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LETTER

Using weather radar to help minimize wind energy impacts on nocturnally migrating birds

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Abstract

As wind energy rapidly expands worldwide, information to minimize impacts of this development on biodiversity is urgently needed. Here we demonstrate how data collected by weather radar networks can inform placement and operation of wind facilities to reduce collisions and minimize habitat-related impacts on nocturnally migrating birds. We found over a third of nocturnal migrants flew through altitudes within the rotor-swept zone surrounding the North American Great Lakes, a continentally important migration corridor. Migrating birds concentrated in terrestrial stopover habitats within 20-km from shorelines, a distance well beyond the current guidelines for construction of new land-based facilities, and their distributions varied seasonally and at local and regional scales, creating predictable opportunities to minimize impacts from wind energy development and operation. Networked radar data are available across the United States and other countries and broad application of this approach could provide information critical to bird-friendly expansion of this globally important energy source.

KEYWORDS
animal migration, Great Lakes, migratory birds, renewable energy, weather surveillance radar, wind development, wind-wildlife

1 | INTRODUCTION

Renewable energy sources are rapidly expanding worldwide as part of efforts to limit greenhouse gas emissions and slow climate change. Wind energy comprises much of this growth, a trend projected to continue (Veers et al., 2019). Compared to fossil fuel-based energy sources, wind generation has minimal environmental impact, emitting no greenhouse gasses and requiring no water use (Jackson et al., 2014; Wiser et al., 2016). However, wind energy can adversely affect wildlife through collisions of volant species with turbines or monopoles, habitat loss, and effects on movements and behavior (Allison et al., 2019). Crucial to wind development is information to inform placement for energy production that minimizes impacts on biodiversity (Martin et al., 2017).

Billions of birds migrate seasonally through North America, with most flying at night (passage) and stopping in terrestrial habitats during the day (stopover). Concentrations of migrating birds often overlap areas with high wind energy potential (e.g., shorelines, ridgelines) (Marques et al., 2014; May et al., 2015; Thaxter et al., 2017). Further, exposure risk for nocturnally migrating birds (hereafter, migrating birds) is expected to be particularly high around stopover areas where migrating birds descend from and ascend to migratory flight, passing through lower altitudes swept by wind turbine blades (i.e., the rotor-swept zone), and due to negative habitat-related effects of wind facilities (Erickson et al., 2014). Wind development is relatively nascent along the world's shorelines but is expected to drastically increase in these areas (Kaldellis & Kapsali, 2013), despite little understanding of the exposure risk this infrastructure poses to birds that use near-shore habitats (Allison et al., 2019).

Several methods have been used to avoid and minimize bird collisions and habitat-related impacts at wind facilities. These include siting facilities to avoid high-risk areas, temporarily shutting down turbines when target species are observed nearby, and visually and aurally deterring birds from near facilities (Allison et al., 2019; Marques et al., 2014; May et al., 2015; Thaxter et al., 2017). All of these management approaches would benefit from more-highly refined estimates of risk, such as those derived from information about spatiotemporal distributions of birds. Although such risk prediction methods are relatively well-developed for bats and raptors (e.g., Smallwood & Bell, 2020; Weaver et al., 2020), fewer exist for non-raptors like nocturnally migrating birds (Aschwanden et al., 2018; May et al., 2020). Moreover, existing approaches to predict collision and habitat-related risks through time are generally limited to local scales (e.g., individual facilities) and do not always accurately characterize impacts post-construction (Ferrer et al., 2012). A well-defined knowledge of where and when large numbers of migrating birds pass through the rotor-swept zone and descend to stopover sites during migration would help refine decisions to site facilities and approaches to minimize impacts at existing facilities (e.g., targeting use of deterrents to specific locations and time periods).

In the context of wind turbine placement, weather surveillance radar (hereafter, weather radar) may help identify areas where large numbers of migrating birds fly through the rotor-swept zone and stopover in high densities (Cohen et al., 2021). Observations of migratory bird activity from weather radar networks have not been used to inform wind facility placement or implement mitigation at operational facilities even though such networks provide unbiased, fine-scale observations of bird migration over regional extents (Buler & Dawson, 2014; Van Doren & Horton, 2018). Radar-derived estimates of bmigration traffic rates can predict numbers of collisions of nocturnally migrating birds, as shown for bird-window collisions (Elmore et al., 2021; Horton et al., 2021), and fine-scale prediction of collision risk is possible at individual wind facilities using mobile radar units (Aschwanden et al., 2018). However, mobile radar studies are often of short duration (i.e., a few months), have limited sampling range (< 5 km radius), and employ a diversity of project and site specifications and operations, which limits applicability of this technology to evaluating collision risk across regions.

Here, we illustrate a novel approach to identify where and when onshore wind energy development may pose the greatest exposure risks for migrating birds. These methods make use of data continuously collected over 4 years by seven radars around the North American Great Lakes, a continentally important bird migration corridor (Ewert et al., 2011b; Van Doren & Horton, 2018) that has over 1600 land-based wind turbines (Hoen et al., 2018) and that is expected to see future rapid expansion of land-based and offshore wind development. Specifically, we modeled multiscale exposure risk across a regional extent by integrating radar observations of terrestrial habitat use during diurnal stopover and aerial movement within the rotor-swept zone during nocturnal passage flight. This approach is intended to be a template for similar efforts to predict and manage exposure from wind turbines and other tall structures (e.g., buildings, towers) that impact migratory birds worldwide.

2 | METHODS

We used established methods (see the Supporting Information) for screening and filtering of data collected by seven WSR-88D radars located around the Great Lakes (Figure 1, Figure S1) to quantify terrestrial habitat use and aerial passage rates of nocturnally migrating birds during bi-weekly periods in spring (1 April – 15 June) and autumn (15 August – 31 October) over a 4-year period (2010 – 2013). The measure of migratory bird biomass departing stopover at the time of peak exodus was transformed into a surface measure of stopover density that correlates with observed stopover density on the ground from field surveys (Buler & Diehl, 2009). Nocturnal passage rates were measured from sunset to sunrise to estimate the proportion of passage through the rotor-swept zone during the night. We

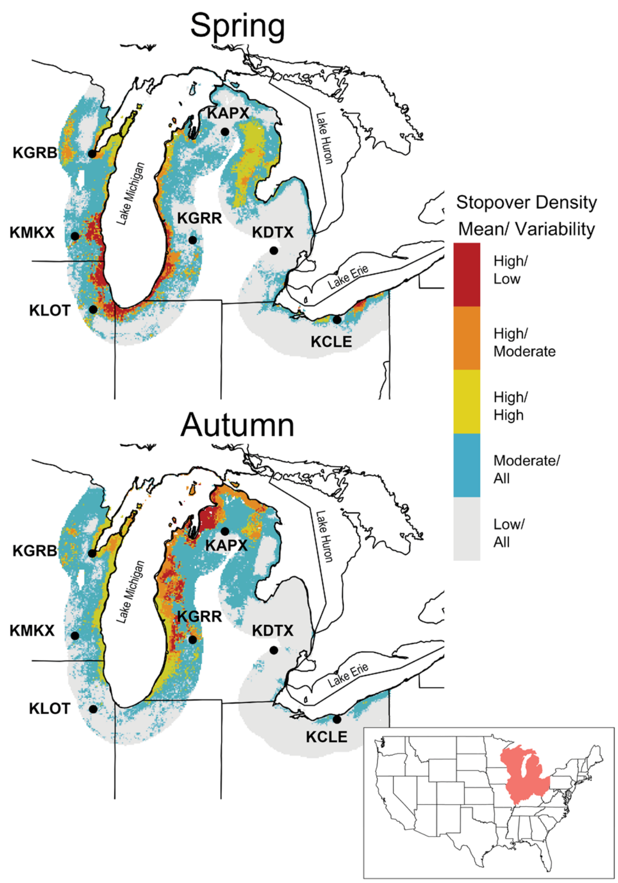

FIGURE 1 Region-wide habitat use of nocturnally migrating birds through the U.S. Great Lakes shorelines interpolated from data collected during spring and autumn by seven weather surveillance radars (KAPX in Gaylord, MI; KCLE in Cleveland, OH; KDTX in Detroit, MI; KGRB in Green Bay, WI; KGRR in Grand Rapids, MI; KMKX in Milwaukee, WI, KLOT in Chicago, IL) over 4 years (2010–2013)

combined measures of stopover and passage to estimate the stopover-to-passage ratio (SPR), a quantitative measure of the percentage of passage migrants that stopover (Cohen et al., 2021). In total, we processed 4256 radar-nights with the number varying among radars due to data availability and weather contamination.

2.1 | Terrestrial concentrations of migrating birds

We measured spatial distributions of terrestrial stopover habitat use, modeled the drivers of stopover densities, and interpolated habitat use around the U.S. Great Lakes shoreline. We measured the density of birds departing from the land area around radars (i.e., 80 km is the average radius within which the beam passes over 95% of the vertical distribution of migrating birds in the air; Figure S1). The study area was composed of a grid of 326,935 1-km^2 cells covering the land area within 100 km of a U.S. Great Lakes shoreline and of a radar (Figure S2). We tested for the influence of 24 variables on stopover distributions, including geographic location, landscape composition, and local weather conditions (Table 1, Supporting Information Methods Section, Figures S2 and S3), known to be influential in this region and others (Archibald et al., 2017; Buler & Dawson, 2014; Cohen et al., 2021; Diehl et al., 2003; McLaren et al., 2018). We used boosted regression trees to model relationships between geographic and landcover variables and observed bi-weekly stopover densities and interpolated densities to each grid cell across the study area. We assessed locations of existing wind turbines in relation to interpolated stopover habitat use (Hoen et al., 2018).

2.2 | Migration through the rotor-swept zone

We estimated migration passage rates to determine the proportion of migrating birds in the rotor-swept zone throughout the night. We conservatively considered the rotor-swept zone as occupying the lowest two 0.1 km altitude bins above the radar antenna. Accordingly, the maximum rotor-swept zone was 219 or 229 m a.g.l. depending on the radar (Supporting Information Methods Section), encompassing a range of altitudes above the tops of currently installed wind turbines in the Great Lakes region but shorter than the tallest turbines in operation (e.g., 240 – 250 m) that are expected to increasingly be used globally (Lantz et al., 2019; Veers et al., 2019). Because night duration varies across days and seasons, we divided nights into decile intervals (i.e., 10 equal periods) and calculated the cumulative biomass of birds passing through each altitudinal bin (Horton et al., 2019). We divided migration passage through the rotor-swept zone by passage through all altitudes through the area sampled by each radar to determine the proportion of migrating birds within the rotor-swept zone.

2.3 | Stopover-to-passage ratio

To estimate SPR, we derived corresponding measures of stopover and passage biomass (cm^2) within 37.5 km of the radar (Cohen et al., 2021). For total passage biomass, we multiplied the total nightly passage by the 37.5 km length of the sampling transect (Horton et al., 2019). We derived the total nightly stopover biomass by multiplying the density at exodus by the land area and dividing by the estimated proportion of nocturnal migrants aloft at the sampling time. Thus, SPR is a unitless ratio with higher percentage values indicating a larger portion of migrating birds stopping

TABLE 1 We tested for the influence of 24 variables, known to influence stopover distributions in this region and others, within the grid of 326,935 1-km^2 cells covering the land area around the U.S. Great Lakes shoreline, and mean relative variable influence among the 24 predictors averaged across the 25 boosted regression tree models for stopover density. Relative variable importance is defined as the percentage of tree nodes within each ensemble model attributable to each predictor, and their order of influence for spring and autumn

	Predictor	**Range of values**	**Relative variable influence (%)**		**Order of influence**	
			Spring	**Autumn**	**Spring**	**Autumn**
Temporal	**Year**	**2010 to 2013**	**9.97**	**6.45**	**2**	**8**
	Bi-weekly period	1 Apr to 15 Jun and 15 Aug-31 Oct	25.52	12.82	1	1
Geographic	Distance to shoreline (km)	0 to 145	4.31	6.54	9	7
	Northing (m)	−400408 – 170,592	5.69	7.66	7	6
	Easting (m)	844,390 to 1,580,390	7.24	11.11	4	2
Landscape	Barren land[†]	0 to 1	0.20	0.23	24	24
	Forested wetland[†]	0 to 1	0.84	1.03	16	16
	Non-forested wetland[†]	0 to 1	0.79	0.78	17	17
	Grassland[†]	0 to 1	0.69	0.65	18	18
	Evergreen forest[†]	0 to 1	0.30	0.30	23	22
	Deciduous forest[†]	0 to 1	1.37	1.75	15	14
	Mixed forest[†]	0 to 1	0.39	0.37	20	20
	Shrubland[†]	0 to 1	0.32	0.35	22	21
	Urban[†]	0 to 1	1.63	1.62	14	15
	Cropland[†]	0 to 1	3.01	2.55	13	13
	Water[†]	0 to 0.75	0.50	0.50	19	19
	Forest stand age (y)	0 to 200	0.36	0.29	21	23
	NDVI[*]	0 to 1	3.84	4.03	11	11
	Distance to light pollution (km)	0 to 181	3.59	3.35	12	12
Weather	Temperature (K)	278 to 301	6.21	8.75	5	4
	Wind velocity to north (m/s)	−2.4 to 3.6	6.05	8.64	6	5
	Wind velocity to east (m/s)	−2.5 to 6.4	7.81	10.56	3	3
Corrective	Distance to radar (km)	7.25 to100	5.30	5.64	8	9
	Elevation relative to radar (m)	−184 to 293	4.06	4.04	10	10

*Normalized difference vegetation index.

[†] Proportion within 5 km radius.

relative to numbers passing through the airspace. To quantify temporal patterns of migration, we used generalized linear mixed effects models for SPR and the proportion of passage within the rotor-swept zone as a function of year and bi-weekly period and, for the proportion of passage within the rotor-swept zone, decile of the night for each radar (see Supporting Information Methods Section). We tested for a correlation between mean SPR and proportion of birds flying through the rotor-swept zone during annual biweekly periods over each radar.

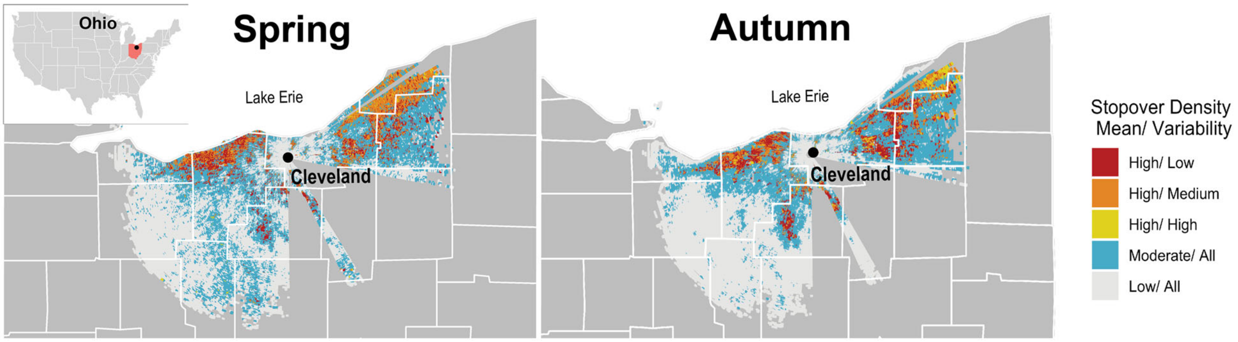

FIGURE 2 Local habitat use of nocturnally migrating birds along the southern shoreline of Lake Erie around Cleveland, Ohio as observed by the KCLE radar. Some areas southeast of the Cleveland radar were obstructed from measurement by building blockage

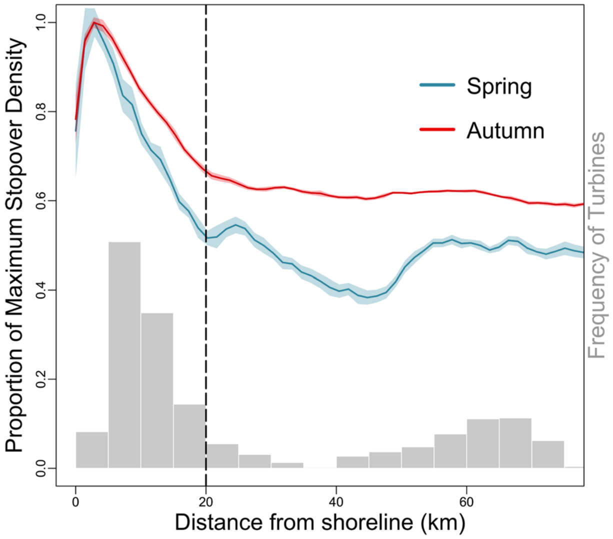

FIGURE 3 Proportion of stopover density (blue and red lines with 95% CI of marginal effect across 25 replicate models) relative to distance from U.S. Great Lakes shorelines and the frequency of existing wind turbine distributions (light gray bars). The dotted black line indicates the 20-km distance where stopover density levels off

3 | RESULTS

3.1 | Terrestrial concentrations of migrating birds

Migrating birds were detected stopping over across 41.9 ± 4.5% and 36.8 ± 2.5% of the 326,935 km^2 study area during spring and autumn, respectively. Migrating birds strongly concentrated around Lake Michigan, where they stopped in higher densities along the northeastern shoreline in autumn and southern shoreline in spring, and in extensive forests of northeastern Michigan during both seasons (Figures 1, S4, S5). The southern Lake Erie shoreline was projected to be a relatively low exposure risk from a region-wide perspective, but high-use areas emerged along the shoreline within the area sampled by the Cleveland, Ohio radar (Figure 2). Stopover density was influenced by geographic location as well as landscape composition (Table 1). For example, models for both seasons revealed the highest stopover concentrations within 20 km from shorelines, a distance band within which 65% of the region's onshore turbines are concentrated (Figure 3). Given this result, we compared stopover densities within 0 – 20 and 20 – 75 km from the shoreline using two-sample *T*-tests and found densities within 20 km were 44% greater in spring ($t = 50$, df = 100,048, $p < 0.001$) and 63% greater in autumn ($t = 114$, df = 165,441, $p < 0.001$).

3.2 | Migration through the rotor-swept zone

Throughout the night, the vertical distribution of bird migration was initially low through the rotor-swept zone and then increased to reach its maximum before sunrise, reflecting stopover take-off and landing periods when many migrating birds are near the ground (Figure 4). Passage through the rotor-swept zone was higher during spring than autumn around five of the seven radars, with the greatest inter-season differences along the eastern shore of Lake Michigan (Figure 5). Conversely, passage through the rotor-swept zone was slightly higher during autumn around the easternmost radar on Lake Erie (Figure 5).

Over a third of birds nocturnally migrating along Great Lakes shorelines flew through the rotor-swept zone (34.67 ± 0.29%). The percent of passage through these lower altitudes was highest in northern Michigan (40.64 ± 0.70%; Figure 5, Table S1) and lowest in the south near Chicago, Illinois (24.32 ± 0.67%). The proportion of passage through the rotor-swept zone was similar during spring (0.368 ± 0.004) and autumn (0.326 ± 0.004) peaking during late spring and moderately higher outside of peak migration during late autumn (Figure 5). Passage rates through the

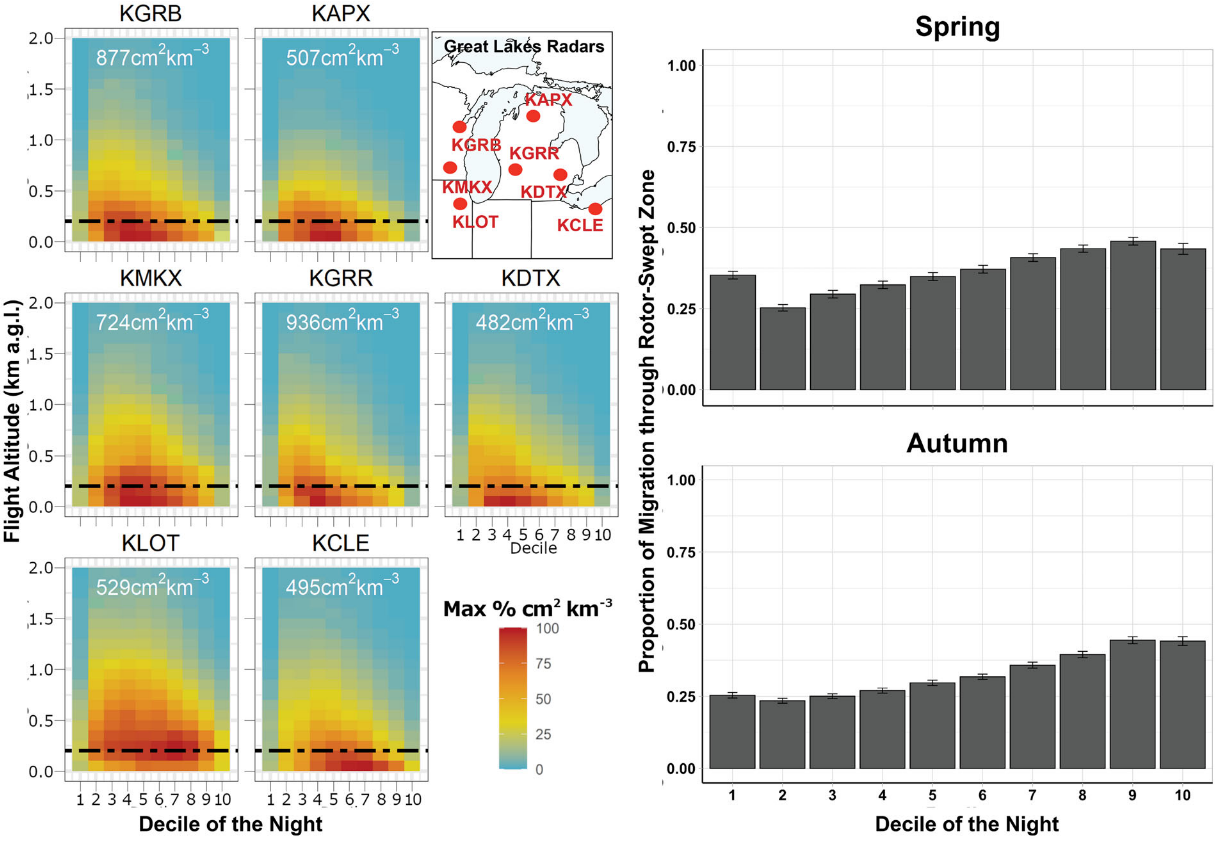

FIGURE 4 Vertical distributions of migrating birds throughout the night; deciles are the tenths of the night from sunset to sunrise standardized across the time of the year. The left panel illustrates the vertical distribution of migration at each of the radars (KAPX in Gaylord, MI; KCLE in Cleveland, OH; KDTX in Detroit, MI; KGRB in Green Bay, WI; KGRR in Grand Rapids, MI; KMKX in Milwaukee, WI, KLOT in Chicago, IL). The horizontal dotted line is the upper rotor-swept zone for each radar (219–229 m a.g.l., depending on the height of the radar antennas). The value in each box is the radar-specific maximum value used to standardize relative passage among radars. The right panels are the proportion of total migration that is within the rotor-swept zone during each decile of the night across radars during spring and autumn, respectively

rotor-swept zone increased with greater frequency of landing and departure of migrants from stopover habitat as supported by the positive correlation between the SPR (the proportion of passage migrants that decide to stop) and the proportion of birds flying through the rotor-swept zone ($r = 0.32$, $t = 3.94$, $p < 0.001$).

3.3 | Stopover-to-passage ratio

Nearly one quarter of passage migrants stopped in terrestrial shoreline habitats across the region (SPR: 26.22 ± 1.77%) with the highest percentage stopping in northern Michigan (46.32 ± 6.19%), and the lowest stopping in the south around Cleveland (14.22 ± 1.61%) (Figure 5, Table S1). The ratio also varied biweekly within seasons ($X^2{}_{24,1} = 57.74$, $p < 0.001$); it reached maximum values during late spring and early and late autumn (Figure 5), outside of peak of stopover densities, and was relatively consistent between seasons (spring 25.90 ± 2.80%; autumn 26.38 ± 2.26%). Conversely, total stopover density increased 55% during autumn as compared to spring (spring $2.16 \times 10^6 \pm 2.22 \times 10^5$ cm^2, autumn $3.36 \times 10^6 \pm 2.36 \times 10^5$ cm^2).

4 | DISCUSSION

Wind energy capacity in North America has tripled over the last decade and this growth is projected to continue due to wind resource potential and increased demand for renewable energy resources (U.S. FWS, 2016). Yet, locations ideal for harvesting wind energy often coincide with wildlife concentrations, potentially leading to collision and habitat-related effects of development (Allison et al., 2019; Loss et al., 2013; May et al., 2017). By quantifying spatiotemporal patterns of aerial and terrestrial habitat use with the U.S. network of weather surveillance radars, we provide an integrated exposure risk evaluation approach that can help guide future wind energy growth and operation to minimize negative impacts to nocturnally migrating birds from

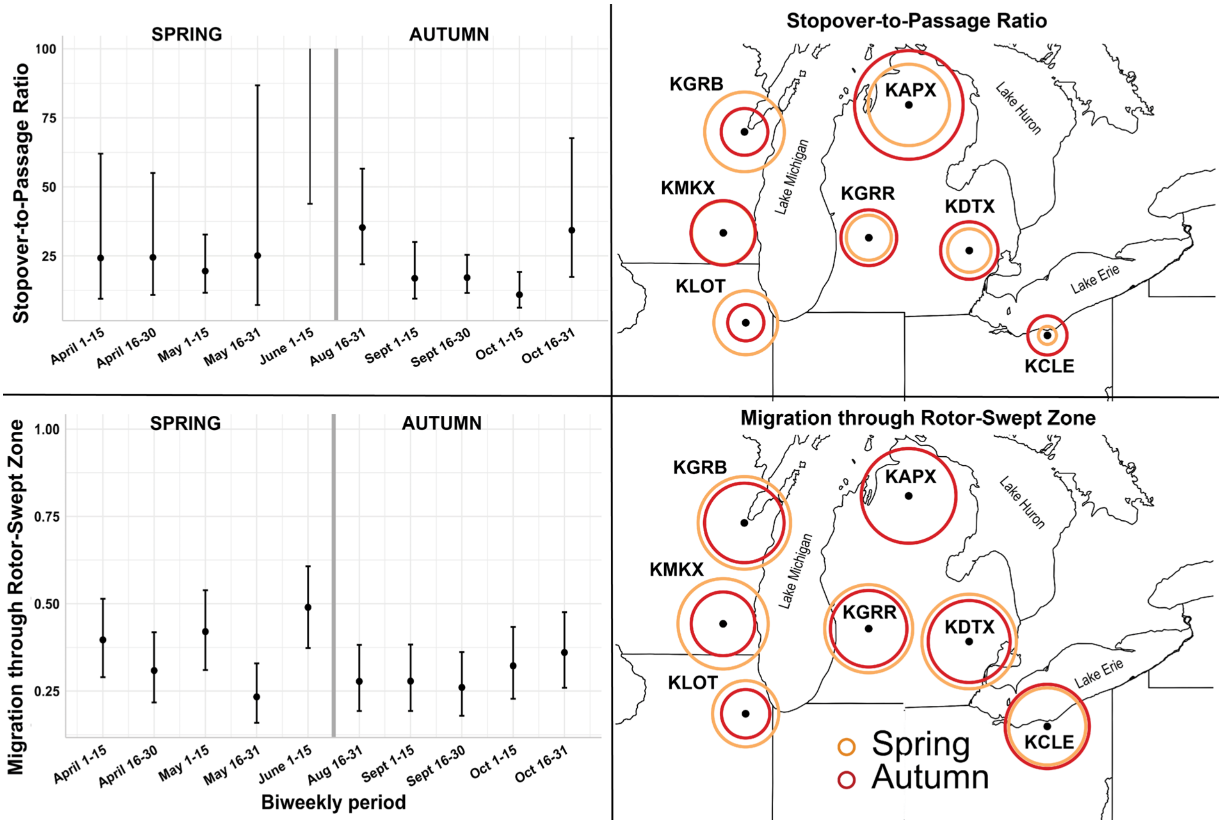

FIGURE 5 The left panels show the marginal means (±95% CI) of the stopover-to-passage ratio (top) and the proportion of flight through rotor-swept zone (bottom), modeled across the seven radars (KAPX in Gaylord, MI; KCLE in Cleveland, OH; KDTX in Detroit, MI; KGRB in Green Bay, WI; KGRR in Grand Rapids, MI; KMKX in Milwaukee, WI, KLOT in Chicago, IL) and weighted by the number of sampling nights per period, around U.S. Great Lake shorelines. The right panels map stopover-to-passage ratio (top) and flight through the rotor-swept zone around each radar (bottom), as illustrated by the size of the circle. There was no difference between seasons for stopover-to-passage ratio at KMKX and proportion of passage at KAPX

turbine collision and habitat loss. For example, although nocturnally migrating birds often fly well above altitudes intersected by wind turbines (La Sorte et al., 2015; Sjöberg et al., 2018), we found that the proportion of birds in the rotor-swept zone peaked at nearly 50% near sunrise when birds migrating through the Great Lakes region were ending nocturnal migration by landing in terrestrial stopover habitats. Therefore, both existing wind facilities and future wind energy development have potential to substantially affect nocturnally migrating birds and exposure risk can be minimized by avoiding placement of turbines in areas with the greatest stopover concentrations, and curtailing turbine operation during crepuscular hours, especially during the small fraction of nights with the majority of migration passage (Horton et al., 2021; Van Doren & Horton, 2018).

Of migrating birds passing through the Great Lakes airspace, 25% land in stopover habitats along shorelines, with highest SPRs occurring outside of peak seasonal migration. The highest stopover concentrations of birds occurred in autumn, as compared to spring, a function of the increased number of fall-migrating birds. Seasonal migrants were not evenly distributed among stopover habitats, creating predictable opportunities for bird-friendly wind energy operation and future development. Region-wide, stopover concentrations were highest along the forested shorelines of Lake Michigan. However, the relative importance of habitats depends on the scale of assessment, and risk to migratory birds also varied locally within the area sampled by individual radars. Thus, knowing the proportion of migrating birds stopping over in an area helps clarify their relative risk for collision with wind turbines independent of the absolute number of birds stopping over, and siting that accounts for both region-wide and local distributions along particular stretches of shoreline may be most effective at minimizing exposure risks.

Current U.S. Fish and Wildlife Service guidelines suggest that no land-based wind facilities be constructed within 5 km (3 mi) of Great Lakes shorelines, and The Nature Conservancy recommends a distance of 8 km (5 mi) (Ewert et al., 2011a; U.S. FWS, 2016). These distances do not appear to be based on documented thresholds of migratory bird distributions. The threshold distance of 20 km

(12 mi), where stopover densities sharply increase with increasing proximity to shoreline, could provide a data-driven guideline for restricting development of new wind facilities and for targeting mitigation activities at existing facilities. Moreover, this threshold distance captures 50% of stopover habitat use in the study area while the current turbine exclusion zone guidelines capture only 8 and 19%, respectively (Ewert et al., 2011a; U.S. FWS, 2016). Only 4 and 5% of current wind turbines are within "high" stopover habitat use areas during spring and autumn, respectively, while an additional 25% and 8% of wind turbines are within "moderate" use areas. All turbines in high stopover density areas are within 7.2 ± 5.5 km of the Lake Michigan shoreline.

Offshore wind development is nascent in much of North America (Allison et al., 2019). However, in the North American Great Lakes, strong winds, shallow bathymetry, and thus relatively high energy capacity, are expected to allow rapid offshore development (Schwartz et al., 2010). Although not assessed in our study, passage of nocturnal migrants is more concentrated over land than over the Great Lakes, which can be traversed by migrating birds in a few hours (Diehl et al., 2014). The strength of weather radars is that their large surveillance area and standardized data collection, makes them useful for quantifying bird migration at regional extents and capturing generalized broad-scale patterns in flight altitude profiles and traffic rates (see Data Limitations Section in the Supporting Information). Estimates of over-water passage rates and flight altitudes under different weather conditions (Archibald et al., 2017; Diehl et al., 2003; Gesicki et al., 2019) are needed, and future work using portable radars (Heist et al., 2018) could be combined with measures of migration patterns from weather radar to validate flight activity locally and determine collision risk at offshore turbines.

5 | CONCLUSION

The comprehensive and systematic data collected by weather surveillance radar networks can inform siting and mitigation measures of wind energy development to minimize exposure risk of nocturnally migrating birds. In the context of the Great Lakes region, we identified a 20-km threshold distance from shorelines containing the vast majority of migrating birds. This threshold may be useful for directing siting of new wind energy development near shorelines, and for identifying peak within-day passage times (i.e., migration lift-off and landing, corresponding to periods near dusk and dawn), seasonal passage times (i.e., peak periods of spring and autumn migration), and even daily migration intensity forecasts that could be targeted for curtailment of turbine operation. Radar-based measures of migration could additionally address indirect effects of wind turbines (i.e., displacement, avoidance) during migration (Marques et al., 2020). Further, radar data could be used in real-time to collect data on migrating bird abundance pre- and post-construction at new developments, or accessed retroactively for existing facilities, since data archives extend back 25 years. Pre-construction measures that accurately predict wind turbine collision risk are urgently needed, as current ground-based bird surveys at proposed wind facilities are often only weakly correlated with postconstruction mortality (De Lucas et al., 2008; Ferrer et al., 2012). Thus, weather surveillance radar can be leveraged to predict exposure risks to migrating birds with the expansion of renewable wind energy. Such a framework can also be broadly instructive for predicting and managing collision risks associated with other tall structures (e.g., buildings, towers) that impact migratory birds worldwide.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

E.B.C, J.J.B, S.R.L, and P.P.M conceived of and designed the study. E.B.C wrote the first draft and all of the authors contributed to the writing. J.J.B, K.G.H, and J.A.S developed and contributed tools for the analyses and E.B.C, J.J.B, K.G.H, S.C.C, J.A.S worked on the data acquisition, processing and analysis.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available at https://datadryad.org/stash/dataset/doi:10.5061/dryad.5dv41ns7m.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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