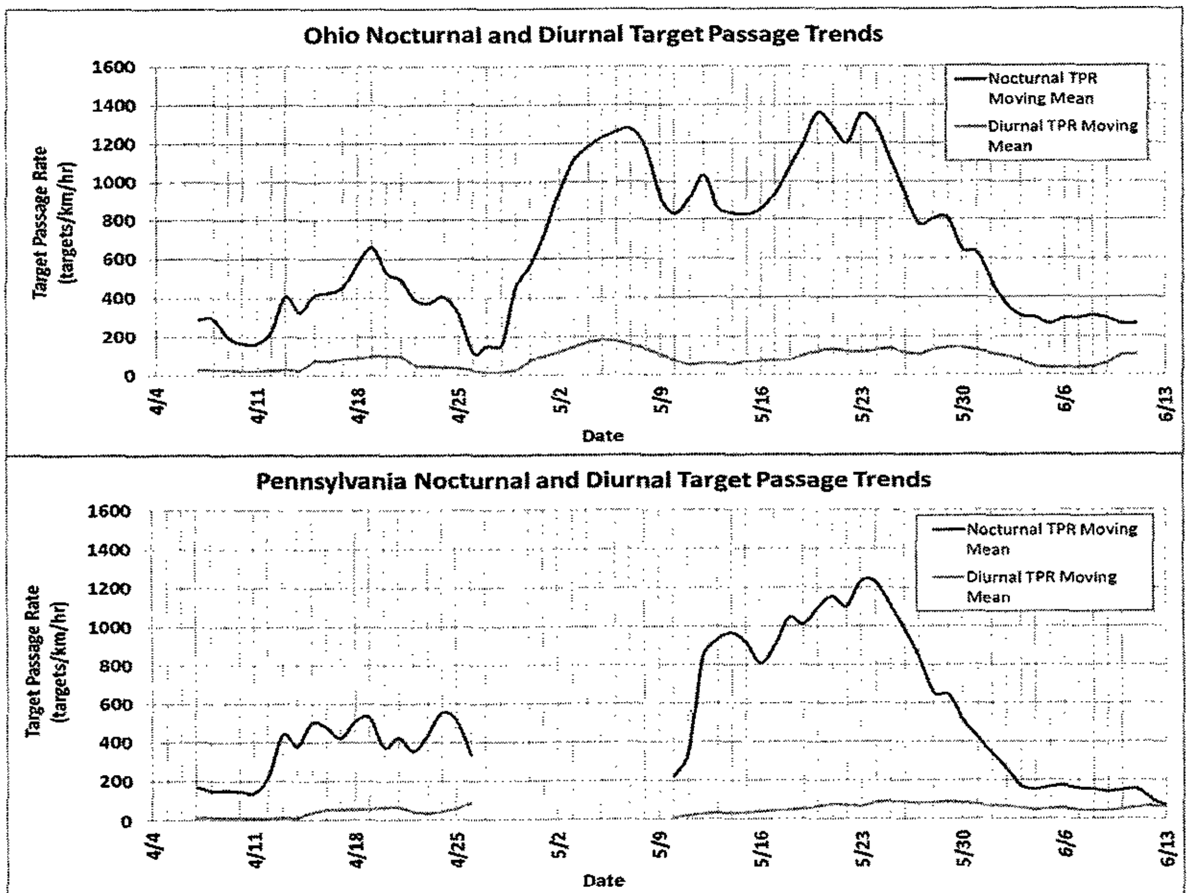


Figure 16. Comparison of the nocturnal and diurnal target passage trends (based on a 7-day moving mean) in spring 2012 in Ohio (top row) and Pennsylvania (bottom row).

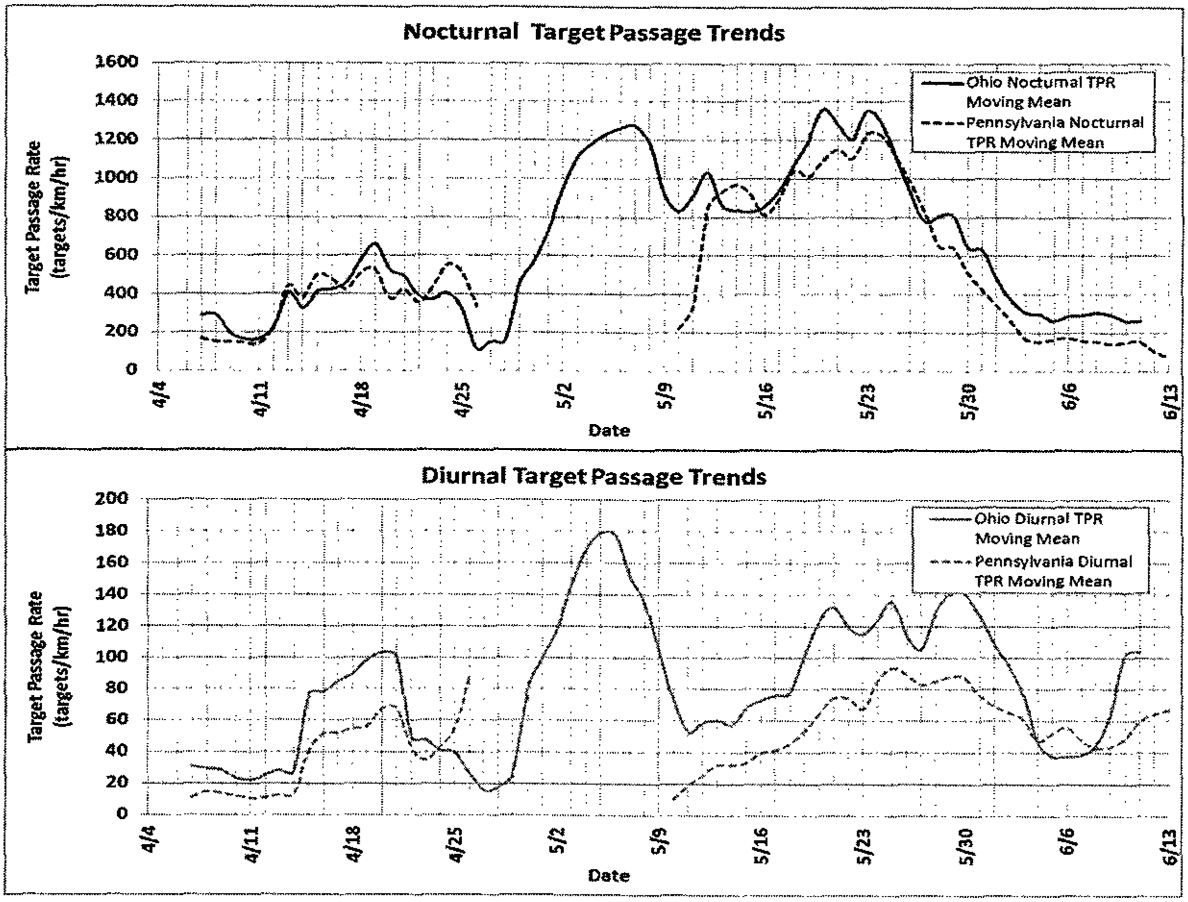


Figure 17 Comparison of the nocturnal (top row) and diurnal (bottom row) target passage trends (based on a 7-day moving mean) in spring 2012 in Ohio and Pennsylvania.

Altitudinal Trends

Our density estimate accounted for the geometric shape of the sampled space and were substantially different than the density estimate that assumed an equal amount of sample volume per altitude band. The dawn and dusk altitude profiles differed between our two locations, and the low elevation density was greater at our Ohio site (Figures 18 and 19). The hourly altitude profiles revealed considerable variation in the use of altitude bands at night (Figures 20 and 21); however, over the course of the season, the 50 – 100 m and 100 – 150 m altitude bands were the most densely used at the Ohio and Pennsylvania sites (Figure 22), which presented a total of 5.83 targets per 1,000,000 m^3 per night hour and 5.44 targets per 1,000,000 m^3 per night hour, respectively. The maximum target density was below 150 m for 75.0% and 68.0% of the nights at the Ohio and Pennsylvania sites, respectively (Figure 23). A similar pattern (although with more variation) occurred when the hours from 20:00 – 04:00 were considered individually and the maximum target density that occurred below 150 m during 64.9% and 64.7% of these night hours at the Ohio and Pennsylvania sites, respectively (Figure 24).

At both sites, targets were observed within the entire range of the sampled altitude bands. The mean altitude of nocturnal targets was 587 m ± 424 m SD and 447 m ± 296 m SD above the ground at our Ohio and Pennsylvania sites, respectively, and the median altitude at night was 522 m and 405 m, respectively. The median altitude was greatest during the night and dawn biological time periods. Although many radar reports include estimates of the mean and median target altitudes, we found that these estimates were poor indicators of maximum density (Table 5) because of differences in the volume of air space sampled at various altitude bands. Figures 25 and 26 are based on target density and show the variation in flight altitudes used by birds and bats that were counted by our vertical scanning radars throughout our survey period (April 1 – June 11, 2012 at the Ohio site and April 4 – June 11, 2012 at the Pennsylvania site).

These graphics show the altitude bands of 0 – 1,300 m where most targets were counted (targets were counted up to 2,750 m, which is the extent of our sampling range). These graphics show that night hours at both sites had the highest density of flight activity and that the range of flight altitudes increased during the night hours. The graphics also show that many targets flew well within a 30 – 130 m RSZ and that the mean and median altitudes do not reflect peak density altitudes, demonstrating how these values can misrepresent flight risk.

The mean altitude per hour during the season showed a similar pattern at the two locations (Figure 27), with the mean altitude increasing after dusk, tapering from 21:00 to 22:00 hours, and decreasing after midnight. A spike in the mean altitude occurred at approximately 04:00 in Ohio and during 04:00 and 05:00 in Pennsylvania, and these time periods occurred during or near dawn in at least a portion of the survey period.

Table 5. Comparison of the mean altitude (m) with the standard deviation, median altitude, and altitude band (50-m bands) that contained the maximum target density during the four biological periods at our sites in Ohio and Pennsylvania in spring 2012. Max Band Density represents the top of the altitude band.

	Ohio			Pennsylvania		
Biological Period	Mean	Median	Max Band Density	Mean	Median	Max Band Density
Dawn	529 ± 393	499	100	479 ± 310	453	100
Day	420 ± 345	337	100	368 ± 302	339	100
Dusk	385 ± 468	233	100	465 ± 467	370	100
Night	587 ± 424	522	100	447 ± 296	405	150

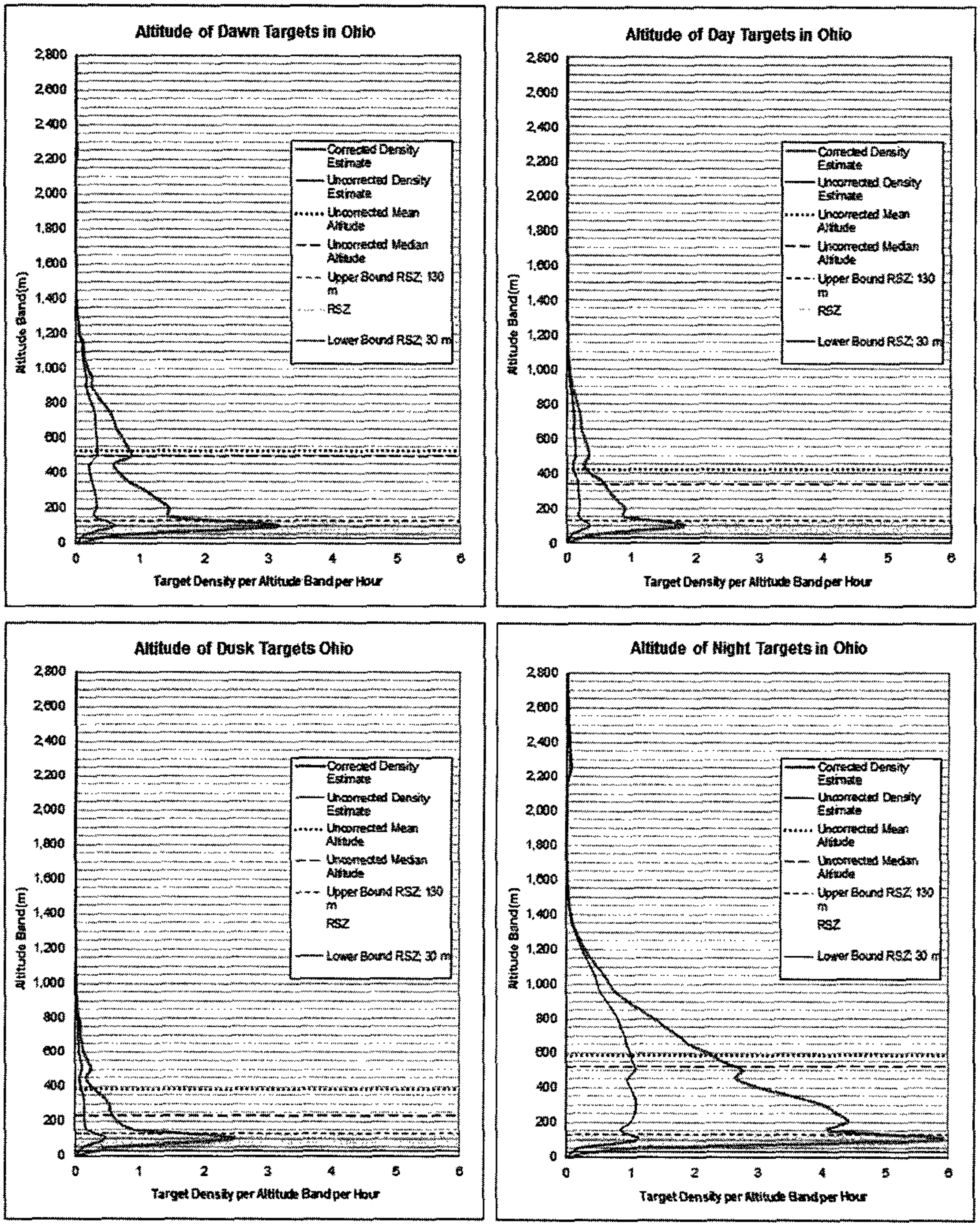


Figure 18. Altitude profile of the targets at our site in Ohio. Corrected lines depict the target density (targets/1,000,000 m^3) per 50-m altitude band per hour after adjusting for the structure of the sample volume. Uncorrected lines depict the target density per 50-m altitude band per hour with an assumed uniform volume distribution (volume of each band is equal to the total volume divided by the number of bands). The red band represents the rotor-swept zone (RSZ) between 30 – 130 m, and the y-axis labels indicate the top of the altitude band.

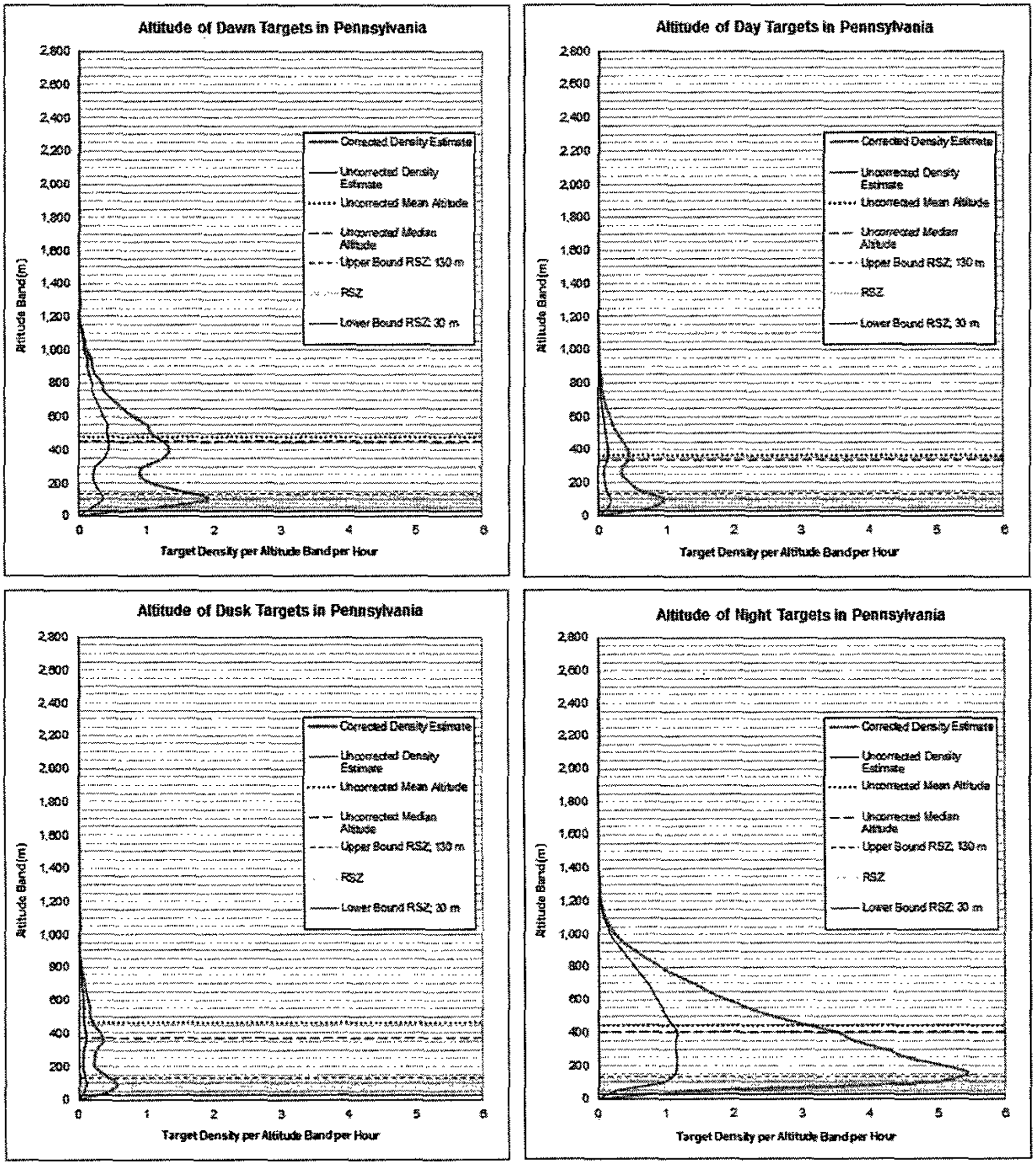


Figure 19. Altitude profile of the targets at our site in Pennsylvania. Corrected lines depict the target density (targets/1,000,000 m^3) per 50-m per hour altitude band after adjusting for the structure of the sample volume. Uncorrected lines depict the target density per 50-m altitude band per hour with an assumed uniform volume distribution (volume of each band is equal to the total volume divided by the number of bands). The red band represents the rotor-swept zone (RSZ) between 30 – 130 m, and the y-axis labels represent the top of the altitude band.

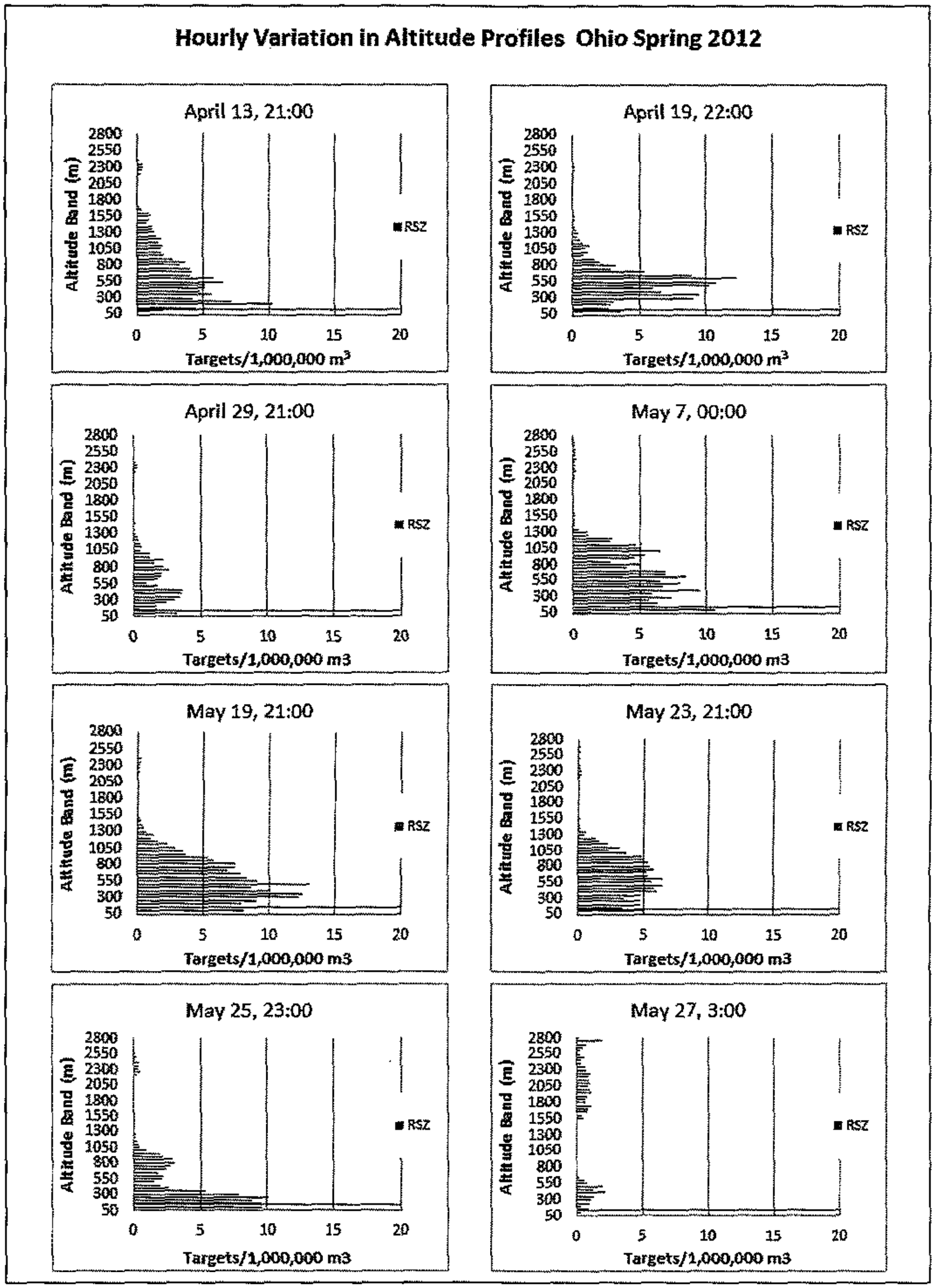


Figure 20. Sample of the hourly altitude profiles corrected for the shape of the sample volume at our site in Ohio in spring 2012. Hours were selected to portray the variability in density per altitude band of the passing targets. The x-axis represents the target density; the red line represents the top of the rotor-swept zone at 130 m; and the y-axis labels represent the top of the altitude band.

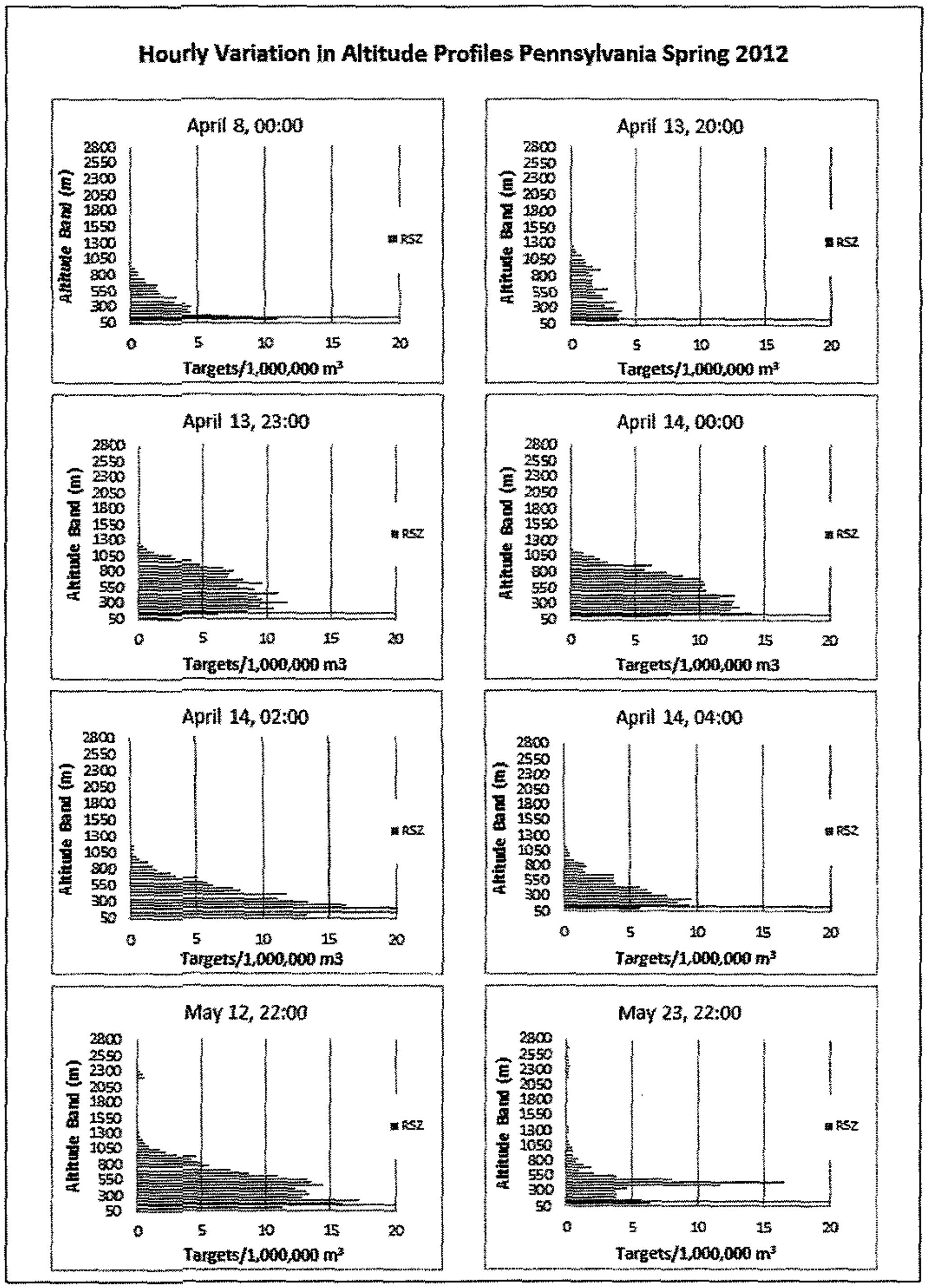


Figure 21. Sample of the hourly altitude profiles corrected for the shape of the sample volume at our site in Pennsylvania *in spring 2012. Hours were selected to portray the variability in density per altitude band of* the passing targets. The x-axis represents the target density; the red line represents the top of the rotor-swept zone at *130* m; and the y-axis labels represent the top of the altitude band.

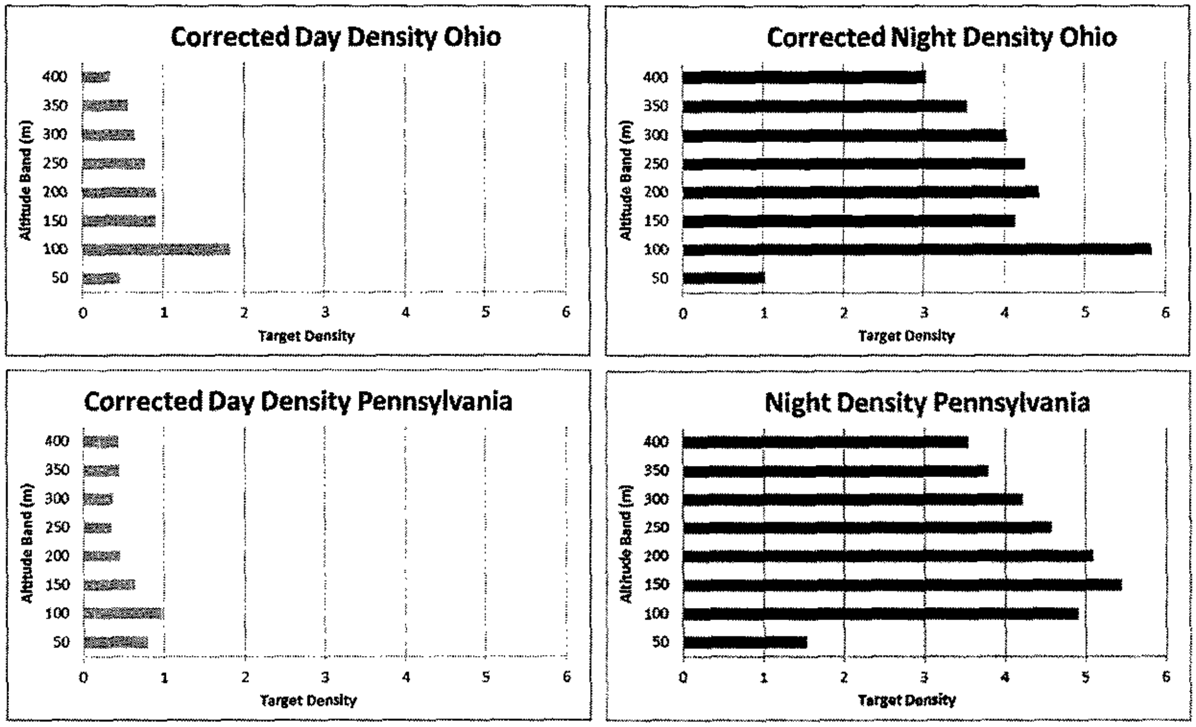


Figure 22. Altitude profile of the corrected target density below 400 m in Ohio and Pennsylvania. The x-axis represents the target density (targets/1,000,000 m^3) per 50-m altitude band, and the y-axis labels represent the top of the altitude band.

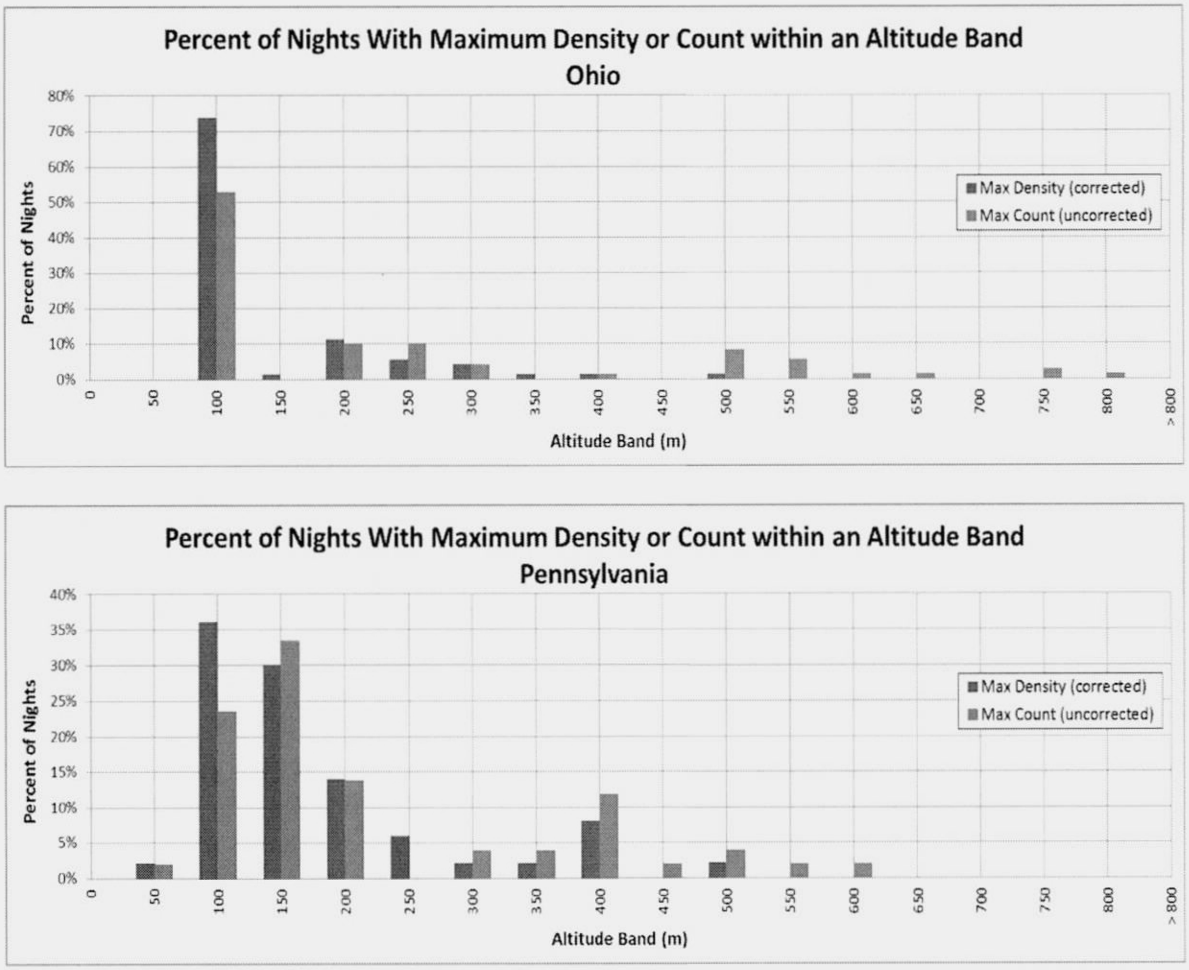


Figure 23 Percent of nights when the maximum density (targets/1,000,000 m^3/ altitude band) or count (targets/altitude band) occurred within a given 50-m altitude band in Ohio and Pennsylvania in spring 2012. X-axis labels represent the top of the altitude band.

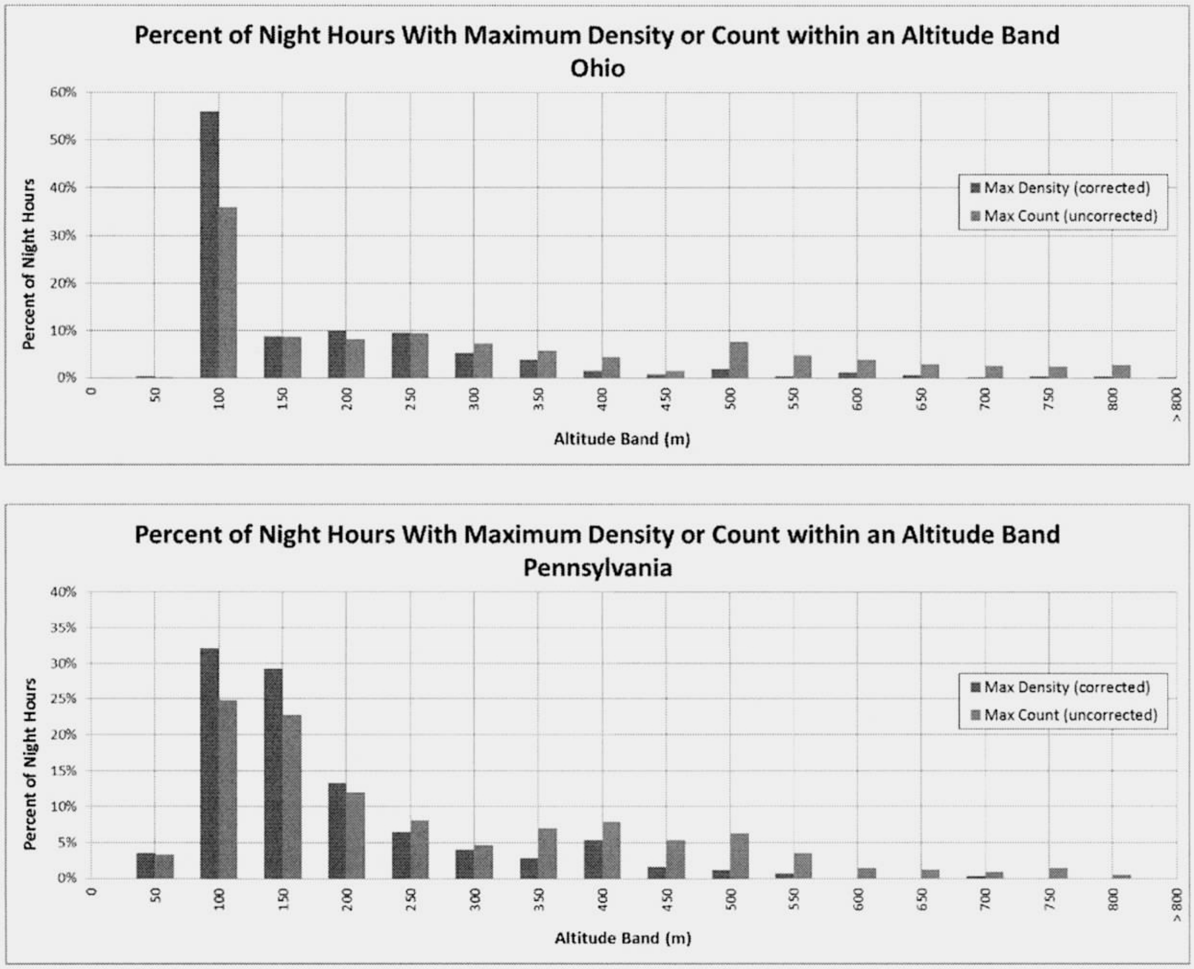


Figure 24. Percent of night hours (20:00 – 04:00) when the maximum density (targets/1,000,000 m^3/ altitude band) or count (targets/altitude band) occurred within a given 50-m altitude band in Ohio and Pennsylvania in spring 2012. X-axis labels represent the top of the altitude band.

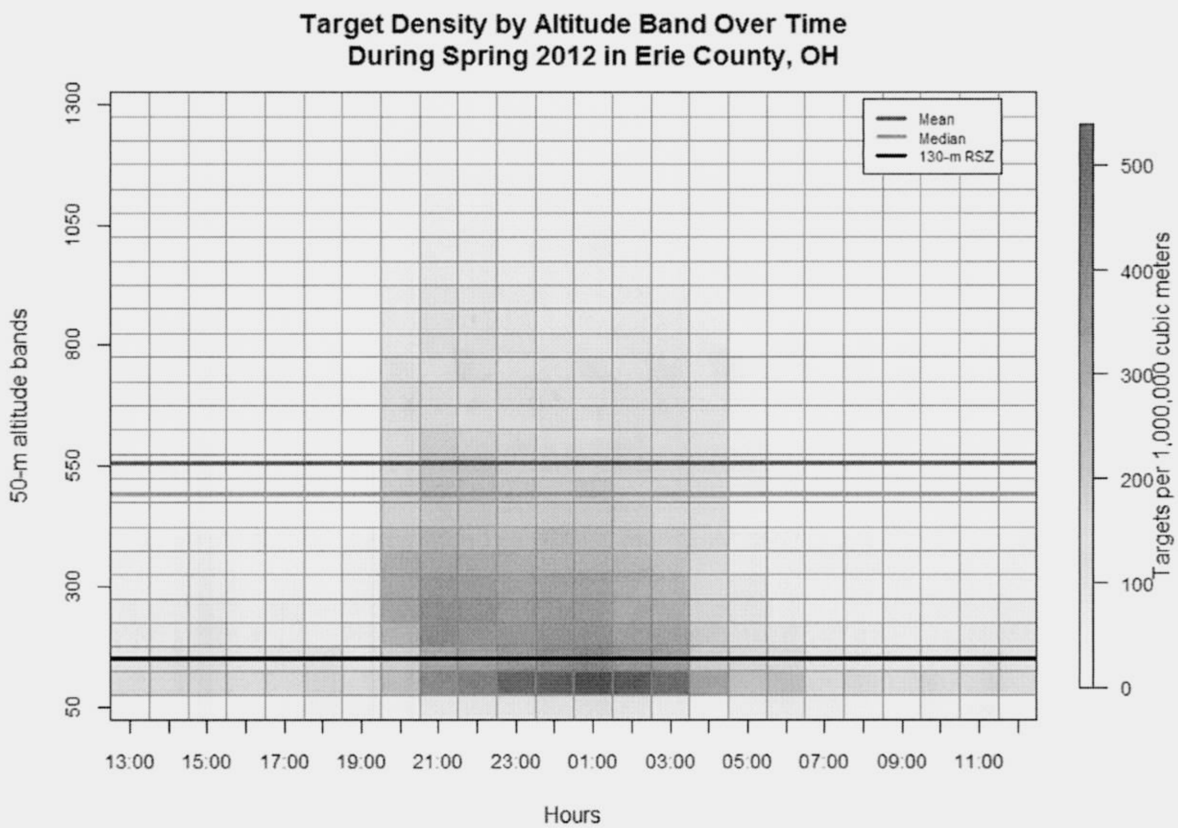


Figure 25. Variation in flight altitudes based on target density (targets per million cubic m) at our site in Erie County, Ohio throughout the spring study period. Altitude bands are in meters and labels represent the max value of each altitude band. Density of targets is in targets per million cubic meters. Colors shown in each rectangle indicate the relative density observed for that altitude (key shown on the right) and time. The dark blue and light blue lines represent the nocturnal mean and median target heights, respectively. The black line at 130 m represents the max height of a turbine with a RSZ of 30 – 130 m. Note the difference in density scale used in Figure 26.

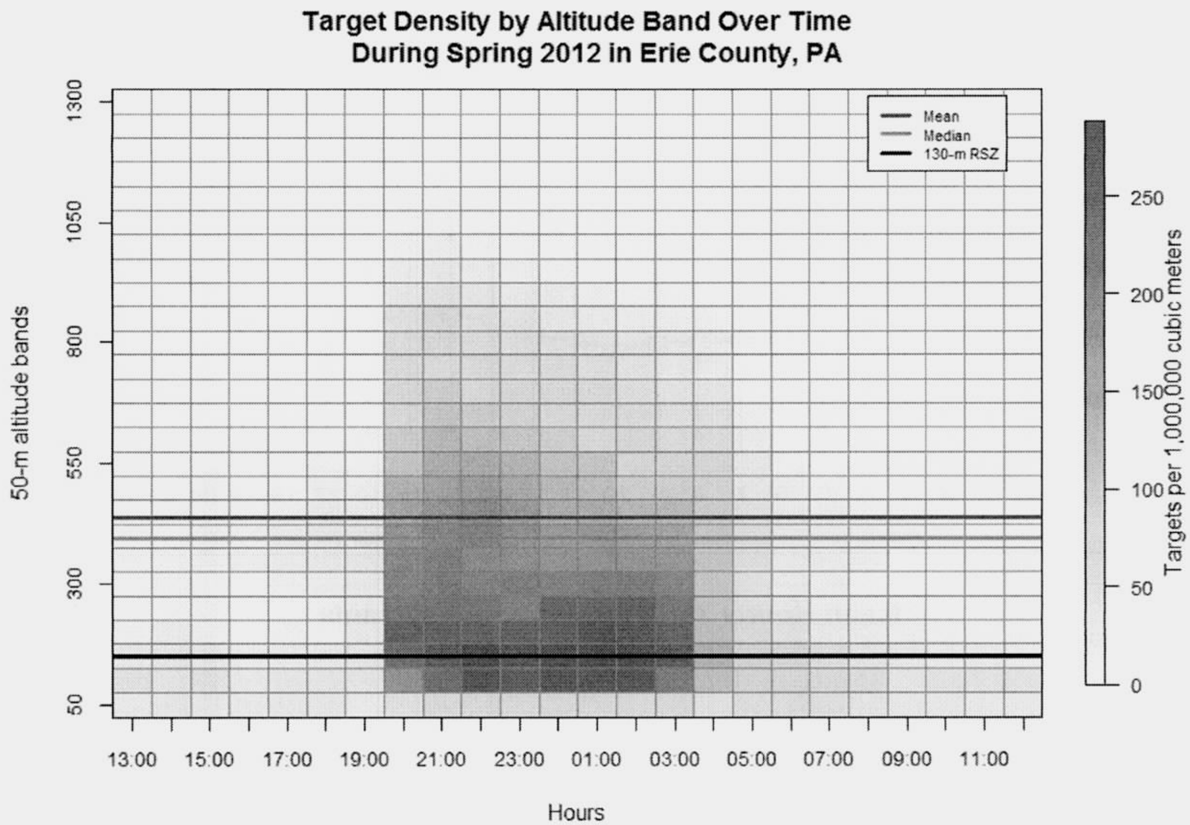
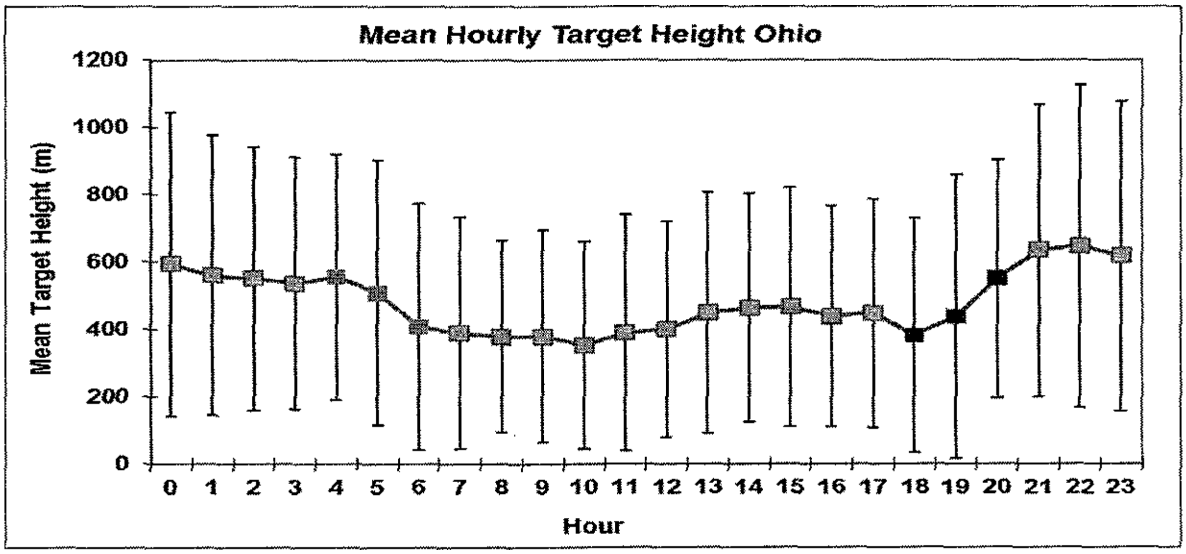


Figure 26. Variation in flight altitudes based on target density (targets per million cubic m) at our site in Erie County, Pennsylvania throughout the spring study period. Altitude bands are in meters and labels represent the max value of each altitude band. Density of targets is in targets per million cubic meters. Colors shown in each rectangle indicate the relative density observed for that altitude (key shown on the right) and time. The dark blue and light blue lines represent the nocturnal mean and median target heights, respectively. The black line at 130 m represents the max height of a turbine with a RSZ of 30 – 130 m. Note the difference in density scale used in Figure 25



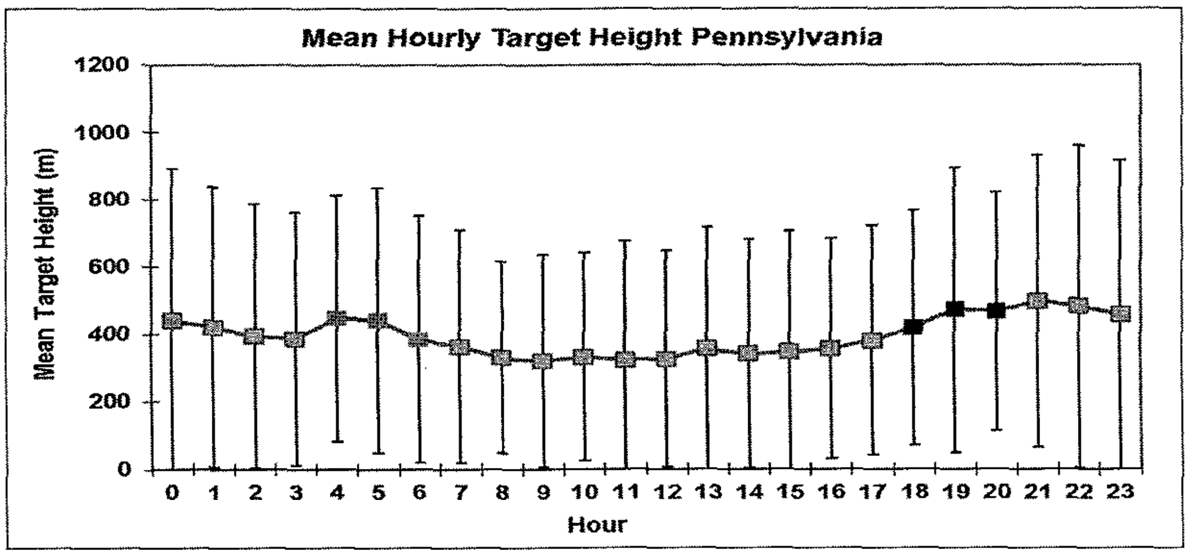


Figure 27. Mean hourly target heights (m) in spring 2012 in Ohio and Pennsylvania. Orange and blue markers indicate the hours in which sunrise and sunset occurred during the season, respectively. Error bars represent one standard deviation.

Discussion

We undertook this study to document migration along the shorelines of the Great Lakes. We found that migration movements were common along the southern shoreline of Lake Erie, where we established our study sites, and we believe that the data collected at these two sites are representative of migration along the rest of the Lake Erie shoreline. Our research contributes to a growing body of literature documenting various aspects of migration and identifies the Great Lakes shorelines as areas important for the conservation of migratory species. Our data further provide unique observations on the magnitude and timing of nocturnal migration that could not be observed without the aid of radar technology.

Sampling Regime

The sampling regime is an important consideration for migration studies because migratory movements are partially guided by environmental conditions and occur in pulses throughout the migratory season (Alerstam 1990). Our continuous sampling scheme captured the timing of migration events and provided a more complete picture of the migratory season than a systematic (once per week) or random sampling scheme, which could have missed pulses of activity (Figure 26). We used diurnal radar observations to provide a baseline to evaluate nocturnal activity, and including this time period in the sampling scheme helped to distinguish the magnitude of the migration events (Figure 16). Our sampling regime was also useful in indicating when the nocturnal migration season for passerines and bats declined in late May, although our April start date may not have included the onset of migration at our study sites. With additional data collection, we will be able to better describe the migration season and its variations according to location and year, and this information will help tailor conservation efforts, such as turbine curtailment, to time frames when they will be most effective.

Site Comparison Considerations

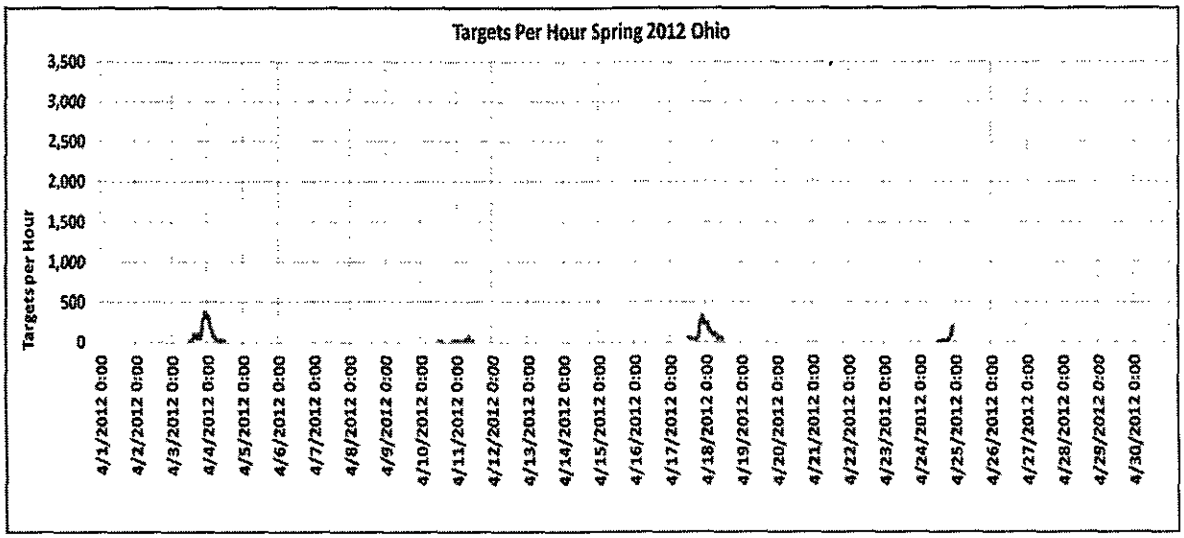
Target counts provided by radar are influenced by the radar type and calibration, filtering of non-intended targets, count algorithms, frequency band, antenna orientation, sampling scheme, and detection probability and sample volume variations (Bruderer 1997, Harmata et al. 1999, Schmaljohann et al. 2008). Even when the same equipment and methodology are used among sites or studies, comparisons should be made cautiously if the probability of detection and sampling volume are ignored (Schmaljohann et al. 2008). Recognizing that our counts represent an index of target passage that is site specific, we are cautious in performing comparisons among other sites or studies. Therefore, rather than relying solely on the magnitude of target passage as an indication of migration, we have assessed the activity patterns among sites to compare the relative strength of migration. For example, a site with a nocturnal passage rate that shows peaks that are multiple times larger than the lulls for the majority of the sampling period would likely experience a greater degree of migration than a site with less of a discrepancy or a site that had a nocturnal passage rate that only occasionally spiked above the baseline value of nocturnal passage rates.

Migration Patterns

The recorded patterns of movement were consistent with other migration observations (Newton 2008) and indicated that nocturnal migratory flights occurred regularly in spring 2012 at both of our surveyed locations. This nocturnal activity was typically oriented in a north/northeast direction (Figure 10) and occurred in seasonal pulses that were captured by the horizontal and vertical radars (Figures 11 and 12). We also observed targets flying over water return to shorelines near dawn, and the target passage rate (mean for the season) was greatest during the nocturnal biological time period at both locations (Table 4, Figure 13). These patterns match with what we have observed at all other sites surveyed around the Great Lakes (Bowden et al. 2015). The mean hourly heights exhibited a pattern previously associated with migration (Harmata et al. 2000, Mabee and Cooper 2004), with heights increasing near dusk, peaking several hours before midnight, and beginning to decrease prior to dawn. The slight increase in mean height near dawn at the Pennsylvania site (Figure 25) was consistent with the migratory behavior described as dawn ascent (Myres 1964, Diehl et al. 2003), which is attributed to migrants that fly at higher altitudes to gain a broader view of the surrounding landscape before selecting a stopover habitat or returning to the shoreline if flying over water. Taken together, we attribute these nocturnal observations to migrants and suggest that the studied shorelines are important for their conservation.

At both of our sample locations, nocturnal targets appeared to move across the landscape in waves, with peaks near April 19 and May 20 at both sites (Figure 17) and an additional peak observed at the Ohio site near May 7. The vertical radar in Pennsylvania was malfunctioning during this time period; however, the data collected on the horizontal radar (Figure 12) indicated that a peak likely occurred during this time as well. These fluctuations may be related to broad-scale weather fronts, variations in temporal patterns among guilds of migrants, or a combination of these and other factors (Newton 2009). The trends at locations of similar latitude but on opposite ends of Lake Erie revealed broad-scale influences and indicated that further investigation into their causes would allow for the prediction of heavy migration events.

The weekly mean nocturnal TPR estimates were consistently higher than the weekly mean diurnal TPR estimates throughout the data collection period (Figures 15 and 16); however, the difference decreased by early June. This shift from time periods with significantly higher nocturnal activity to time periods with diminished nocturnal activity indicates that migration substantially contributed to the aeroecology above our study areas.



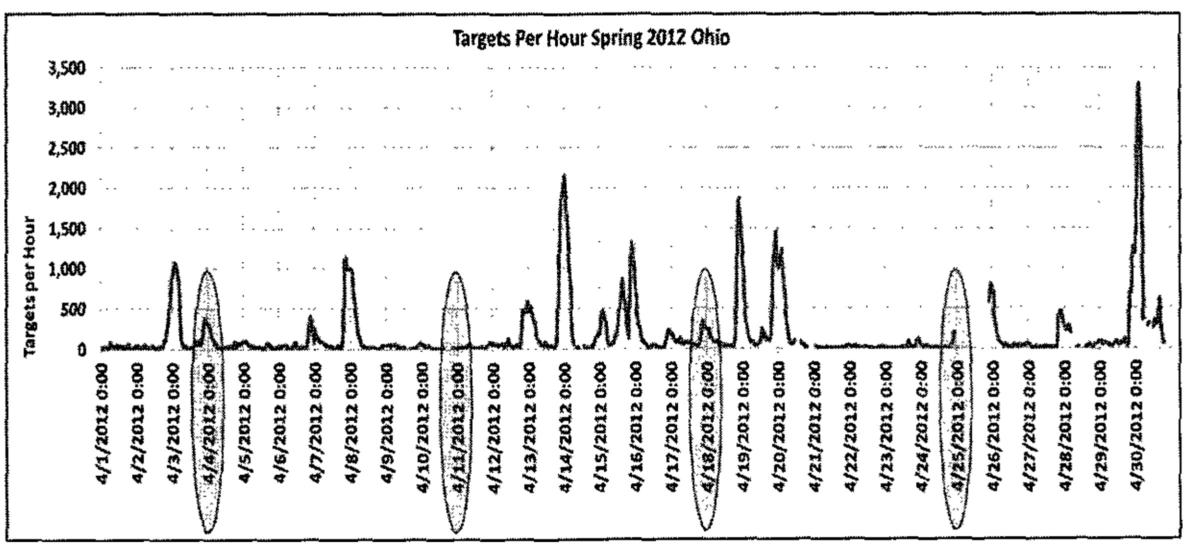


Figure 28. Example of a hypothetical sampling schedule in which data are collected once per week (top graphic) versus the actual continuous sampling schedule (bottom graphic). Red lines represent the number of targets counted per hour by the vertical scanning radar from April 1 – April 30, 2012 in Erie County, Ohio.

Flight Altitude

The altitude profiles indicated that most of the nocturnal targets passed below 800 m with peak densities in the 50 – 150 m altitude bands (Figures 18, 19 and 22). We corrected for the approximate shape of the survey volume and included this correction in our density estimates, although this correction is based on the manufacturer's estimate of beam geometry, which may not be precise. Furthermore, beam propagation was not consistent over time because it was affected by side lobes, target size and distance, and atmospheric conditions. Nevertheless, we believe that the correction was an improvement over the altitude profiles that ignored 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), and our vertical scanning radars lost detection at a range of approximately 1,400 – 2,000 m, which was where the radar transitioned from the short to medium pulse. For these reasons, our estimates likely under-represented the density as altitude increases. However, the densities per altitude band were already decreasing (Figure 18) before the 1,400 m band, and any undercount would be unlikely to change the overall picture.

The reported altitude profiles varied considerably among the nighttime hours at our sites in Ohio and Pennsylvania (Figures 20 and 21). Migrants adjusted their flight altitude according to the wind direction and speed, visibility, time, and the landscape below the flight trajectory (Alerstam 1990, Hueppop et al. 2006, Liechti 2006). For example, headwinds aloft have resulted in migrants moving *en masse* to lower altitudes that present reduced wind speeds (Gauthreaux 1991). In addition, migrants typically returned to land at least twice during every 24-hour period; therefore, changes in flight altitude occurred at various times over the course of the night and were associated with targets ascending from and descending to stopover sites. Depending on the location, these altitude changes may place migrants at risk of collision with wind turbines and other tall human-made structures.

Radar Study and Management Considerations

Although 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 of radar used to track the movements of birds and bats (Larkin 2005), and its use in risk assessments will likely increase with wind energy development. Despite this growing trend, standardized equipment and methodologies for establishing radar settings, ground-truthing biological targets, and data processing have not been adopted, although such considerations would substantially improve the quality of the data. Standardization presents an enormous challenge; however, without it, comparisons among studies may be more reflective of changes in equipment, methodology, and site conditions rather than differences in migratory activity among sites.

Additionally, the metrics reported in radar surveys can be misleading to anyone unfamiliar with avian radar. For example, the mean altitude of target passage is often reported to be above the rotor-swept zone and has been interpreted to indicate 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 zone because of the long range over which radars collect altitude data, which was up to 3 km above the ground in our study; thus, high flying targets can inflate the mean altitude. This bias was apparent in our data and can be observed by comparing the mean altitude of nocturnal targets to the most densely populated altitude band (Figures 18, 19, 25, 26, and Table 5). It is also 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 were three 50-m altitude bands below 150 m (an estimate for the height of the rotor-swept zone) and 53 altitude bands above 150 m. Based on our model, we estimated that approximately 1% of the potential survey volume was below 150 m. Therefore, we would expect a small percentage of targets to be recorded at or below the rotor-swept zone, although this does not necessarily indicate low risk. Additionally, sampling in areas in the lower altitude bands is often poor due to the effects of ground clutter (Figure 4).

When examining general migration patterns, high nighttime migrant activity was documented at our two Lake Erie radar sites as demonstrated by our Trackplots (Figures 8 and 9), the time series plots from each site (Figures 11 and 12), high target passage rates (Figures 13 - 15 and Table 4). Percent of targets within a 30 – 130 m rotor-swept zone were high during all biological time periods, with target density being highest at night (Figures 18, 19, 25 and 26). Throughout the migration season, nighttime targets were recorded flying along the shorelines and across the lake (Figure 10); as dawn approaches nighttime migrants need a place for refuge, rest, and foraging, thus migrants flying over water have been recorded returning towards shore around dawn. The combination of these behaviors indicates that high numbers of nighttime migrants may be at risk of collision with wind facilities, communication towers or other tall structures located along the shorelines of Lake Erie.

Although the target passage rate and target density were lower during the dawn, day, and dusk periods, the migrants may still be at risk of collision during these time periods. Targets were recorded flying along the lakeshore during these time periods, indicating that the Lake Erie shoreline is used by migrants during all times of the day in the migration season for both flightpaths and stopover habitat.

Conclusions

In this report, we provide examples of methodologies and analyses that are helpful in the interpretation of radar data. We suggest that relative changes in the counts at a single site indicate the level of migration activity, and these data provide a better indicator than comparisons between the magnitude of counts recorded in different studies. Careful attention should be given to how these indices fluctuate over fine temporal scales, such as at hourly scales compared with monthly or seasonal scales. Our clutter maps provided information on our ability to detect targets at various altitudes, and we believe that it is important for radar operators to address their ability to detect targets at low altitudes, particularly for collision risk assessments. We provide the basis for a method of accounting for the structure of the sample volume that offers a partial solution, albeit with limitations (Schmaljohann et al. 2008), instead of ignoring the biases associated with sampling effort. Overall, we found that radar provides insights into nocturnal migration that would be otherwise unattainable, and we believe that its continued development and careful interpretation will result in valuable contributions to the management and conservation of migrating birds and bats.

The results of our research highlight the potential role of radar in implementing recommendations from the Land-based Wind Energy Guidelines (USFWS 2012) for the identification of areas where impacts to wildlife should be minimized. We documented clear examples of migrant activity along the southern shorelines of Lake Erie at our study sites in Ohio and Pennsylvania, and the density of targets at lower altitudes is of concern. Additionally, increases in turbine heights and blade lengths increase the size of the rotor-swept zone, thus creating larger areas of flight risk for birds and bats. The collected data may be of interest to public and private entities involved with wind energy development and the potential placement of turbines 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 their use in risk assessments of wind energy developments.

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Appendices

Appendix 1: **Spring 2012 Report Summary**

Appendix 2: **Percent Land Cover Associated with Study Sites and the 2006 National Land Cover Database Classification**

Appendix 3: **Corrected Density per Hour by Biological Period**

Appendix 4: **Comparison of Static and Corrected Density Estimates**

Appendix 1

Spring 2012 Report Summary

- Migration occurred on the southern shoreline of Lake Erie at both ends of the lake during spring 2012
  - Migration is identified by uniformity of movement of direction (northwards) at night, high target passage rate, and nighttime peaks
  - Patterns and timing of migration were similar between the sites
    - Waves of migration with highest concentrations near April 19 and May 20 occurred at both sites
    - Wave of migration also occurred near May 7 in Ohio. A migration wave likely occurred in Pennsylvania at this time; however the vertical scanning radar malfunctioned during this time.
- Date range of pulses that occurred during the migration season
  - April 13 – May 30 in Erie County, Ohio
  - April 13 – May 28 in Erie County, Pennsylvania
- Patterns of activity were different between Dawn, Day, Dusk, and Night time periods
  - Movement north, during the night
    - 76% of nights surveyed the mean direction of travel was generally northerly at Erie County, Ohio
    - 68% of nights surveyed the mean direction of travel was generally northerly at Erie County, Pennsylvania
  - Movement in towards shore at dawn
    - Observed at both sites
  - Highest target passage rate at night
  - Dawn ascent
    - Increase in height around dawn hours observed at all both sites
- Peak density of targets in volume corrected counts
  - Max density below 150 m 75% of nights and 65% of night hours at Erie County, Ohio
  - Max density below 150 m 68% of nights and 65% of night hours at Erie County, Pennsylvania
- Standards for radar studies need to be established and recommendations are included in this report
  - Using radar counts as an index of activity and not a population estimate
  - Surveying continuously over the whole migration season
  - Examining smaller time periods (Dawn/Day/Dusk/Night or Hourly) rather than seasonal metrics
  - Using volume corrected counts on the vertical radar to better estimate use of low altitudes and the rotor swept zone
  - Using 50-m altitude bands to represent height distributions rather than mean or median heights
  - Examining the most densely populated altitude bands rather than comparing numbers or percentages of targets below, within, and above the rotor swept zone
  - Recognizing that migrants change altitude for various reasons over time (due to wind, weather, topography, and time of day, for example) and that targets flying several altitude bands above the rotor swept zone may still be at risk.

Appendix 2

Percent Land Cover Associated with Study Sites and the 2006 National Land Cover Database Classification

Percent landcover found within 3.7 km of radar locations in Ohio and Pennsylvania.

National Land Cover Class	Ohio % of Land Cover	Pennsylvania % of Land Cover
Barren Land	0.00%	0.31%
Cultivated Crops	35.62%	29.44%
Deciduous Forest	28.41%	4.46%
Developed*	10.96%	16.23%
Evergreen Forest	0.11%	0.01%
Hay/Pasture	0.21%	7.01%
Herbaceous	0.05%	0.41%
Mixed Forest	0.00%	1.02%
Open Water	24.40%	35.79%
Shrub/Scrub	0.00%	1.00%
Wetlands**	0.23%	4.32%

* Includes low, medium and high intensity development and developed open space.

**Includes woody and emergent herbaceous wetlands.

Classification Description for the 2006 National Land Cover Database (taken from http://www.mrlc.gov/nlcd06_leg.php; accessed 5/5/2014).

Classification Description
Water
Open Water - areas of open water, generally with less than 25% cover of vegetation or soil.
Perennial Ice/Snow - areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover.
Developed
Developed, Open Space - areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
Developed, Low Intensity - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.
Developed, Medium Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
Developed High Intensity -highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.

Barren
Barren Land (Rock/Sand/Clay) - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
Forest
Deciduous Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
Evergreen Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
Mixed Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.
Shrubland
Dwarf Scrub - Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation.
Shrub/Scrub - areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
Herbaceous
Grassland/Herbaceous - areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
Sedge/Herbaceous - Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra.
Lichens - Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation.
Moss - Alaska only areas dominated by mosses, generally greater than 80% of total vegetation.
Planted/Cultivated
Pasture/Hay – areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
Cultivated Crops – areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
Wetlands
Woody Wetlands - areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
Emergent Herbaceous Wetlands - Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

Appendix 3

Corrected Density per Hour by Biological Period

Estimated density of targets by altitude band during spring biological time periods (dawn, day, dusk, night) in Ohio (targets/1,000,000 m³/time period).

Altitude Band	Dawn	Day	Dusk	Night
50	0.8	0.5	0.6	1.0
100	3.1	1.8	2.5	5.8
150	1.5	0.9	0.9	4.1
200	1.5	0.9	0.7	4.4
250	1.3	0.8	0.6	4.3
300	1.1	0.6	0.5	4.0
350	0.8	0.6	0.4	3.5
400	0.7	0.3	0.2	3.0
450	0.6	0.3	0.2	2.7
500	0.9	0.3	0.2	2.8
550	0.8	0.3	0.2	2.4
600	0.7	0.3	0.1	2.2
650	0.6	0.2	0.1	1.9
700	0.6	0.2	0.1	1.8
750	0.5	0.2	0.1	1.5
800	0.4	0.2	0.0	1.4
850	0.3	0.1	0.0	1.2
900	0.3	0.1	0.0	1.0
950	0.3	0.1	0.0	0.8
1000	0.2	0.0	0.0	0.7

Estimated density of targets by altitude band during spring biological time periods (dawn, day, dusk, night) in Pennsylvania (targets/1,000,000 m³/time period).

Altitude Band	Dawn	Day	Dusk	Night
50	1.1	0.8	0.5	1.5
100	1.9	1.0	0.6	4.9
150	1.5	0.6	0.4	5.4
200	1.1	0.5	0.2	5.1
250	0.9	0.4	0.2	4.6
300	1.0	0.4	0.3	4.2
350	1.3	0.4	0.4	3.8
400	1.3	0.4	0.3	3.5
450	1.3	0.4	0.2	3.0
500	1.1	0.3	0.2	2.6
550	1.0	0.2	0.2	2.2
600	0.8	0.2	0.1	1.9
650	0.7	0.1	0.1	1.6
700	0.5	0.1	0.1	1.4
750	0.4	0.1	0.1	1.2
800	0.3	0.0	0.0	0.9
850	0.2	0.0	0.0	0.7
900	0.2	0.0	0.0	0.5
950	0.2	0.0	0.0	0.4
1000	0.1	0.0	0.0	0.3

Appendix 4

Comparison of Static and Corrected Density Estimates

Comparison of methods to estimated target density by altitude band during the *dawn* biological period in Ohio, spring 2012.

Altitude Band (m)	Target Count	Running Total Target Count[1]	Static Volume	Corrected Volume	Static Target Density per Hour	Corrected Target Density per Hour[2]	% Total Targets	% Static Density	% Corrected Density
50	302	302	31.3	5.6	0.1	0.8	2.3%	2.3%	4.6%
100	1,249	1,551	31.3	5.9	0.6	3.1	9.7%	9.7%	17.8%
150	633	2,184	31.3	6.5	0.3	1.5	4.9%	4.9%	8.3%
200	694	2,878	31.3	7.1	0.3	1.5	5.4%	5.4%	8.3%
250	677	3,555	31.3	7.9	0.3	1.3	5.3%	5.3%	7.3%
300	621	4,176	31.3	8.5	0.3	1.1	4.8%	4.8%	6.2%
350	529	4,705	31.3	9.5	0.3	0.8	4.1%	4.1%	4.7%
400	470	5,175	31.3	10.3	0.2	0.7	3.7%	3.7%	3.9%
450	444	5,619	31.3	11.2	0.2	0.6	3.5%	3.5%	3.4%
500	711	6,330	31.3	12.2	0.3	0.9	5.5%	5.5%	4.9%
550	723	7,053	31.3	13.3	0.3	0.8	5.6%	5.6%	4.6%
600	699	7,752	31.3	14.1	0.3	0.7	5.4%	5.4%	4.2%
650	664	8,416	31.3	15.3	0.3	0.6	5.2%	5.2%	3.7%
700	647	9,063	31.3	16.2	0.3	0.6	5.0%	5.0%	3.4%
750	616	9,679	31.3	17.2	0.3	0.5	4.8%	4.8%	3.0%
800	515	10,194	31.3	18.2	0.2	0.4	4.0%	4.0%	2.4%
850	414	10,608	31.3	19.4	0.2	0.3	3.2%	3.2%	1.8%
900	351	10,959	31.3	20.4	0.2	0.3	2.7%	2.7%	1.5%
950	370	11,329	31.3	21.4	0.2	0.3	2.9%	2.9%	1.5%
1,000	289	11,618	31.3	22.4	0.1	0.2	2.2%	2.2%	1.1%

1 Total target counts recorded up to the 2,800 m band during the dawn time period was 12,855.

2 Total density of targets per hour recorded up to the 2,800 m band during the dawn time period was 17.65.

Comparison of methods to estimated target density by altitude band during the *day* biological period in Ohio, *spring 2012*.

Altitude Band (m)	Target Count	Running Total Target Count[1]	Static Volume	Corrected Volume	Static Target Density per Hour	Corrected Target Density per Hour[2]	% Total Targets	% Static Density	% Corrected Density
50	2,248	2,248	31.3	5.6	0.1	0.5	3.1%	3.1%	2.6%
100	9,301	11,549	31.3	5.9	0.3	1.8	12.8%	12.8%	10.3%
150	5,009	16,558	31.3	6.5	0.2	0.9	6.9%	6.9%	5.1%
200	5,511	22,069	31.3	7.1	0.2	0.9	7.6%	7.6%	5.1%
250	5,238	27,307	31.3	7.9	0.2	0.8	7.2%	7.2%	4.4%
300	4,692	31,999	31.3	8.5	0.2	0.6	6.5%	6.5%	3.6%
350	4,557	36,556	31.3	9.5	0.2	0.6	6.3%	6.3%	3.2%
400	3,037	39,593	31.3	10.3	0.1	0.3	4.2%	4.2%	1.9%
450	2,504	42,097	31.3	11.2	0.1	0.3	3.5%	3.5%	1.5%
500	3,641	45,738	31.3	12.2	0.1	0.3	5.0%	5.0%	2.0%
550	3,660	49,398	31.3	13.3	0.1	0.3	5.1%	5.1%	1.8%
600	3,305	52,703	31.3	14.1	0.1	0.3	4.6%	4.6%	1.5%
650	2,965	55,668	31.3	15.3	0.1	0.2	4.1%	4.1%	1.3%
700	3,033	58,701	31.3	16.2	0.1	0.2	4.2%	4.2%	1.2%
750	2,856	61,557	31.3	17.2	0.1	0.2	3.9%	3.9%	1.1%
800	2,379	63,936	31.3	18.2	0.1	0.2	3.3%	3.3%	0.9%
850	1,889	65,825	31.3	19.4	0.1	0.1	2.6%	2.6%	0.6%
900	1,476	67,301	31.3	20.4	0.1	0.1	2.0%	2.0%	0.5%
950	1,164	68,465	31.3	21.4	0.0	0.1	1.6%	1.6%	0.4%
1,000	822	69,287	31.3	22.4	0.0	0.0	1.1%	1.1%	0.2%

1 Total target counts recorded up to the 2,800 m band during the day time period was 72,396.

2 Total density of targets per hour recorded up to the 2,800 m band during the day time period was 8.82.

Comparison of methods to estimated target density by altitude band during the *dusk* biological period in Ohio, spring 2012.

Altitude Band (m)	Target Count	Running Total Target Count[1]	Static Volume	Corrected Volume	Static Target Density per Hour	Corrected Target Density per Hour[2]	% Total Targets	% Static Density	% Corrected Density
50	235	235	31.3	5.6	0.1	0.6	5.2%	5.2%	8.0%
100	994	1,229	31.3	5.9	0.5	2.5	22.2%	22.2%	32.1%
150	408	1,637	31.3	6.5	0.2	0.9	9.1%	9.1%	12.1%
200	316	1,953	31.3	7.1	0.1	0.7	7.1%	7.1%	8.5%
250	298	2,251	31.3	7.9	0.1	0.6	6.7%	6.7%	7.2%
300	303	2,554	31.3	8.5	0.1	0.5	6.8%	6.8%	6.8%
350	263	2,817	31.3	9.5	0.1	0.4	5.9%	5.9%	5.3%
400	174	2,991	31.3	10.3	0.1	0.2	3.9%	3.9%	3.2%
450	127	3,118	31.3	11.2	0.1	0.2	2.8%	2.8%	2.2%
500	191	3,309	31.3	12.2	0.1	0.2	4.3%	4.3%	3.0%
550	180	3,489	31.3	13.3	0.1	0.2	4.0%	4.0%	2.6%
600	119	3,608	31.3	14.1	0.1	0.1	2.7%	2.7%	1.6%
650	113	3,721	31.3	15.3	0.1	0.1	2.5%	2.5%	1.4%
700	82	3,803	31.3	16.2	0.0	0.1	1.8%	1.8%	1.0%
750	93	3,896	31.3	17.2	0.0	0.1	2.1%	2.1%	1.0%
800	61	3,957	31.3	18.2	0.0	0.0	1.4%	1.4%	0.6%
850	42	3,999	31.3	19.4	0.0	0.0	0.9%	0.9%	0.4%
900	35	4,034	31.3	20.4	0.0	0.0	0.8%	0.8%	0.3%
950	32	4,066	31.3	21.4	0.0	0.0	0.7%	0.7%	0.3%
1,000	32	4,098	31.3	22.4	0.0	0.0	0.7%	0.7%	0.0%

1 Total target counts recorded up to the 2,800 m band during the dusk time period was 4,479.

2 Total density of targets per hour recorded up to the 2,800 m band during the dusk time period was 7.73.

Comparison of methods to estimated target density by altitude band during the *night* biological period in Ohio, spring 2012.

Altitude Band *(m)*	Target *Count*	Running Total Target *Count*[1]	Static *Volume*	Corrected *Volume*	Static Target Density *per Hour*	Corrected Target Density per *Hour*[2]	% Total *Targets*	% Static *Density*	% Corrected *Density*
50	3,437	3,437	31.3	5.6	0.2	1.0	0.9%	0.9%	1.9%
100	20,788	24,225	31.3	5.9	1.1	5.8	5.6%	5.6%	11.0%
150	16,036	40,261	31.3	6.5	0.9	4.1	4.3%	4.3%	7.8%
200	18,862	59,123	31.3	7.1	1.0	4.4	5.1%	5.1%	8.3%
250	20,205	79,328	31.3	7.9	1.1	4.3	5.4%	5.4%	8.0%
300	20,556	99,884	31.3	8.5	1.1	4.0	5.5%	5.5%	7.6%
350	20,101	119,985	31.3	9.5	1.1	3.5	5.4%	5.4%	6.7%
400	18,801	138,786	31.3	10.3	1.0	3.0	5.1%	5.1%	5.7%
450	17,872	156,658	31.3	11.2	1.0	2.7	4.8%	4.8%	5.0%
500	20,205	176,863	31.3	12.2	1.1	2.8	5.4%	5.4%	5.2%
550	19,563	196,426	31.3	13.3	1.0	2.4	5.3%	5.3%	4.6%
600	18,883	215,309	31.3	14.1	1.0	2.2	5.1%	5.1%	4.2%
650	17,697	233,006	31.3	15.3	0.9	1.9	4.8%	4.8%	3.6%
700	17,153	250,159	31.3	16.2	0.9	1.8	4.6%	4.6%	3.3%
750	15,957	266,116	31.3	17.2	0.9	1.5	4.3%	4.3%	2.9%
800	15,079	281,195	31.3	18.2	0.8	1.4	4.1%	4.1%	2.6%
850	13,529	294,724	31.3	19.4	0.7	1.2	3.6%	3.6%	2.2%
900	11,754	306,478	31.3	20.4	0.6	1.0	3.2%	3.2%	1.8%
950	10,092	316,570	31.3	21.4	0.5	0.8	2.7%	2.7%	1.5%
1,000	9,117	325,687	31.3	22.4	0.5	0.7	2.5%	2.5%	1.3%

1 Total target counts recorded up to the 2,800 m band during the night time period was 371,776.

2 Total density of targets per hour recorded up to the 2,800 m band during the night time period was 53.18.

Comparison of methods to estimated target density by altitude band during the *dawn* biological period in Pennsylvania, spring 2012.

Altitude Band (m)	Target Count	Running Total Target Count[1]	Static Volume	Corrected Volume	Static Target Density per Hour	Corrected Target Density per Hour[2]	% Total Targets	% Static Density	% Corrected Density
50	296	296	31.3	5.6	0.2	1.1	3.5%	3.5%	6.7%
100	527	823	31.3	5.9	0.4	1.9	6.3%	6.3%	11.2%
150	454	1,277	31.3	6.5	0.3	1.5	5.4%	5.4%	8.9%
200	352	1,629	31.3	7.1	0.2	1.1	4.2%	4.2%	6.3%
250	332	1,961	31.3	7.9	0.2	0.9	3.9%	3.9%	5.3%
300	382	2,343	31.3	8.5	0.3	1.0	4.5%	4.5%	5.7%
350	546	2,889	31.3	9.5	0.4	1.3	6.5%	6.5%	7.3%
400	638	3,527	31.3	10.3	0.4	1.3	7.6%	7.6%	7.8%
450	650	4,177	31.3	11.2	0.5	1.3	7.7%	7.7%	7.3%
500	609	4,786	31.3	12.2	0.4	1.1	7.2%	7.2%	6.3%
550	619	5,405	31.3	13.3	0.4	1.0	7.4%	7.4%	5.9%
600	533	5,938	31.3	14.1	0.4	0.8	6.3%	6.3%	4.8%
650	461	6,399	31.3	15.3	0.3	0.7	5.5%	5.5%	3.8%
700	379	6,778	31.3	16.2	0.3	0.5	4.5%	4.5%	2.9%
750	302	7,080	31.3	17.2	0.2	0.4	3.6%	3.6%	2.2%
800	283	7,363	31.3	18.2	0.2	0.3	3.4%	3.4%	2.0%
850	216	7,579	31.3	19.4	0.2	0.2	2.6%	2.6%	1.4%
900	186	7,765	31.3	20.4	0.1	0.2	2.2%	2.2%	1.2%
950	177	7,942	31.3	21.4	0.1	0.2	2.1%	2.1%	1.0%
1,000	110	8,052	31.3	22.4	0.1	0.1	1.3%	1.3%	0.6%

1 Total target counts recorded up to the 2,800 m band during the dawn time period was 8,413.

2 Total density of targets per hour recorded up to the 2,800 m band during the dawn time period was 17.23.

Comparison of methods to estimated target density by altitude band during the *day* biological period in Pennsylvania, spring 2012.

Altitude Band (m)	Target Count	Running Total Target Count[1]	Static Volume	Corrected Volume	Static Target Density per Hour	Corrected Target Density per Hour[2]	% Total Targets	% Static Density	% Corrected Density
50	2,669	2,669	31.3	5.6	0.1	0.8	8.3%	8.3%	4.6%
100	3,467	6,136	31.3	5.9	0.2	1.0	10.8%	10.8%	5.7%
150	2,467	8,603	31.3	6.5	0.1	0.6	7.7%	7.7%	3.7%
200	1,981	10,584	31.3	7.1	0.1	0.5	6.2%	6.2%	2.7%
250	1,672	12,256	31.3	7.9	0.1	0.4	5.2%	5.2%	2.1%
300	1,890	14,146	31.3	8.5	0.1	0.4	5.9%	5.9%	2.2%
350	2,507	16,653	31.3	9.5	0.1	0.4	7.8%	7.8%	2.6%
400	2,675	19,328	31.3	10.3	0.1	0.4	8.4%	8.4%	2.5%
450	2,413	21,741	31.3	11.2	0.1	0.4	7.5%	7.5%	2.1%
500	2,038	23,779	31.3	12.2	0.1	0.3	6.4%	6.4%	1.6%
550	1,688	25,467	31.3	13.3	0.1	0.2	5.3%	5.3%	1.2%
600	1,503	26,970	31.3	14.1	0.1	0.2	4.7%	4.7%	1.0%
650	1,118	28,088	31.3	15.3	0.1	0.1	3.5%	3.5%	0.7%
700	900	28,988	31.3	16.2	0.0	0.1	2.8%	2.8%	0.5%
750	689	29,677	31.3	17.2	0.0	0.1	2.2%	2.2%	0.4%
800	495	30,172	31.3	18.2	0.0	0.0	1.5%	1.5%	0.3%
850	365	30,537	31.3	19.4	0.0	0.0	1.1%	1.1%	0.2%
900	306	30,843	31.3	20.4	0.0	0.0	1.0%	1.0%	0.1%
950	193	31,036	31.3	21.4	0.0	0.0	0.6%	0.6%	0.1%
1,000	156	31,192	31.3	22.4	0.0	0.0	0.5%	0.5%	0.1%

1 Total target counts recorded up to the 2,800 m band during the day time period was 31,965.

Comparison of methods to estimated target density by altitude band during the *dusk* biological period in Pennsylvania, spring 2012.

Altitude Band (m)	Target Count	Running Total Target Count[1]	Static Volume	Corrected Volume	Static Target Density per Hour	Corrected Target Density per Hour[2]	% Total Targets	% Static Density	% Corrected Density
50	120	120	31.3	5.6	0.1	0.5	6.9%	6.9%	11.9%
100	154	274	31.3	5.9	0.1	0.6	8.9%	8.9%	14.4%
150	110	384	31.3	6.5	0.1	0.4	6.3%	6.3%	9.5%
200	76	460	31.3	7.1	0.1	0.2	4.4%	4.4%	6.0%
250	86	546	31.3	7.9	0.1	0.2	4.9%	4.9%	6.0%
300	102	648	31.3	8.5	0.1	0.3	5.9%	5.9%	6.7%
350	161	809	31.3	9.5	0.1	0.4	9.3%	9.3%	9.4%
400	152	961	31.3	10.3	0.1	0.3	8.7%	8.7%	8.2%
450	119	1,080	31.3	11.2	0.1	0.2	6.8%	6.8%	5.9%
500	101	1,181	31.3	12.2	0.1	0.2	5.8%	5.8%	4.6%
550	99	1,280	31.3	13.3	0.1	0.2	5.7%	5.7%	4.1%
600	84	1,364	31.3	14.1	0.1	0.1	4.8%	4.8%	3.3%
650	72	1,436	31.3	15.3	0.0	0.1	4.1%	4.1%	2.6%
700	57	1,493	31.3	16.2	0.0	0.1	3.3%	3.3%	2.0%
750	49	1,542	31.3	17.2	0.0	0.1	2.8%	2.8%	1.6%
800	27	1,569	31.3	18.2	0.0	0.0	1.6%	1.6%	0.8%
850	15	1,584	31.3	19.4	0.0	0.0	0.9%	0.9%	0.4%
900	12	1,596	31.3	20.4	0.0	0.0	0.7%	0.7%	0.3%
950	16	1,612	31.3	21.4	0.0	0.0	0.9%	0.9%	0.4%
1,000	11	1,623	31.3	22.4	0.0	0.0	0.6%	0.6%	0.0%

1 Total target counts recorded up to the 2,800 m band during the dusk time period was 1,739.

2 Total density of targets per hour recorded up to the 2,800 m band during the dusk time period was 3.86.

Comparison of methods to estimated target density by altitude band during the *night* biological period in Pennsylvania, spring 2012.

Altitude Band (m)	Target Count	Running Total Target Count[1]	Static Volume	Corrected Volume	Static Target Density per Hour	Corrected Target Density per Hour[2]	% Total Targets	% Static Density	% Corrected Density
50	3,527	3,527	31.3	5.6	0.3	1.5	1.7%	1.7%	3.0%
100	12,026	15,553	31.3	5.9	0.9	4.9	5.7%	5.7%	9.8%
150	14,477	30,030	31.3	6.5	1.1	5.4	6.9%	6.9%	10.8%
200	14,878	44,908	31.3	7.1	1.2	5.1	7.1%	7.1%	10.1%
250	14,876	59,784	31.3	7.9	1.2	4.6	7.1%	7.1%	9.1%
300	14,738	74,522	31.3	8.5	1.1	4.2	7.0%	7.0%	8.4%
350	14,740	89,262	31.3	9.5	1.1	3.8	7.0%	7.0%	7.5%
400	15,080	104,342	31.3	10.3	1.2	3.5	7.1%	7.1%	7.0%
450	14,102	118,444	31.3	11.2	1.1	3.0	6.7%	6.7%	6.1%
500	13,056	131,500	31.3	12.2	1.0	2.6	6.2%	6.2%	5.2%
550	12,120	143,620	31.3	13.3	0.9	2.2	5.7%	5.7%	4.4%
600	11,070	154,690	31.3	14.1	0.9	1.9	5.2%	5.2%	3.8%
650	10,280	164,970	31.3	15.3	0.8	1.6	4.9%	4.9%	3.2%
700	9,387	174,357	31.3	16.2	0.7	1.4	4.5%	4.5%	2.8%
750	8,172	182,529	31.3	17.2	0.6	1.2	3.9%	3.9%	2.3%
800	6,960	189,489	31.3	18.2	0.5	0.9	3.3%	3.3%	1.8%
850	5,757	195,246	31.3	19.4	0.4	0.7	2.7%	2.7%	1.4%
900	4,609	199,855	31.3	20.4	0.4	0.5	2.2%	2.2%	1.1%
950	3,344	203,199	31.3	21.4	0.3	0.4	1.6%	1.6%	0.8%
1,000	2,313	205,512	31.3	22.4	0.2	0.3	1.1%	1.1%	0.5%

1 Total target counts recorded up to the 2,800 m band during the night time period was 210,917.

2 Total density of targets per hour recorded up to the 2,800 m band during the night time period was 50.29.

Notes

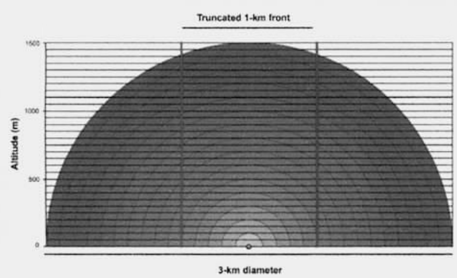
Attachment WE-8

A Tool to Estimate Potential Sample Volume and Density per Altitude Band for Avian Radar

T.S. Bowden[1], J. M. Ferguson[2], J.C. Gosse[1]
U. S. Fish and Wildlife[1]; National Institute for Mathematical and Biological Synthesis[2]

As a means of standardization, avian radar studies often report target counts as the number of targets per 1-km front. We are aware of two methods to calculate this metric:

1) the "**truncated**" method, cuts the sampled space at 500 m on both sides of the radar unit;
2) the "**mean**" method, divides the total number of targets by the diameter of the surveyed semi-circle.



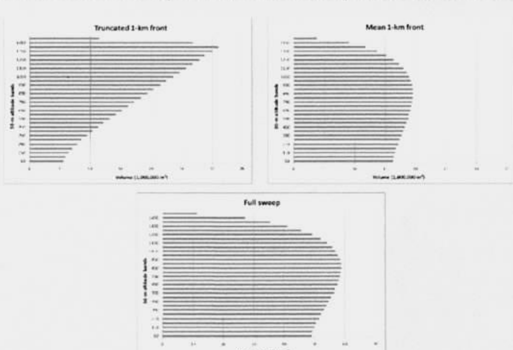
These approaches may be problematic because:

- the radar beam expands as it travels away from the unit —resulting in greater sample volume with distance, and;
- the energy available to detect targets is dispersed with distance, thereby reducing the probability of detection(Schmaljohan et al. 2008[1]).

Given these issues, we developed a model as a first order correction and applied it to data collected in 2011. We used this information to compare altitude profiles, density estimates, and examine the effect of signal attenuation with distance.

Volume per Altitude Band and the 1-km Front

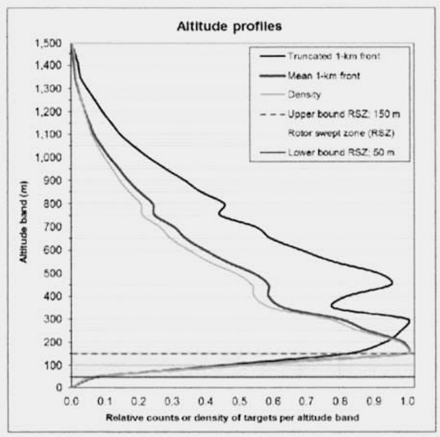
The two methods of calculating a 1-km front result in different distributions of sample space among altitude bands and are compared to a full sweep of the radar beam.

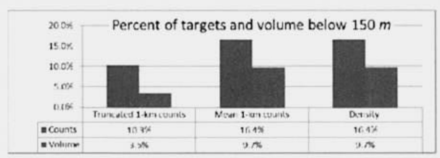


Schmaljohann, H., F. Liechti, E. Baechler, T. Steuri, and B. Bruderer. 2008. Quantification of bird migration by radar - a detection probability problem. Ibis 150:342-355.

Altitude Bias

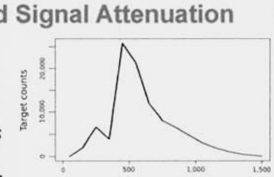
The distribution of volume among altitude bands for the **truncated** 1-km front results in an upward bias in the band with the maximum number of targets. In the below figure, a value of 1 indicates where the maximum occurred.



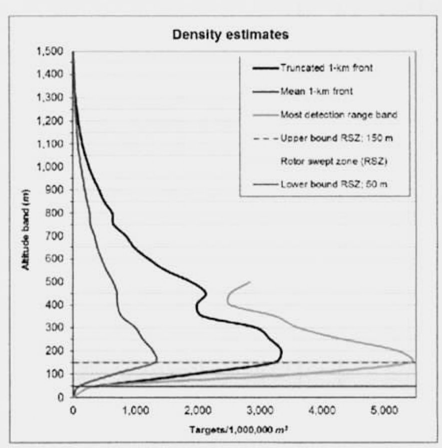


Density Estimation and Signal Attenuation

Not all range bands are created equal. Signal attenuation likely contributes to reduced counts with range.

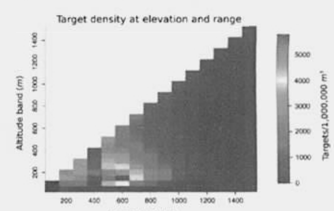


The two 1-km front methods resulted in different density estimates. Selecting a single range band limits the effect of signal attenuation and a band can be chosen to avoid other detection issues such as side lobes.



Key Findings

- The **truncated** method resulted in a biased estimator.
- The **mean** method resulted in a low density estimate—likely due to incorporating range bands with signal attenuation.
- The 3-dimensional approximation of sample space is closer to truth than the 2-dimensional 1-km front metric.
- This tool allows flexibility to account for signal attenuation and improve density estimates.
- Our 500 m range band likely provided the best estimate of density because errors were held constant while the strength of the signal was strong.
- This tool showed where we had the most detection and how a side lobe at 400 m affected counts (see figure below).



Model Development

The volume swept by avian radar depends , in part, on the opening angle of the radar beam and the radar's maximum range of detection. To estimate total survey volume we integrated a pie-slice shaped area, defined by the maximum range and opening angle, from horizon to horizon using R software. Calculating the volume contained within altitude bands is more complex. Therefore, we used Monte Carlo integration to estimate the volume of these bands. This tool will be publicly available soon.

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with questions or requests