

Utilizing NEXRAD Weather Data and a Hotspot Analysis to Determine Bird Migration Concentration Areas



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ABSTRACT

Areas such as the Lake Michigan shoreline have long been considered bird migration concentration areas. There is however, the simple fact that things are found where you look for them and these areas have long been popular with birders. However, one cannot differentiate any particular area as a high concentration area relative to any other area without examining multiple areas simultaneously. In this study, we use NEXRAD data from four installations to simultaneously examine avian concentration areas during Spring and Fall migrations; this approach in essence allows for examination of 4 approximately 200 km transects simultaneously. Additionally, while NEXRAD data has been used to examine avian migration patterns by other researchers, this study represents the first application of rigorous spatial statistical analyses to mathematically identify avian concentration areas. The analysis revealed a number of such concentration areas: the western portion of the Upper Peninsula of Michigan; north-central portion of the Lower Peninsula; the southern shore of Lake Michigan; the south-central area of the Lower Peninsula; and the Lake St. Claire-Detroit River-western Lake Erie corridor. Of particular note is the south-central Lower Peninsula area, which has not previously been identified as a concentration area. The concentration patterns also revealed differences between Spring and Fall migrations, as well as peak migration time and sunrise. These differences can be explained by effects of landforms and avian flight patterns. The results of this study can inform decision makers with respect to siting of wind farms in coastal areas. While most nocturnal migrants fly at heights above typical rotor swept areas, birds may be particularly vulnerable to adverse interactions with wind turbines during periods of ascent and descent. Additionally, inclement weather may increase the probability of adverse interactions and decision makers should be particularly sensitive to these factors in high concentration areas.

INTRODUCTION

Wind power is considered an environmentally friendly way of producing electricity that should lessen reliance on fossil fuels and the overall problem of global climate change. Due to the propensity for high, steady winds on the Great Lakes, these areas are targeted for offshore, near shore, and on shore wind farm development. In Michigan, the rate of wind turbine construction is expected to increase due to the abundance of areas with high potential for wind development, tax credits, and renewable energy mandates. According to the Michigan Department of Energy, Labor, and Economic Growth, the Great Lakes and their coasts are specifically targeted for increases in wind farm development due to their propensity for high, steady winds (http://www.michigan.gov/cis/0,1607,7-154-25676_25774-101765--,00.html).

Avian collisions with wind towers are well documented in the literature (Johnson 2002, Smallwood 2008, Kunz 2007, Kuvlesky 2007). Avian migration periods, when large numbers of birds are moving across the landscape, present the possibility of large numbers of avian impacts with wind towers. The numbers of avian fatalities are directly related to the placement of wind farms on the landscape (U.S. Fish and Wildlife Service 2003). Carefully planned placement of wind farms is considered to be one of the most important variables when attempting to minimize ecological impacts.

Michigan coastal areas have been recognized as migratory bird stopover sites (Diehl et al. 2003, Ewert et al. 2005, Shieldcastle 2004, Bonter et al. 2009). Stopover concentrations of migrating birds along the shorelines are likely the result of nocturnal migrants over the Great Lakes reorienting towards shorelines at dawn to rest and refuel. Migration occurs throughout the night. While stopover sites are important to delineate and protect, migration concentration areas in general are also important to delineate. Nocturnal bad weather events will force migrants down, increasing the likelihood of collisions with manmade structures. Placement of large wind farms in close proximity to

nocturnal migration concentration areas increases the likelihood of bird-structure collision events in the event of bad weather. These events may involve very substantial numbers of birds due to the higher concentration of migrants in these near stopover areas.

Currently, planners and resource managers have no landscape scale datasets that delineate avian migration concentration areas on the Great Lakes. While localized coastal stopover areas have been studied, a systematic statewide analysis of concentration areas has not been undertaken. Such an analysis will allow us to examine coastal concentration areas in relation to the whole state. Weather radar data, from Next Generation Radar (NEXRAD), provide a platform to undertake such a large scale study (<http://en.wikipedia.org/wiki/NEXRAD>).

The WSR-88D (Weather Surveillance Radar, 1988 Doppler) system of radar was designed in 1988 and currently consists of 159 sites operated by the United States National Weather Service. Widely referred to as “NEXRAD” radar, the system detects precipitation and wind, but is also sensitive enough to detect biological targets such as birds, bats, and insects, making it useful for ornithological research (Larkin 1991, Gauthreaux and Belser 1998, Russell et al. 1998, Gauthreaux and Belser 2003, Gauthreaux and Belser 2005, Diehl et al. 2003, Gauthreaux et al. 2008, Buler and Diehl 2009).

The system is capable of delineating large-scale patterns in migration (Gauthreaux et al. 2008), identifying stopover locations (Bonter et al. 2009, Diehl and Larkin 2005), and studying migration around large water bodies (Diehl et al. 2003, Gauthreaux et al. 2006).

In this paper we present a novel approach for utilizing NEXRAD radar data to delineate nocturnal bird migration concentration areas. While this paper focuses on the results in Michigan, the analysis technique is appropriate for use elsewhere.

METHODS

Approach

There are a number of technologies available to measure avian migration patterns and determine concentration areas. Various radar technologies have been used to study avian migration for approximately 70 years (See Gauthreaux and Belser 2003 for a review). Weather surveillance radar technologies are useful for quantifying large scale migration events and patterns. Radar in general is particularly useful for quantifying nocturnal migrants which may be difficult to adequately detect by other methods. Portable radar studies, however, may be impeded by cost of acquiring and maintain field equipment and logistics of collecting data over large geographic scales (Mead et al 2010).

The WSR-88D (Weather Surveillance Radar, 1988 Doppler) system of radar was designed in 1988 and currently consists of 159 sites operated by the United States National Weather Service. Widely referred to as “NEXRAD” radar, the system detects precipitation and wind, but is also sensitive enough to detect biological targets such as birds, bats, and insects, making it useful for ornithological research (Larkin 1991, Gauthreaux and Belser 1998, Russell et al. 1998, Gauthreaux and Belser 2003, Diehl et al. 2003, Gauthreaux et al. 2008, Buler and Diehl 2009). The system is capable of illuminating large-scale patterns in migration (Gauthreaux et al. 2008), identifying stopover locations (Bonter et al. 2009, Diehl and Larkin 2005), and studying migration around large water bodies (Diehl et al. 2003, Gauthreaux et al. 2006). In addition the data covers large portions of the United States, is widely available at no cost, and has been archived since the early 1990s (Mead et al. 2010).

While numerous researchers have used NEXRAD data to quantify avian migration, none to date have incorporated a spatial statistics approach into their work. Our objective was to explore a methodology that would provide a straightforward technique for utilizing NEXRAD weather radar data to delineate nocturnal migration bird concentration areas. Rather than quantify absolute bird densities, we looked at relative densities throughout a migration season and utilize a spatial statistical procedure to determine statistically significant seasonal hotspots. We further determined where hotspots consistently occur over a

six year period.

Study Area and Data

We obtained data from the National Climatic Data Center (National Climatic Data Center 2012) for the four WSR-88D radar sites located in Michigan: KAPX (44.90722°, -84.71972°) located in Gaylord; KDTX (42.69972°, -83.47167°) located in Detroit; KGRR (42.89389°, -85.54472°) located in Grand Rapids; and KMQT (46.53111°, -87.54833°) located in Marquette (Figure 1).

We downloaded Level II reflectivity data during the periods of peak migration (the time closest to 2330 hours local time) (Gauthreaux and Belser 2003, Lowery and Neuman 1966) and near dawn (closest time prior to civil sunrise) for the spring (April 20 – May 31) and fall (September 1 – October 31) migration seasons during the years of 2003 – 2008. By the time of peak migration birds have had opportunity to reach altitude and disperse into the airspace. Near dawn, the birds, particularly those over water, descend and look for suitable landing locations (Diehl et al. 2003).

The WSR-88D radar is a S-band (10 cm wavelength) radar with a range of 230 km and an azimuth resolution of 0.95°. Reflectivity is measured every 1 km along the beam and this space is known as the pulse volume. The pulse volume increases in size and altitude with increasing distance from the radar. During May 2008, as an update of the WSR-88D system, the range resolution increased from 1 km to 0.25 km at the KDTX site. By the Fall of 2008, all four sites had been updated to collect so-called “super-resolution” data. In clear-air mode the temporal resolution of the radar is 10 minutes; the beam completes a sequence of 360° azimuthal sweeps at 5 different elevations in ~1° increments beginning at 0.5°.

Level II data are the base data collected in polar coordinates at the radar site at the full spatial and temporal resolution of the radar (Crum et al. 1993, National Climatic Data Center 2005). Basic data moments collected are reflectivity, radial velocity and velocity spectrum width. Base reflectivity is a complete 360° sweep of return energy intensity, and represents the amount of returned energy from contact with targets in the pulse volume. On precipitation-

Figure 1. Study area and radar locations.



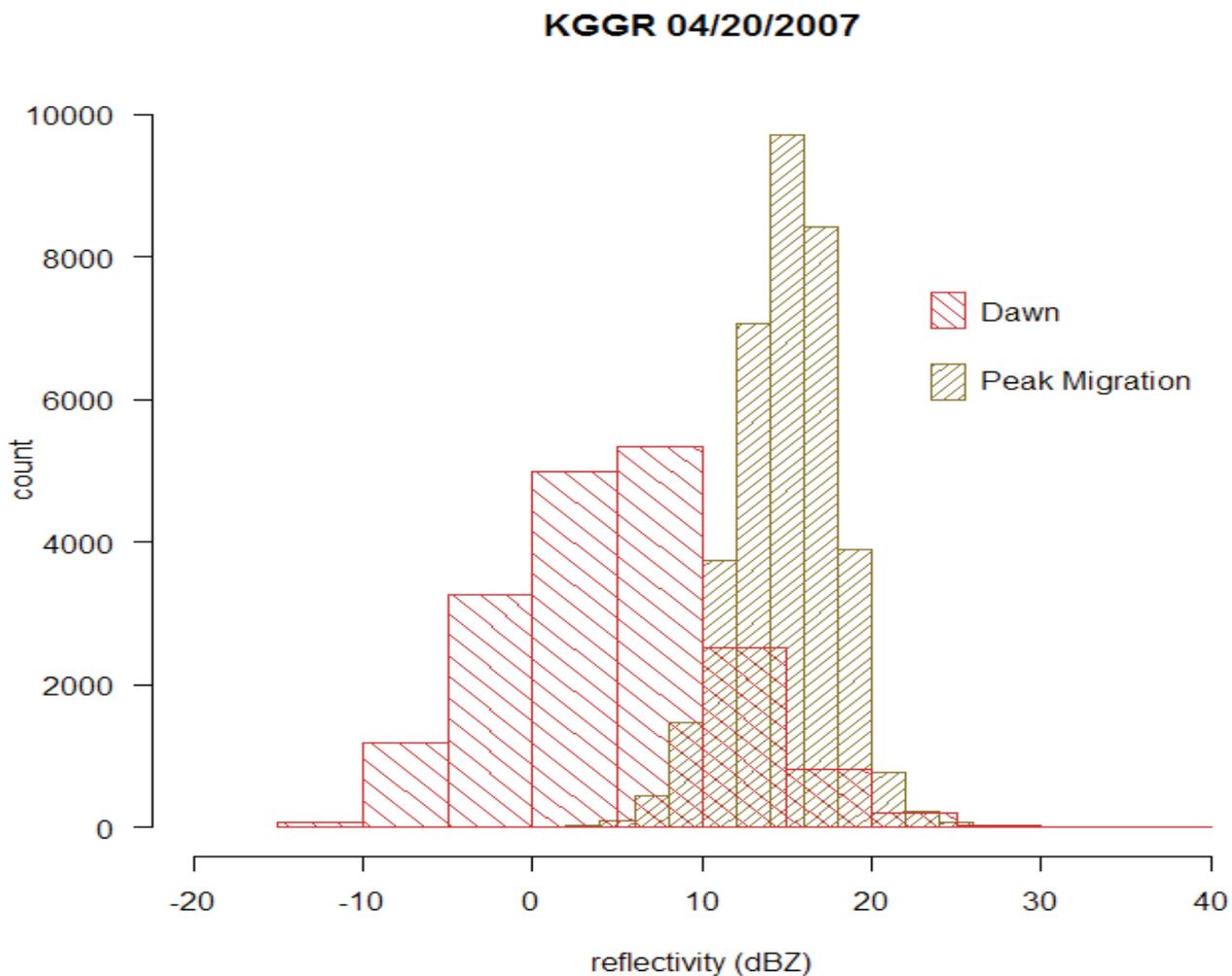
free nights during migration the targets are generally birds, but can also be bats, insects, and anomalies. The greater the density of the targets, the larger the returned reflectivity, and greater reflectivity values are related to greater numbers of birds (Gauthreaux and Belser 1998). In our study the influence of insects was minimized as we selected only the strongest reflectivity values (see Methods) that are generally not attainable by insects (Larkin 1983, Gauthreaux and Belser 1998).

We used the reflectivity moment at the lowest tilt of the radar coverage, approximately 0.5° above the horizon. The beam height at this tilt is consistent with the altitude of migratory birds. We excluded radar data within 20 km of the radar site to avoid echoes from ground clutter such as buildings and hills, and beyond 120 km because the beam altitude

is likely passing over the migration layer at that distance. We visually inspected the reflectivity images selected for analysis and excluded those dominated by precipitation, radar artifacts, obvious refraction, and weak migration. Over the six years, 40 % of the screened data met the selection criteria.

Data were downloaded as point features, where each point represented the reflectivity measured in units of strength of echo, Z, on a logarithmic decibel scale (dBZ) of the pulse volume centroid, at that geographic location. While some studies have converted this value to a substitute for bird density, we do not require an absolute estimate of bird numbers or density for our analysis. Figure 2 shows a typical frequency distribution of Z values from the KGRR radar for both the peak migration time and the dawn descent time period.

Figure 2. Typical frequency distribution of reflectivity values for the times of peak migration and dawn (KGRR, April 20, 2007).



Data Analysis

Reflectivity values at different ranges cannot be directly compared. Because of the tilt of the radar and the curvature of the Earth, the altitude measured by the radar increases with increasing range (range bias – see Diehl and Larkin 2005), and the reflectivity tends to decrease with distance from the radar (Figure 3). Bird density may be greater at certain altitudes because they are responding to wind direction and velocity, which vary with altitude. We avoid direct comparison of reflectivity at different ranges by analyzing the values within each range gate in concentric circles from the radar.

We analyzed each site in 1 km concentric distances, starting 20 km from the site and going out to 120 km from the site. For each distance, a cumulative

distribution of the reflectivity values was computed to determine the threshold reflectivity value where no more than five percent of the points would be at that threshold value or higher. These high reflectivity locations were selected and combined to represent the daily high concentration areas for a site at a time period. The daily high concentration areas were overlaid and combined for the migration season (spring or fall), so that each location included an attribute indicating how many days it had been a high concentration area over the course of the season (Figure 4).

The hot spot analysis tool in ArcGIS 10 (ESRI 2011) was used to calculate the Getis Ord G_i^* statistic (Getis and Ord 1992, Ord and Getis 1995) on the count of days for each location. The hot spot analysis examines the count at each point in relation to the counts at other

Figure 3. Reflectivity values for the KGRR radar (April 21, 2008) illustrate a typical bull's-eye spatial pattern, where values decrease with increasing distance from the radar.

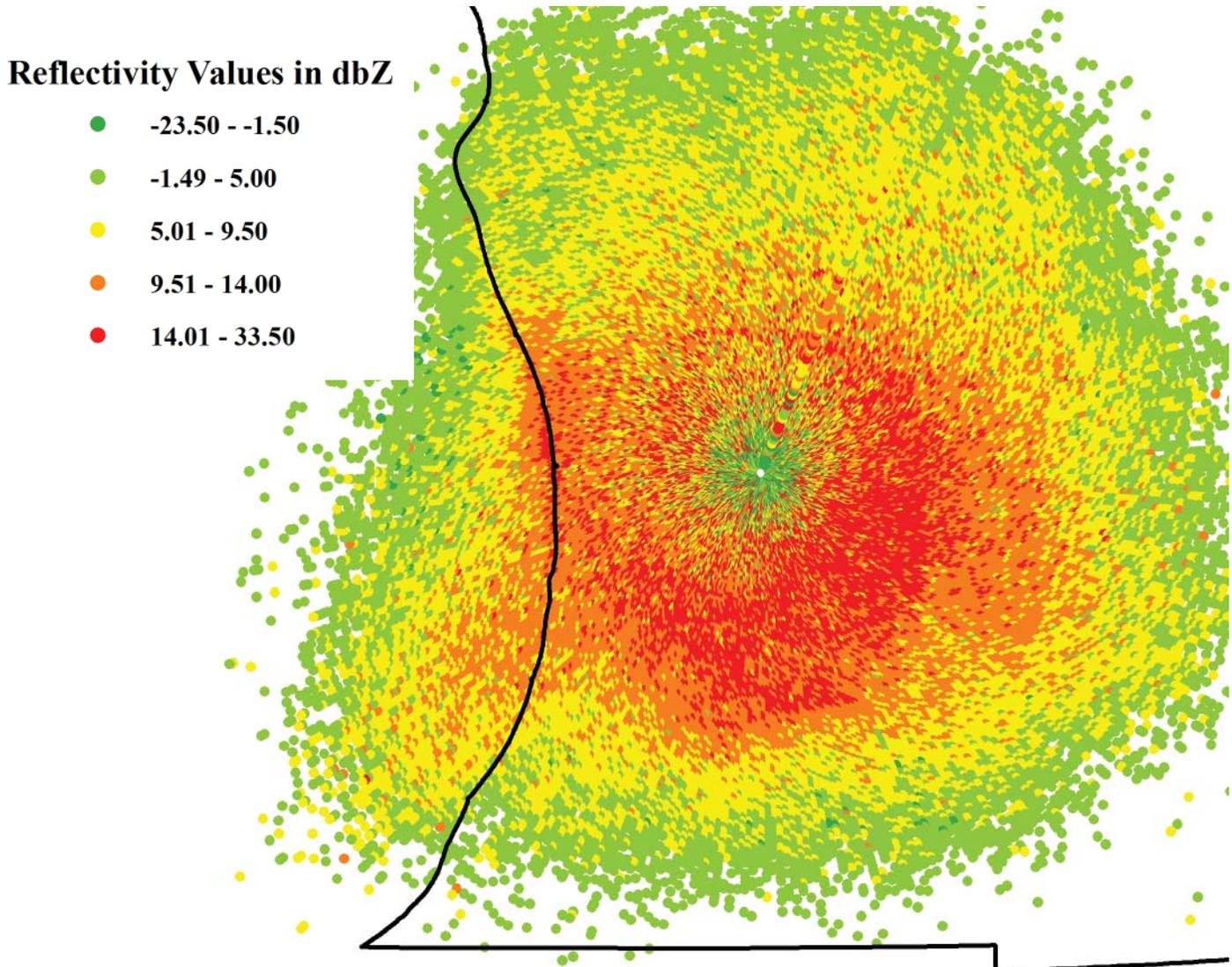
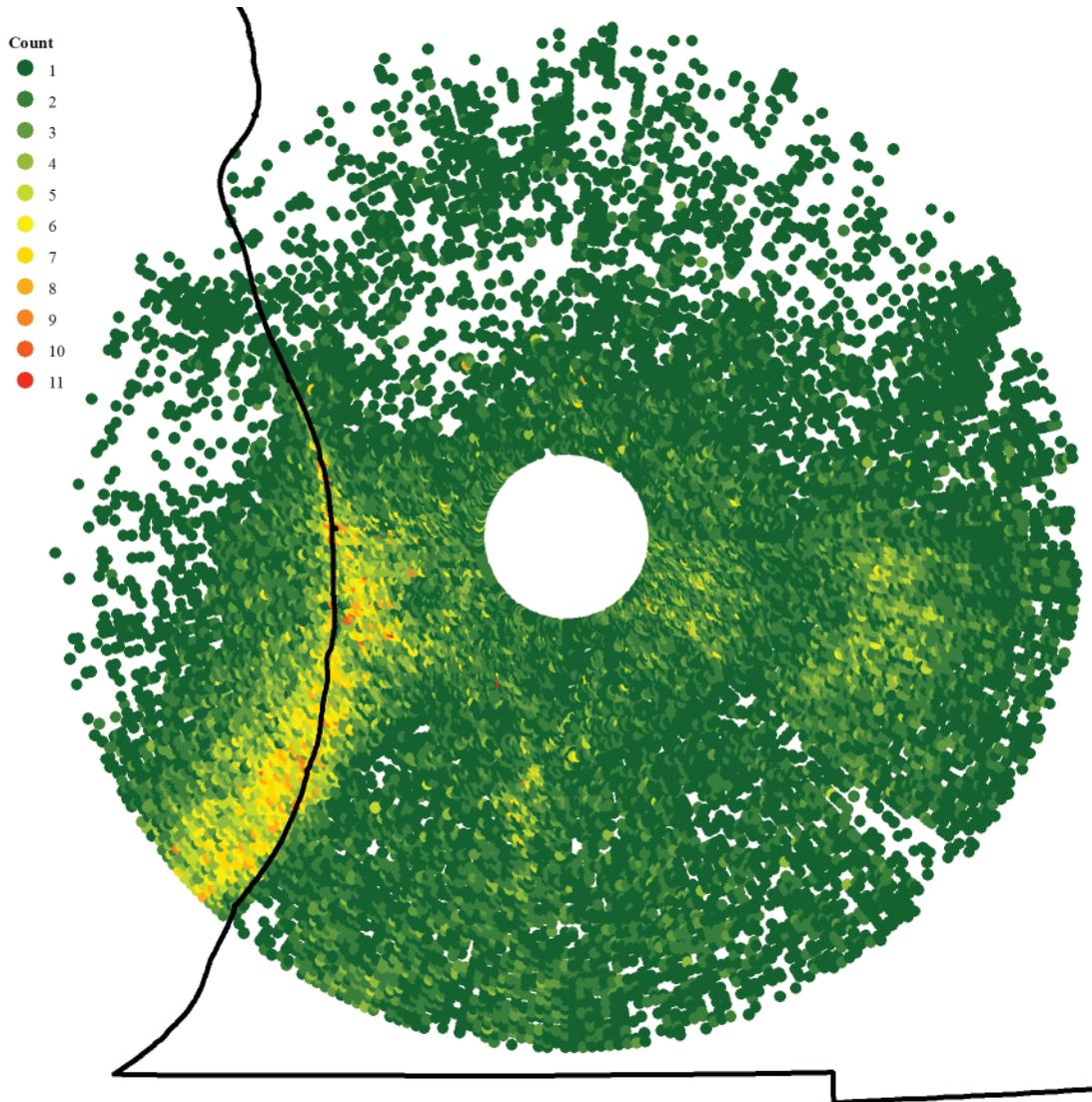


Figure 4. The number of days a point was in the top 5% of daily reflectivity values for the KGRR radar during Spring 2008 migration at the peak migration time.



points within a neighborhood to determine if there is a statistically significant clustering of hot or cold points (Mitchell 2009).

Given a set of weighted data points, in our case the number of days a location was high in bird density, the Getis-Ord G_i^* statistic is calculated as:

$$G_i^* = \frac{\sum_{j=1}^n w_{i,j} x_j - \bar{X} \sum_{j=1}^n w_{i,j}}{S \sqrt{\frac{n \sum_{j=1}^n w_{i,j}^2 - \left(\sum_{j=1}^n w_{i,j} \right)^2}{n-1}}}$$

where x_j is the attribute value for feature j , $w_{i,j}$ is the spatial weight between feature i and j , n is equal to the total number of features and:

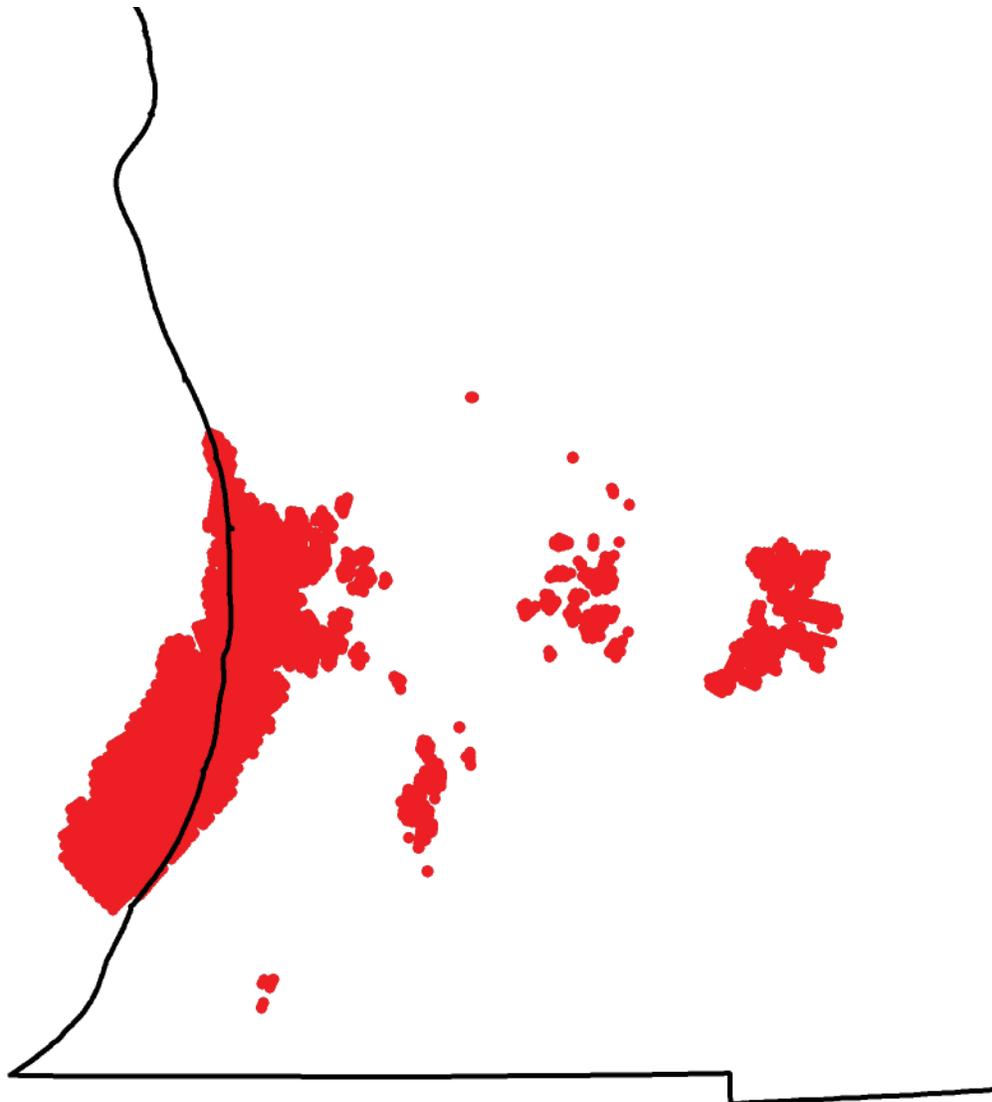
$$\bar{X} = \frac{\sum_{j=1}^n x_j}{n}$$

$$S = \sqrt{\frac{\sum_{j=1}^n x_j^2}{n} - (\bar{X})^2}$$

We used the k nearest neighbors spatial conceptualization of neighborhood ($k = 12$). The Getis Ord G_i^* calculates a normal z-score given a set of features. Hot spots are statistically significant ($p \leq 0.05$) clusters of high values as compared to random occurrence. The G_i^* value returned for each feature is a z-score, with an associated probability value. Significant ($p \leq 0.05$) positive z-scores (≥ 1.96) allow rejection of the null hypothesis of complete

spatial randomness and indicate clusters of high values. For our data these clusters represent areas of greatest migration density over the course of the migration season (Spring or Fall) at the sampled time period (peak migration or dawn). Figure 5 shows the statistically significant clusters for the KGRR radar during the Spring 2008 migration, at the peak migration time period.

Figure 5. Statistically significant hotspots ($G_i^* \geq 1.96$) for the KGRR radar during Spring 2008 migration at the peak migration time period.



RESULTS

Figure 6 through Figure 9 present the results for both the Spring and Fall migrations, at the peak migration time and at dawn. To examine hotspot consistency over years, the yearly hotspots for each site/season/time grouping were additively combined to produce a layer indicating the number of years (0-6) a location was considered a hotspot.

The general pattern of the results, for both the Spring and the Fall migrations, is not unexpected. There are more and larger clusters of migration hotspots during the peak migration hours. At dawn, as nocturnal migrants cease flight, the size and intensity of migration hotspots decreases. The following discussion breaks the results into three regions; Upper Peninsula (KMQT), northern Lower Peninsula (KAPX) and the southern Lower Peninsula (KDTX and KGRR). The southern Lower Peninsula sites are viewed together because of their overlapping coverage area.

Upper Peninsula (KMQT)

During the peak migration time slot, there is a consistent clustering of hotspots to the west of the KMQT site. While the hotspot pattern varies in size and shape from year to year, and between the Spring and the Fall migration seasons, it is present during the peak migration time frame in all study years.

In both the Spring and Fall seasons there is a less consistent clustering of hotspots to the East of the KMQT site. This eastern oriented cluster is not as concentrated or as consistent as the cluster to the west of the KMQT site. Only a small area has hotspots in all six study years.

Northern Lower Peninsula (KAPX)

The most consistent pattern of hotspot clusters for the KAPX site is to the east and southeast of the site. This concentration is largest at the time of the Fall peak migration, followed by the Spring peak time, Fall sunrise, and Spring sunrise.

During the Spring migration there seems to be some affinity for the north-west Lower Peninsula shoreline. During the dawn time period there are some concentrations around the islands in Lake Michigan, possibly the result of nocturnal migrants seeking landfall at dawn. This pattern does not hold during the Fall migration.

Southern Lower Peninsula (KDTX and KGRR)

Because the KDTX and the KGRR sites overlap in their coverage of south-central Michigan, their results are viewed together.

The most consistent pattern is the concentration of hotspots along the Lake Michigan shoreline, west of the KGRR site. This shoreline pattern holds up during both the peak time and sunrise, for both the Spring and Fall migration season. Another consistent pattern, although not as strong as the Lake Michigan shoreline, is along the Detroit River – Lake St. Clair corridor, east of the KDTX site.

During the Spring and the Fall peak migration time periods, both the KGRR site and the KDTX site independently show hotspot concentrations over the south-central Lower Peninsula. As would be expected, these hotspots disappear at dawn as nocturnal migrants cease flying.

DISCUSSION

Avian migration takes place over large continental spatial scales. In North America, many avian migrants tend to move in broad fronts on north-south oriented flyways possibly dictated by north-south oriented mountain ranges (Berthold 2001, Lowrey and Newman 1966). A number of factors can affect localized concentrations of migrating birds (birds per unit volume) within a larger scale flyway, including wind and weather events, terrain, availability of stopover sites, and physiographic features (Lowrey and Newman 1966).

In the Great Lakes region, the juxtaposition of land masses and large water bodies are likely to affect nocturnal avian migration patterns. Nocturnal passerine migrants traveling over large water bodies need places to land sometime during the second half of the night (Bruderer and Liechti 1998). Perkins delineated 17 Great Lakes flyways based on observations of nocturnal migrants landing on Great Lakes ships (Perkins 1964 and 1965). A number of researchers have noted a preference for nocturnal

Figure 6. Number of years (0 - 6) a point was a statistically significant hotspot ($G_i^* \geq 1.96$), for the Spring migration at peak migration time.

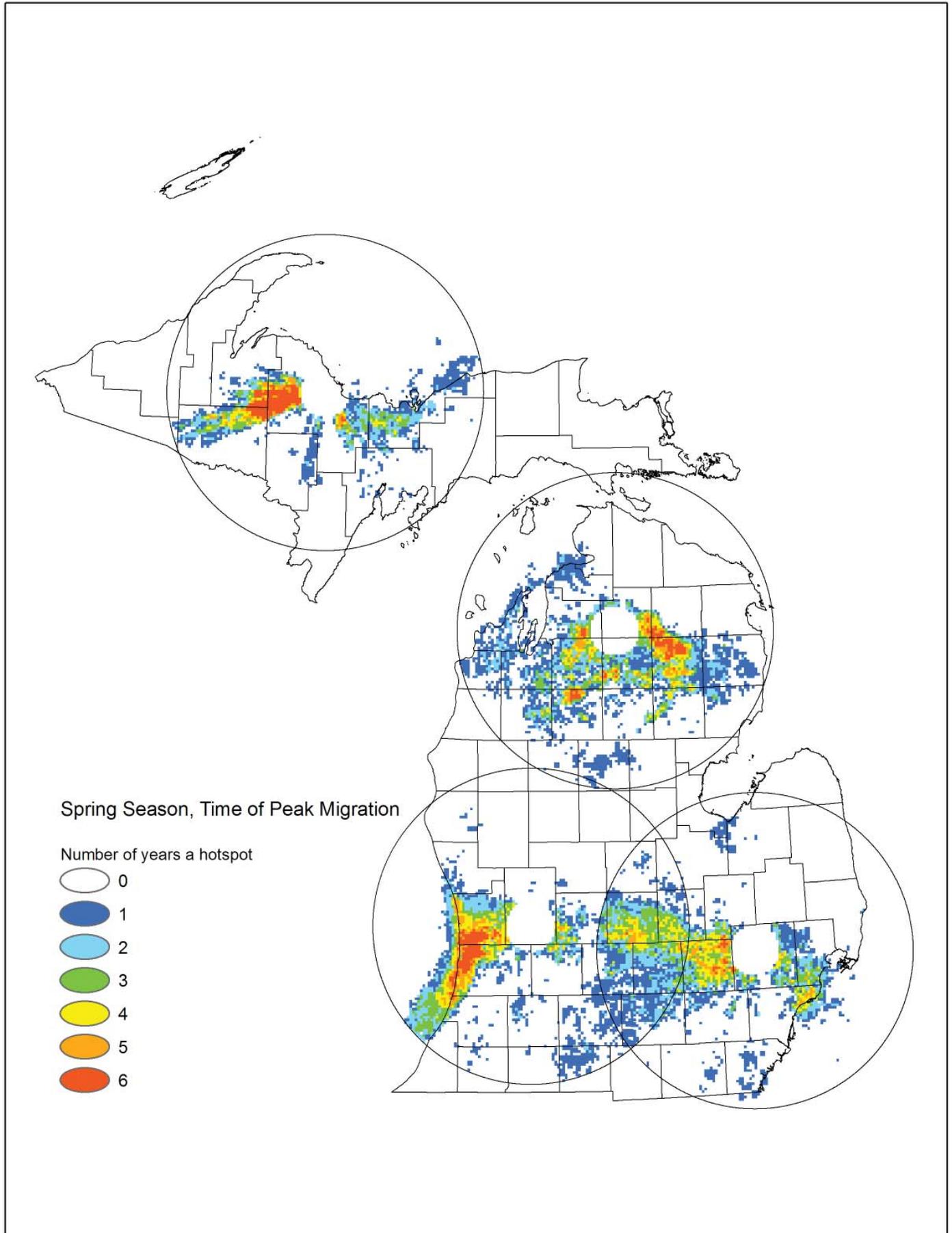


Figure 7. Number of years (0 - 6) a point was a statistically significant hotspot ($G_i^* \geq 1.96$), for the Spring migration at sunrise.

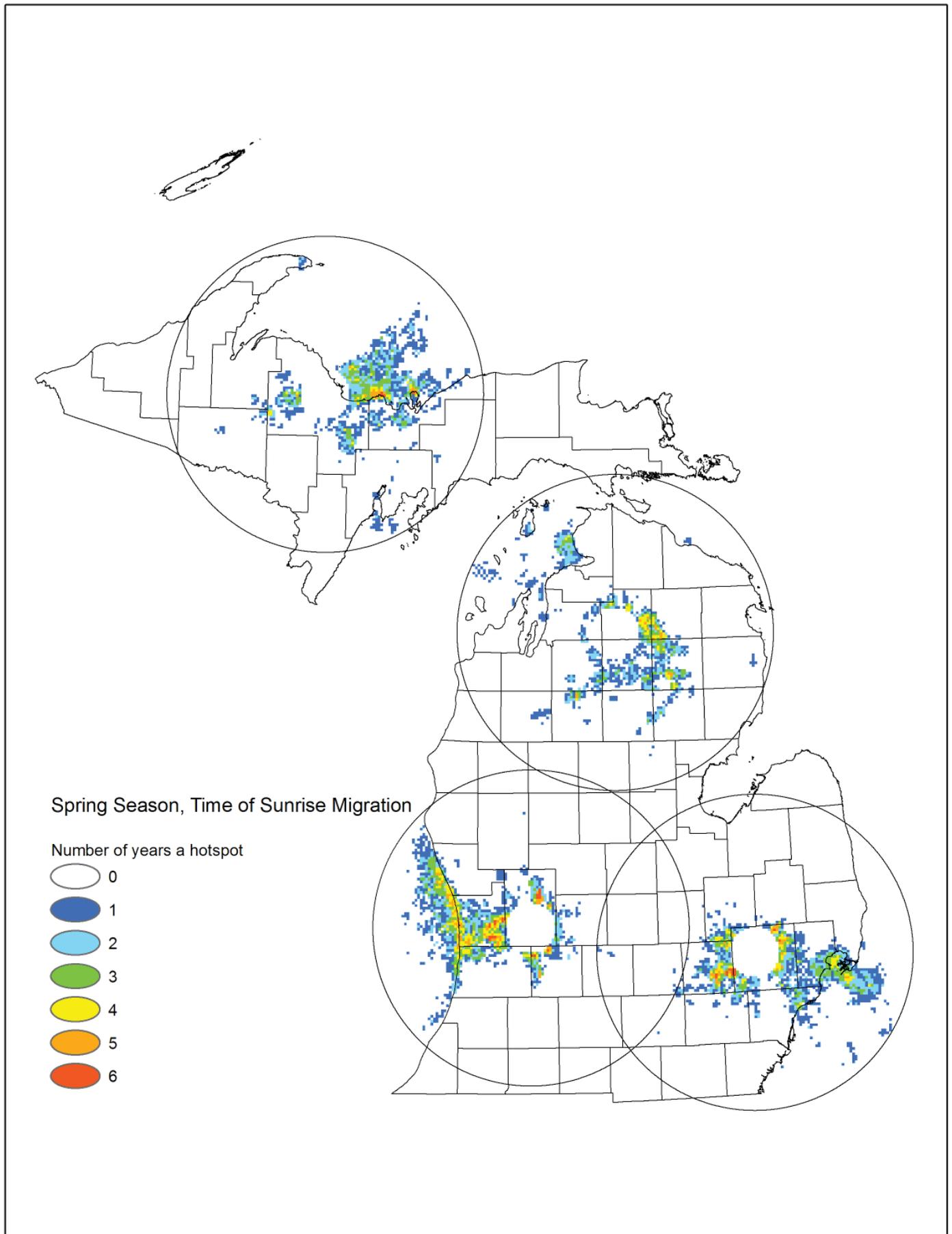


Figure 8. Number of years (0 - 6) a point was a statistically significant hotspot ($G_i^* \geq 1.96$), for the Fall migration at peak migration time.

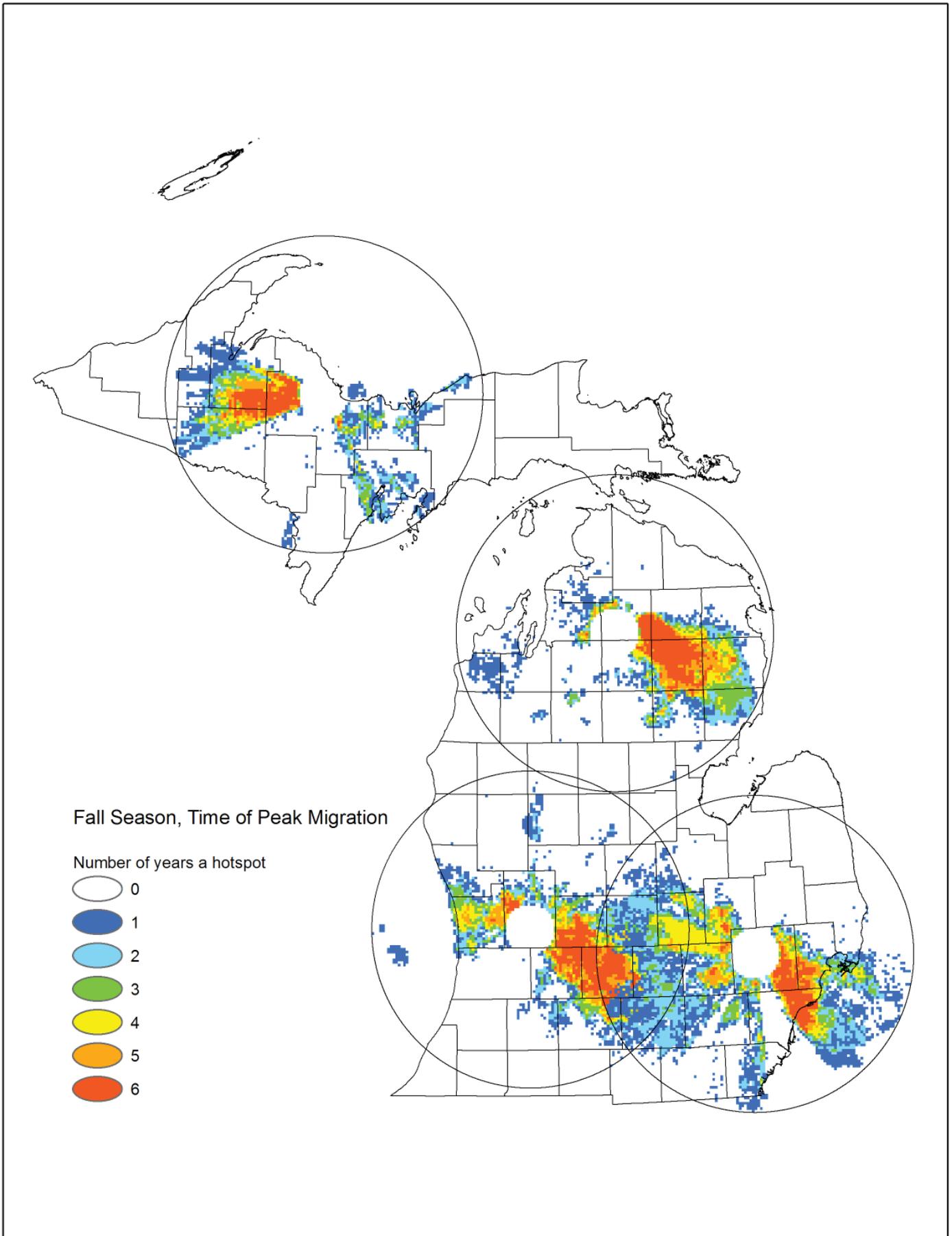
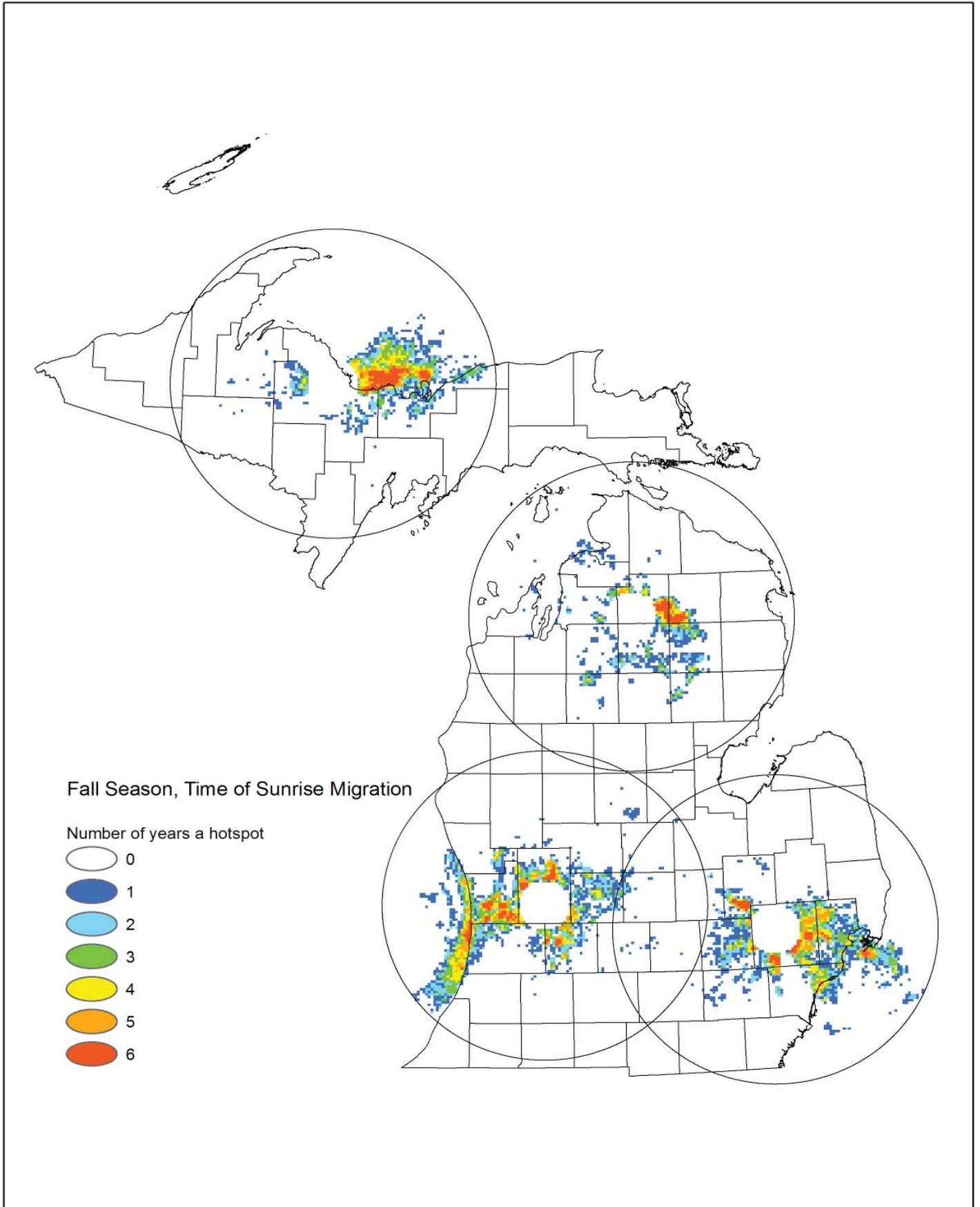


Figure 9. Number of years (0 - 6) a point was a statistically significant hotspot ($G_i^* \geq 1.96$), for the Fall migration at sunrise.



migrants to avoid crossing obstacles such as long water crossings when there is insufficient time to complete crossing before sunrise (Newton 2008, Bruderer and Liechti 1998, Bruderer and Liechti 1995). Bruderer and Liechti noted that some birds, notably those with less fat reserves, have been observed starting an overwater excursion but reversing course and returning to land at daybreak (Bruderer and Liechti 1998). Others have reported that when the coastline is perpendicular to the direction of migration there appears to be no shoreline effects on migration direction, however, when the coastline is oriented along the direction of migration there is some bias to migrating in the proximity of the coastline (Bruderer and Liechti 1998, Lowrey and Newman 1966, Dury and Nisbet 1964). Because of the potential for conflict between coastal wind energy development and avian migrations, proper delineation of avian shoreline migration concentration areas is critical for informed decision making.

Our approach of applying spatial statistical analysis is novel to the study of bird migration and one should ask, “Does this approach and methodology seem reliable?”

One simple test of our methodology is to compare the results from two known and documented extremes of nocturnal migration patterns available from other researchers; the peak time when one would expect to see larger and more numerous concentrations, and the dawn descent when the size and number of concentrations areas should decrease. Our results are compatible with what would be expected between these two events: large overland concentrations are detected at the peak migration time and they disappear at the dawn descent.

The migration concentration areas delineated utilizing our procedures are consistent from year to year and, as stated above, they generally agree with the work of others (Bonter et al. 2009, Diehl et al. 2003). In addition, both the KGRR and the KDTX radars independently show a migration concentration area during the peak migration time period where their coverage overlaps in south-central Michigan.

Of particular interest for this study is the relationship between nocturnal migrants and coastlines. The results from the KGRR, KMQT, and KDTX radars show consistent coastal concentration areas during both

the Spring and Fall migration periods in all six years of data. The results for the KAPX radar show some migration concentrations along the northwest coast of the Lower Peninsula but these concentrations are not as consistent year to year as concentrations detected by the other three radars.

Our results agree with the observations of others regarding the dawn reorientation of nocturnal migrants caught over water at sunrise (Diehl et al. 2003, Bruderer and Liechti. 1998). In this behavior, nocturnal migrants caught over open water at sunrise tend to reorient their direction to the nearest possible landfall. Some migrants have been documented to start across a water body, only to turn back if they cannot make the crossing before daylight. Dawn concentration areas, in particular those detected by the KGRR and KMQT sites, are consistently in close proximity to shorelines. While our analysis looked only at bird densities and not route directional changes, these results are consistent with prior observations of overwater nocturnal migrants reorienting to landfall at dawn.

KMQT (Western Upper Peninsula)

During both the Spring and the Fall migrations the strongest, most persistent, peak migration time concentrations occur over land to the west of the KMQT radar. This concentration aligns with a north-south migratory flyway across Lake Superior delineated by Perkins (Perkins 1964 & 1965) and occurs over the Peshekee Highlands (Schaetzl et al. in press), the highest elevations in Michigan. Our results may be a function of vertical space compression. Utilizing the National Elevation dataset (NED; Gesch et al. 2009), there is as much as a 375 meter change in elevation from the Lake Superior surface to the top of the Peshekee Highlands (184 meters - 559 meters). Most migration takes place within a band from the surface of the Earth to approximately 1600 meters (one mile) above the surface (Lowery and Neuman 1966) and 75% of songbirds migrate between 150 and 600 meters (Smithsonian 2012). Birds migrating at an altitude higher than the highlands are able to pass over the highlands without changing altitude. However, birds crossing the highlands at a lower elevation will need to increase their elevation in order to cross the highlands. A change of 375 meters represents an approximate 23% compression of overall migration space and 63% compression of the space used by 75%

of migrating songbirds.

Another possible explanation for this consistent pattern is a combination of temperature influenced beam refraction and topographical interference. Buler and Deihl (2009) reported the potential for temperature inversions to refract the radar beam earthward. As shown in Figure 10, when compared to the NED portions of the radar beam may interact with the surrounding hills. Diehl et al (2003) did not use the KMQT radar in their analysis because of concerns about beam blockage. The combination of downward refraction coupled with topographic interference may result in measured reflectivity values higher than what can be explained solely by concentrations of migrating birds.

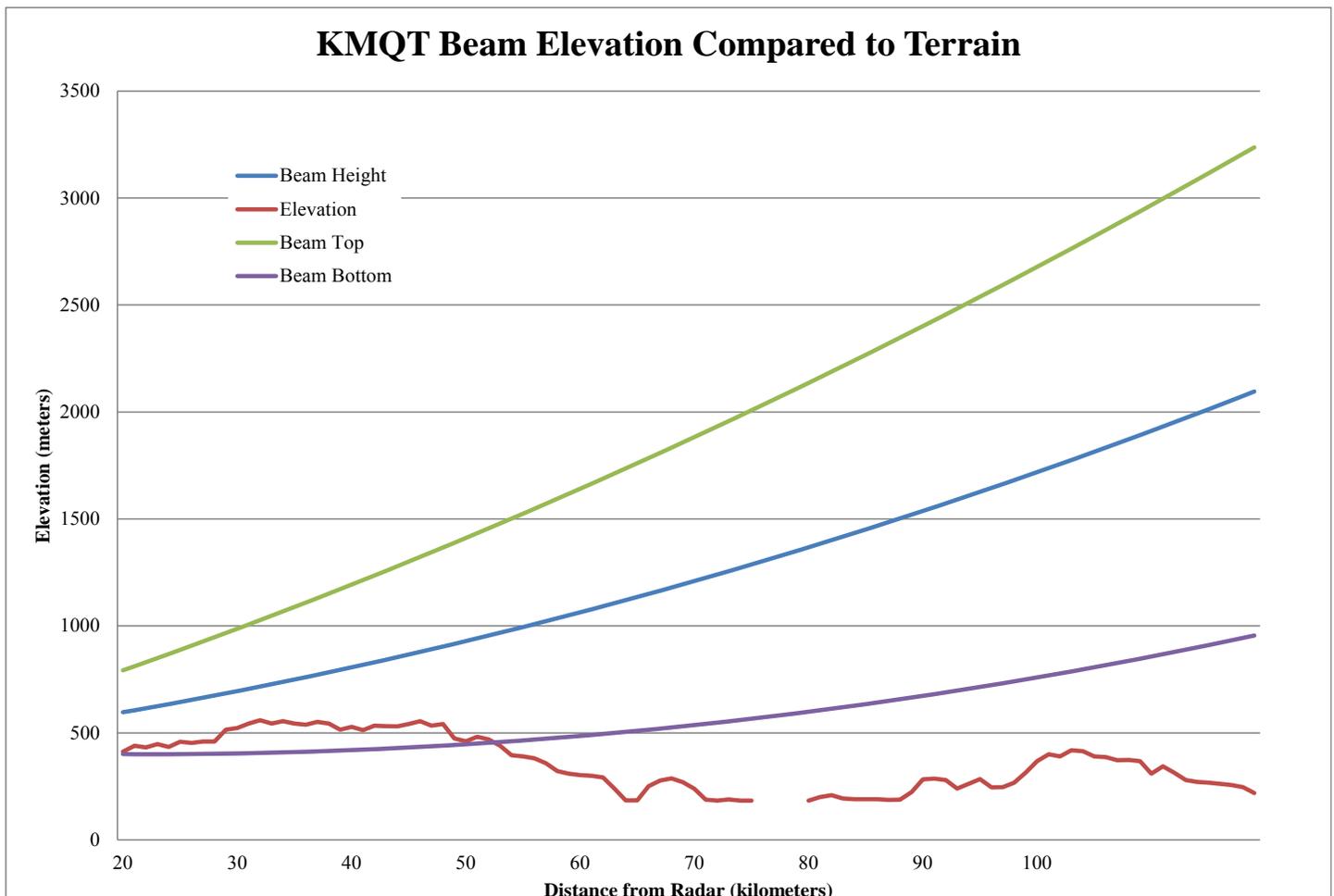
The concentration areas over the Peshekee Highlands reduce in size and intensity during the dawn descent, providing some evidence that the peak migration time results cannot be entirely attributed to beam refraction and topographical interference. Beam refraction

should be strongest in Spring, due to more frequent inversions, but we see similar patterns in both the Spring and the Fall (Diehl et al. 2003). In fact the Fall concentration is larger than the Spring concentration. The opposite would be true if beam refraction was a significant component of the measured reflectivity values, providing further evidence that our results for the peak time concentrations are in fact valid migration concentration areas.

During the dawn descent, as would be expected, the overland migration concentrations decrease in size and intensity while concentrations over Lake Superior or near the shoreline dominate.

The mechanics of the dawn shoreline concentration areas detected by the KMQT radar are likely different between the Spring and Fall migrations. At dawn, during the Spring migration, nocturnal migrants must choose between dropping to land, crossing Lake Superior during daylight hours, or starting the lake crossing and turning back. During the Fall migration

Figure 10. KMQT beam elevation and the underlying topography, at a bearing of approximately 300° from the radar.



at dawn, the nocturnal migrants detected in proximity to the shoreline have already crossed Lake Superior and are trying to make landfall.

Our results appear to track the expected differences between the Spring and Fall migrations. During Fall migration the dawn concentration areas along the shoreline are larger and more intense than those of the Spring migration. The Fall concentrations extend further north into Lake Michigan while the Spring concentrations are in close proximity to the shoreline. This result makes sense biologically as the birds during Spring migration are more likely to drop from migration before dawn rather than start crossing Lake Superior at dawn or start the crossing and turn back. The more intense Fall migration concentrations are the result of birds trying to make landfall having already crossed Lake Superior.

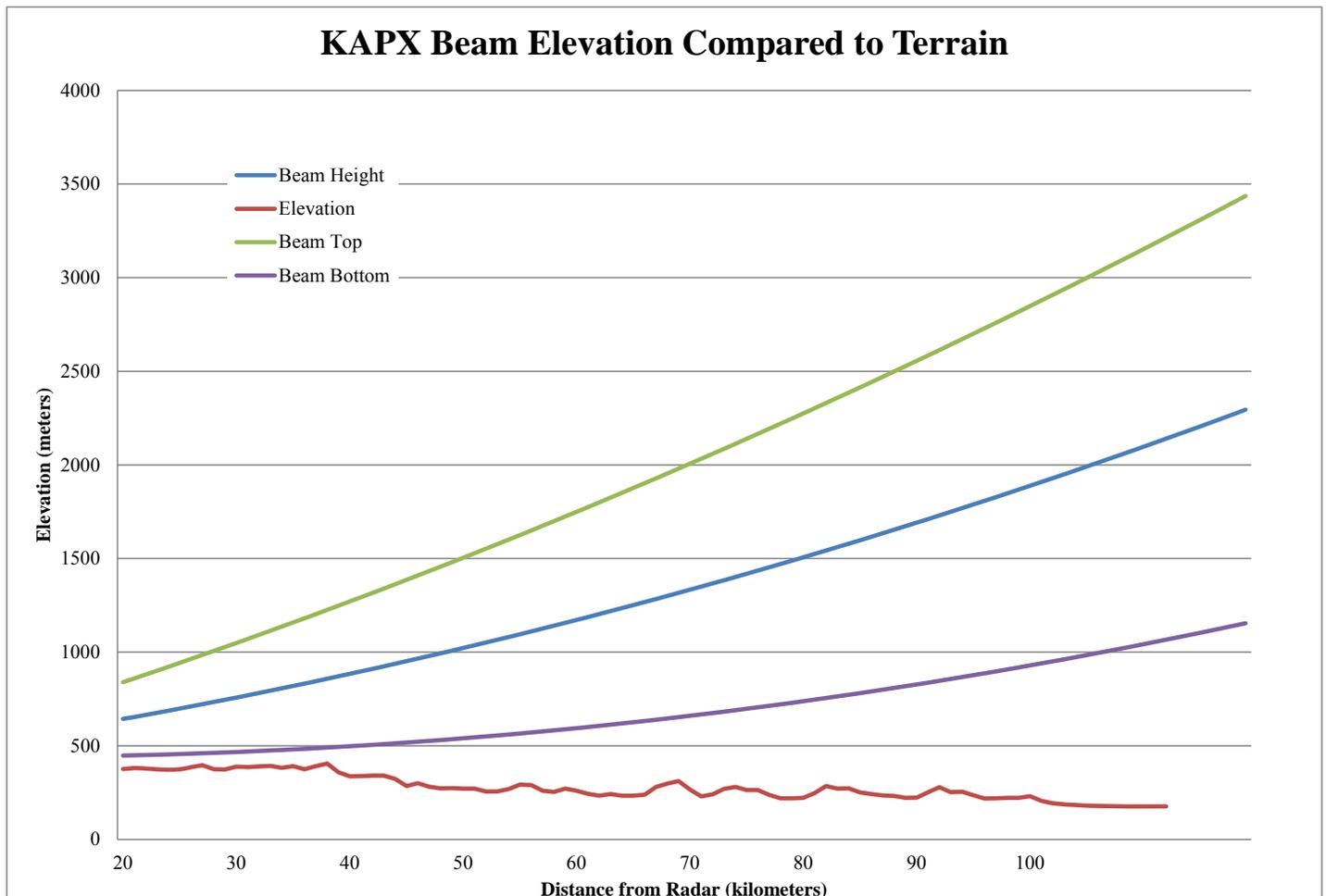
KAPX (Northern Lower Peninsula)

The KAPX radar is located within an upland

physiographic region termed the High Plains (Schaetzl, et al. in press). During each of the four time slots, the high concentration areas appear to align with the northeast boundary of the region. While there may be the same concerns about temperature influenced beam refraction and topographical interference as with the Pesheeke Highlands and the KMQT radar, comparisons of the radar beam height and the NED show little likelihood of terrain interference influencing the results (Figure 11).

There are notable differences in the distribution pattern of high concentration areas detected by the KAPX radar between the Spring and Fall migrations. During the Spring migration, at the peak time, concentration areas are smaller, less intense, and generally more spread over an extended east-west band than the Fall high concentration areas for the same time period. As with the pattern observed in the Upper Peninsula, the difference between the patterns for the peak migration time of the two seasons may be

Figure 11. KAPX beam elevation and the underlying topography, at a bearing of approximately 90° from the radar.



explained by the seasonal direction of the migration and the landforms underlying the general flight paths.

At the peak nocturnal migration time, birds migrating northward during the Spring migration have predominately come overland, without their flight path significantly altered by crossing or traveling along significant water bodies. The placement of the Spring year to year high concentration areas appears consistent with the idea of a broad overland migration front. Conversely, birds migrating southward during the Fall migration time have encountered Lakes Huron, Michigan, Superior and their respective shorelines. In addition, as southward migrants encounter the High Plains, they will encounter an approximately 230 meter change in elevation between the elevation of Lake Huron and that of the High Plains, resulting in a compression effect similar to that seen due to the Peshekee Highlands.

As would be expected, at sunrise when the nocturnal migrants cease flying, the concentration areas in both the Spring and Fall migration significantly decrease in size and intensity.

KGRR and KDTX (Southern Lower Peninsula)

Because of the coverage overlap between the KGRR and the KDTX radars, it is worth examining their results together. Taken together their coverage is bounded on the west by Lake Michigan, (a large north-south oriented water body), has a large inland land mass, and has an eastern boundary bounded by a complex mixture of land masses and Lakes Huron and Erie.

One striking pattern in the KGRR results is the apparent affinity of migrating birds for the Lake Michigan shoreline and near shore area. This pattern holds for both the Spring and Fall migration and for both peak time period and the dawn time period. These results are in agreement with others who have reported a general tendency for migrating birds to follow appropriately oriented shorelines and in particular with Diehl et al. (2003) who found migrating birds tended to move parallel to the Lake Michigan shoreline.

During the Spring peak migration time there is a consistent and intense concentration area over water and land that aligns with the north-south oriented shoreline. This concentration is likely a function of some northbound migrants redirecting their flight

from over water to closer to the shoreline. At the dawn descent, however, as the overland birds drop from migration and the overwater birds redirect to landfall, the high concentration areas appear immediately along the shoreline.

The importance of the shoreline at the dawn descent is also evident in the KGRR Fall migration data. However, at the peak migration time period the largest, most intense concentration area for the KGRR radar is to the east in southern Lower Peninsula interior. While there is a smaller high concentration area in proximity to the shoreline, it is not as large or as intense as the interior concentration area or as the Spring migration concentration area for the same time period. A year to year high concentration area appears in close proximity to the shoreline, very similar in position and size as the Spring migration results for dawn. As in the Spring migration, this result is indicative of overwater birds reorienting to the shoreline to make landfall. This result also agrees with the results observed by others (Diehl et al. 2003). These differences between the Spring and Fall peak migration time concentrations are likely a function of migration direction, timing, and liftoff locations. At the dawn descent, as the overland birds are dropping out of the flight, the inland concentrations disappear.

The area to the southeast of the KDTX radar shows consistent, year to year high concentration areas along the Lake Huron-Lake St. Clair-Lake Erie corridor. At peak migration time, the Fall migration concentration is much larger and more intense than that of the Spring migration. This area is a juxtaposition of two land masses, Michigan and Ontario, Canada, interspersed with portions of Lake Huron, Lake St Clair, and Lake Erie. Birds migrating southward during the Fall migration have had to cross Lake Huron or migrated along the Lake Huron shorelines in Michigan and Ontario. The shape of Lake Huron could be acting as a funnel, directing southward bound birds into a concentration along the Lake Huron-Lake St. Clair-Lake Erie corridor. During the Spring migration the northward bound birds are largely flying over a continuous land mass until they come to Lake Erie. The Spring peak migration time concentration area to the southwest of the KDTX radar may be indicative of some northbound migrants redirecting their path along the western coast of Lake Erie rather than a straight lake crossing.

Of particular note is the finding that during both the Spring and the Fall migration peak times both the KGRR radar and the KDTX radar independently show high migration concentration areas over south central Michigan. To the best of our knowledge, this finding is the first report of a concentrated flyway directly through the center of the Lower Peninsula of Michigan. When looking at the larger landscape scale, the combined results of the two radar sites in south-central Michigan are consistent with a broad overland migration front. Assuming a lift off time of 1800 hours and an average songbird migration speed of 30 mph (USGS 2012), southbound migrants have traveled at most approximately 150 miles at the time of detection. This means that the majority of the southbound migrants detected in south-central Michigan have been migrating overland with minimal if any influence from coastlines. Northbound migrants in south-central Michigan have come overland from Indiana and Ohio, without influences of large water bodies. This detection of the same high concentration area by independent radars provides support that our methodology to detect nocturnal migration concentration areas is valid.

Relevance to wind energy

The high concentration areas delineated using our methodology are those areas with statistically significantly greater concentrations of migrating birds as compared to other areas. Migration, however, occurs on broad fronts throughout the study area, not only in the high concentration areas. During the peak migration time period, and in clear weather, wind farms are not likely to cause large scale bird kills. Wind turbine towers typically have hub heights 60 – 90 meters above ground, with blade length ranging from 20 – 40 meters (http://en.wikipedia.org/wiki/Wind_turbine), for an effective rotor swept area of 40 – 130 meters above ground, while 75% of songbird migrants occur between 150 and 600

meters of the surface of the earth (Smithsonian). This spatial separation lessens the likelihood of interactions between nocturnal migrants and wind towers, while the birds are in flight during good weather.

The situation is different for nocturnal migrants that encounter inclement weather during the peak migration time period. Inclement weather can force migrants to lower altitudes or the ground, increasing their risk of encountering wind farms. Consequently, wind farms placed in consistently high nocturnal migration concentration areas have higher potential over time to have large weather related fatality events than wind farms located in areas with lesser nocturnal migrant concentrations.

While the greatest concern with wind farms situated in overland high concentration areas comes during inclement weather events, wind farms sited in coastal areas have the ability to negatively impact migrating birds on a daily basis. As shown in our results, and the work of others, shorelines become high concentration areas at the dawn descent. This is the time that migrants are within the elevation of wind towers, increasing the likelihood of collisions. Consequently, wind farms in the vicinity of the shoreline concentration areas have a daily increased risk of adversely impacting nocturnal migrants.

However, it should also be noted that the high concentration areas delineated during this study also correspond to the areas of highest wind energy in the state, namely along the east coast of Lake Michigan. Placement of wind farms near the shore could result in significant levels of interaction between birds and turbines during periods of ascent and descent during migration. Current wind farm siting guidance and public acceptability of wind farms with respect to the Great Lakes shoreline however, counterbalance this possibility; current thought on siting wind farms is that they need to be at least six miles from shorelines to prevent unacceptable impacts to viewsheds.

LIMITATIONS

Inversions of temperature and moisture will cause anomalous propagation of the radar beam (usually refraction) (Turton et al. 1988) and this effect can vary diurnally, seasonally and geographically. Temperature inversions often occur at sunset and increase into the night, as radiative cooling from the ground warms the air close to the surface. Our data at the time of

peak migration would be more likely to be affected by refraction than the data near dawn. At the Marquette site, greater than standard refraction may result in some degree of topological blockage.

We did not account for possible directional bias; specifically, when birds fly parallel to the radar beam

a larger cross-sectional area is exposed than when perpendicularly oriented, which may cause higher reflectivity values (Edwards and Houghton 1959). For example, the absence of hot spots in the Saginaw Bay area may be due to the fact that it is located directly north of the KDTX radar site, and flight patterns are likely parallel to the beam. Also, this area is near the maximum range of the radar and the beam altitude may be passing over the majority of the migratory layer.

CONCLUSION

Areas such as the Lake Michigan shoreline have long been considered bird migration concentration areas. There is however, the simple fact that things are found where you look for them. One cannot differentiate any particular area as a high concentration area relative to any other area without examining multiple areas simultaneously. As shown by our study and the results of others, using NEXRAD radar to examine migration patterns allows us to perform near simultaneous monitoring of numerous locations in a quantifiable manner. Each NEXRAD radar site can be essentially be used as an approximately 200 km transect to examine avian migration patterns.

The results of our analysis agree with the results of others, produced using different methodologies. The methodology we present allows for a relatively straightforward use of “one of the largest biological data archives in the world” (Chilson et al. 2012), with readily available technology, to quantify avian migration patterns. Portions of the processing can be automated, increasing the utility of the methodology and the data.

The results of our analysis demonstrate that there are consistent, predictable areas of avian concentration during migration periods. These areas include areas of the western Upper Peninsula of Michigan; the north-eastern portion of the Lower Peninsula, shoreline areas along Lake Michigan, especially along southern Lake

Daily measures of reflectivity near dawn may reflect differences due to the timing of the data and the location, thus introducing some error into the results. The landing of birds at dawn is a relative short-term behavior in relation to the temporal resolution of the radar, and the onset is not necessarily synchronized. Additionally, there is an east-west gradient to the time of sunrise, and given the 240 km difference from east to west in our data this may be a source of bias.

Michigan, the Lake St. Claire-Detroit River-western Lake Erie corridor, and the south-central portion of the Lower Peninsula. This last finding is of particular note, as this study is the first to document this avian migratory concentration area and was confirmed by two independent NEXRAD installations.

These findings can be directly useful in siting wind farms. While the concentration areas, especially along Lake Michigan coincide with areas of high wind energy, current guidance for siting wind farms and public acceptance will help to avoid avian-wind farm interactions. Additionally, the flight behavior of nocturnal migrants, especially during periods of fair weather will also act to reduce the potential for bird-turbine interactions (flight elevations are above the typical rotor swept areas) during most of their migratory flights, except during ascent and descent. However, this mitigatory factor may not be operate during periods of inclement weather.

Further use of these data and our methodology should be explored. For instance, Kelly et al (2012) suggest utilizing the 20 year archive of NEXRAD data to examine seasonal phenology changes in volant species that could be a result of climate change. While our study focused on radar sites located in Michigan, a comprehensive quantification of Great Lakes migration patterns would come from expanding the geographic scope of our study.

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