THE EFFECT OF HURRICANE SANDY ON LANDBIRD MIGRATION IN THE NORTHEASTERN UNITED STATES

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Entomology and Wildlife Ecology

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TABLE OF CONTENTS

LIST OF TABLES vi
LIST OF FIGURES vii
ABSTRACT xi

Chapter

1 ANALYIS OF BIRD MOVEMENTS SAMPLED BY RADAR AT SUNSET IN THE COASTAL NORTHEASTERN UNITED STATES IN AUTUMN 1

Methods 4

Radar data processing and analysis 4

Field Surveys 7

Analysis 9
Results 10
Discussion 25

2 THE EFFECT OF HURRICANE SANDY ON STOPOVER DISTRIBUTIONS OF MIGRATING LANDBIRDS IN THE NORTHEASTERN UNITED STATES 36

Methods 40
Analysis 45
Results 46
Discussion 60

3 ANALYSIS OF MIGRANT TRAFFICE RATES BEFORE AND AFTER PASSAGE OF HURRICANE SANDY IN THE NORTHEASTERN UNITED STATES 66

Methods 71
Analysis 74
Results 75
Discussion 79

REFERENCES 83

LIST OF TABLES

Table 1 Model estimates from the spatial error model explaining change in bird density after Hurricane Sandy from 15,000 observations. (*) denote if the parameter estimate was significantly different from zero in the model. 60

LIST OF FIGURES

Figure 1 Study area and field sites across two radars identified by their call sign in the Mid-Atlantic. The four main field sites, identified by their names. Additionally, I performed a single survey at four other sites for presence of communal roosting activity: 1. Allentown, NJ 2. Iron Works Park, NJ, 3. Ashbrooke Elementary, NJ, and 4. Dover, DE. Bird density measured from radar reflectivity for years 2008-2015 at sunset. Blue areas represent low bird density and increase towards red areas with high bird density 5

Figure 2 Total species at survys. Individual birds counted by species among 14 surveys. Species are identified by four letter AOU code (COGR – Common Grackle, AMRO – American Robin, EUST – European Starling, CAGO – Canada Goose, RWBL – Red-winged Blackbird, HEGU – Herring Gull, ABDU – American Black Duck). 12

Figure 3 Total bird counts and average reflectivity on nights with no sunset exodus (n=11). Species are identified by their four letter banding code. Common Grackles were by far the highest count species across all surveys. 13

Figure 4 Mean reflectivity at four field sites measured from radar on nine total nights. Two nights could not be calculated due to range detection issues. Sun elevation angle is measured as the elevation before sunset. One sun elevation at this time of year and location approximately equals 5 minutes. 14

Figure 5 Total bird counts and average reflectivity on nights with a sunset exodus (n=3). Species are identified by their four letter banding code. . 16

Figure 6 Total reflectivity derived from radar scans at 3 survey sites on nights when radar detected birds leaving habitats at sunset. Sun elevation angle is measured as the elevation before sunset. One sun elevation at this time of year and location approximately equals 5 minutes. 17

Figure 7 Average reflectivity on nights with a sunset exodus identified from October 15 – November 30, 2008 – 2015. 18

Figure 8 Interpolated reflectivity mapped along the Delaware Bay for 2015. Bayside Drive and Turkey Point field sites are along the bay shore in emergent marsh with forest just inland. Reflectivity increases at forested sites inland and shifts laterally over emergent marsh starting at 91°, which are corroborated by field surveys showing American Robins leaving forested habitats. After 91° reflectivity is over emergent marsh where field surveys reported birds after birds left the forested edge inland. 19

Figure 9 Average reflectivity on nights with a sunset exodus identified from October 15 – November 30, 2008 – 2015. 21

Figure 10 Proportion of each land cover type in 'high use' areas on nights with a sunset exodus and without one. High use areas on nights without a sunset exodus are primarily (+60%) developed cover type followed by agriculture. 22

Figure 11 Identified 'high use' areas on nights with a sunset exodus and without at KOKX (Long Island, NY) and KBOX (Boston, MA). High use areas are sample volumes which are one standard deviation above the mean. 23

Figure 12 Identified 'high use' areas on nights with a sunset exodus and without at KDIX (Mt. Holly, NJ) and KDOX (Dover, DE). High use areas are sample volumes which are one standard deviation above the mean. 24

Figure 13 Identified 'high use' areas on nights with a sunset exodus and without at KLWX (Washington D.C.) and KAKQ (Norfolk, VA). High use areas are sample volumes which are one standard deviation above the mean. 25

Figure 14 Presence of American Robins on individual checklists taken from eBird.org at five locations decreasing in latitude. Presences are the proportion of checklists that entered at least one American Robin. 29

Figure 15 Average reflectivity for all nights with no discernible exodus from October 15- November 30 2008 - 2015. Points are locations where I confirmed the presence of a roosting site used by American Robins, Common Grackles, and European Starlings. All sites were checked either with evening surveys (visually tracking birds as they entered a roost) or morning sites (visually tracking the location as birds left a roost). 33

Figure 16 The six radars identified by their call sign along the Atlantic coast in the northeastern United States. Hurricane Sandys path is indicated by the red line. 43

Figure 17 Mean bird density of sample volumes with > 75% of a single cover type at six radars. Red is baseline years (2008 – 2011) and blue is the Sandy year (2012). 49

Figure 18 Change in bird density at KOKX (Long Island, NY) and KBOX (Boston, MA) after Sandy compared to baseline years. Decreases in bird density in blue and increases are in red. 50

Figure 19 Change in bird density at KDIX (Mt. Holly, NJ) and KDOX (Dover, DE) after Sandy compared to baseline years. Decreases in bird density in blue and increases are in red. 51

Figure 20 Change in bird density at KLWX (Washington D.C.) and KAKQ (Norfolk, VA) after Sandy compared to baseline years. Decreases in bird density in blue and increases are in red 52

Figure 21 Maps of high-bird-use areas measured during November of baseline years 2008-2011 (blue), after Hurricane Sandy in 2012 (green), or during all years (black) at KOKX (Long Island, NY) and KBOX (Boston, MA). Sample volumes were categorized as ‘high use’ if it was greater than one standard deviation above the mean bird density. 53

Figure 22 Maps of high-bird-use areas measured during November of baseline years 2008-2011 (blue), after Hurricane Sandy in 2012 (green), or during all years (black) at KDIX (Mt. Holly, NJ) and KDOX (Dover, DE). Sample volumes were categorized as ‘high use’ if it was greater than one standard deviation above the mean bird density. 54

Figure 23 Maps of high-bird-use areas measured during November of baseline years 2008-2011 (blue), after Hurricane Sandy in 2012 (green), or during all years (black) at at KLWX (Washington D.C.) and KAKQ (Norfolk, VA). Sample volumes were categorized as ‘high use’ if it was greater than one standard deviation above the mean bird density. 55

Figure 24 Composition of habitats used by late-season migrants across all radars during the month of November of 2012 in blue (after Hurricane Sandy) and baseline years in red (2008-2011). 56

Figure 25 Difference in average bird density at the onset of evening flights during November between 2012 and previous years (2008-2011) as a function of distance north (dark gray) and south (light gray) of Sandy's path. Error bars are standard error. 58

Figure 26 Difference in average bird density at the onset of evening flights during November between 2012 and previous years (2008-2011) as a function of distance from the coastline. Error bars are standard error. .. 59

Figure 27 Difference in average bird density at the onset of evening flights during November between 2012 and previous years (2008-2011) as a function of change in NDVI (greenness) after Sandy's landfall. Dark gray are positive changes and light gray are negative changes. Error bars are standard error. 59

Figure 28 The six radars identified by their call sign along the Atlantic coast in the Northeast United States. Hurricane Sandys path is indicated by the red line 73

Figure 29 Migration Traffic Rate (MTR) on October 27, 2012 (blue) prior to Sandy through the first three hours of the night at five radars across the northeastern United States compared to baseline years (black) during the similar time period (October 25 – October 30). Pink areas are those where rain from Hurricane Sandy interfered with calculation of traffic rate. Bars are 90% confidence intervals calculated for every temporal segment during baseline years... 76

Figure 30 Migration Traffic Rate (MTR) at six radars in the Northeast United States before and after passage of Hurricane Sandy. Pink areas are those where Hurricane Sandy dominated the region with high winds and rain. The Sandy year is in red and the baseline years are in black. Bars are 90% confidence intervals calculated for every temporal segment during baseline years. 78

ABSTRACT

The annual migration of birds between wintering and breeding grounds requires birds to traverse novel landscapes while minimizing mortality and energetic costs in route. In autumn, birds in the eastern United States migrate at a time when large scale hurricane systems typically make landfall along the coastal United States. These storms are capable of killing birds as well as modifying food resources and habitats for birds via extreme winds and storm surge. Hurricane Sandy was a large Category 1 hurricane that made landfall at Brigantine, New Jersey on October 29, 2012. Sandy brought high winds (>90mph), torrential rains, and storm surge up to 12m to the area. Sandy made landfall late in the migration season when landbird migrants like the American Robin *(Turdus migratorius*) and Yellow-rumped Warbler (*Setophaga coronate)* were actively migrating through the storm-affected region. I used six radars across the coastal northeastern US from Boston, MA to Norfolk, VA to analyze how Sandy might have affected birds migrating around the time of the storm. Additionally, I investigated what birds aloft were being observed by weather radars around sunset by performing surveys of birds at sites where birds were concentrated around Delaware and New Jersey during late October and November of 2015. Bird counts consisted primarily of communally roosting species like American Robins, Common Grackles (*Quiscalus quiscula*), and European Starlings (*Sturnus vulgarus*). American Robins were the most common birds seen migrating south around sunset that matched radar observations of birds moving south. I used this information to test how habitat use of birds before and after Sandy changed, by analyzing radar reflectivity measured at sunset at the six radars for baseline years (2008 – 2011) compared to the Sandy year (2012). Densities of birds leaving stopover areas increased in developed areas and decreased in agricultural and wetland areas across the study area after the passage of Sandy. The largest decreases in bird density were within 150km of Sandy’s path, and changes to bird density were unrelated to distance to the coast and changes in vegetation (measured by Normalized Difference Vegetation Index). I tested whether these changes in bird density were due to a shift in migration intensity due to the storm. I analyzed traffic rates at all six radars for the baseline years and the Sandy year. Migration Traffic Rates were three times higher in regions around New York City and New Jersey the night Sandy entered the region (October 27). After the passage of the storm all radars observed significantly higher traffic rates compared to previous years. Two weeks after the storm, the majority of radars observed traffic rates similar to previous years. Current climate models predict an increase in hurricane severity in the future due to climate change. This research shows that birds are relatively plastic in their response to hurricanes, likely due to their high mobility, which may help to mitigate negative effects from future storms.

Chapter 1

ANALYIS OF BIRD MOVEMENTS SAMPLED BY RADAR AT SUNSET IN THE COASTAL NORTHEASTERN UNITED STATES IN AUTUMN

There are two main approaches for studying bird migration: local scale and broad scale. A local scale analysis focuses on tracking individual birds generally by fitting them with radio transmitters (Smolinsky et al. 2013, Hallworth and Marra 2015) or banding birds as they migrate through the region (Wood 1945). These strategies are useful for ascertaining what an individual does but requires large sample sizes to extrapolate across populations and species. These technologies often are not yet appropriate for smaller animals like passerine birds (Bridge et al. 2011). A broad scale approach tracks groups and focuses on the general trends of migration, these include radar studies (Chilson et al. 2012) and moon watching (Lowery and Newman 1966). They capture the general patterns of migration but suffer from the lack of target identity and the high variability inherent in the data. Weather radar, in particular, has been widely used to observe nocturnal bird migration since the 1960’s (Baird and Nisbet 1960), and has been used to track birds as they cross the Gulf of Mexico (Gauthreaux 1971), at the onset of nocturnal migration flight as they leave terrestrial daytime sites(Buler and Dawson 2014), and reacting to weather while aloft (Gauthreaux 1991). Radar can be a powerful monitoring tool when target’s IDs are known (Bridge et al. 2015), or when paired with other methods such as acoustic recordings and thermal imaging (Larkin et al. 2002, Farnsworth et al. 2004).

The northeastern United States is home to some of the most intense migrant land bird traffic during autumn on the continent. Birds that migrate north across the Gulf of Mexico in spring to breed, return south with their offspring along the Atlantic seaboard in autumn in much greater numbers (La Sorte et al. 2014). The peak period of migration is during September and October (Farnsworth et al. 2015) and is dominated by long-distance Nearctic-Neotropical migrants that breed in the temperate and boreal regions of North America and winter in the tropical regions of the Caribbean and South America. By mid-October, birds wintering in the United States dominate and the last migrating passerines (e.g., Dark-eyed Juncos (*Junco hyemalis*) , Yellow-rumped Warblers (*Setophaga coronata*), American Robins (*Turdus migratorius*), finches, etc.) arrive at their wintering destinations by mid-November (Allen and Peterson 1936, Bennet 1952). Many studies of bird migration in the northeastern US have been conducted only during the peak season, likely because many species which can be identified as passage migrants that neither breed nor winter in the region. The study of late-season migration is difficult because birds migrating through the region cannot reliably be distinguished from those that will winter there. Thus, the understanding of the migratory movements of late-migrating passerines remains poorly understood.

On October 29, 2012, Hurricane Sandy made landfall in Brigantine, New Jersey (Blake et al. 2013). Sandy's landfall coincided with the end of migration when late season migrants typically migrate through the northeast United States (Allen and Peterson 1936). Hurricanes can impact migrant birds by destroying crucial habitat required for refueling during migration (Barrow et al. 2005), disrupting the timing of migration (Wiley and Wunderle 1993), and resulting in birds translocated to regions out of their native range (Thurber 1980). Migration is the time of a birds annual cycle when they suffer the highest mortality (Sillett and Holmes 2002), and damaging storms, like hurricanes, are thought to be one cause of declines for already declining species of songbirds in the United States (Butler 2000). Because of this, it is crucial to understand the potential species affected by Hurricane Sandy and to what extent the Hurricane may have disrupted migration.

Nocturnal migrating birds typically initiate migrant flights starting approximately twenty minutes after sunset and continue to leave sites up to four hours after sunset (Åkesson et al. 1996). On weather radar this nightly exodus appears as a large ‘bloom’, as migrants leave habitats and enter the airspace (Gauthreaux and Belser 1998). Analysis of radar scans taken at the moment of exodus correlate with densities of birds on the ground, and can be used to study the stopover use of migrants through the season (Buler and Diehl 2009, Buler and Moore 2011). Sampling birds at the onset of well-synchronized flights has been used to measure ground distributions of multiple bird guilds including waterfowl (Buler and Moore 2011), shorebirds (Sieges et al. 2014), and songbirds (Ruth et al. 2012, Buler and Dawson 2014).

The purpose of this study was to investigate nocturnal flights of migrating landbirds during early November within the coastal mid-Atlantic region of the US. I had three goals: 1) identify the likely bird species engaged in late-season nocturnal flights, 2) characterize the timing of the onset of nocturnal migrant flights for sampling bird stopover distributions with radar, and 3) quantify spatial distributions and habitat use of late-season migrant birds.

Methods

Radar data processing and analysis

I downloaded WSR-88D Level II data from the National Climatic Data Center website at ncdc.noaa.gov for the time period October 15 to November 30 during 2013 – 2015 at six radars: KBOX, KOKX, KDIX, KDOX, KLWX, and KAKQ (Fig. 1). These radars sample the airspace over coastal regions from Massachusetts to Virginia comprised by a mosaic of different land cover types including urban areas, coastal emergent marshes, agricultural fields, and coniferous and deciduous forests.

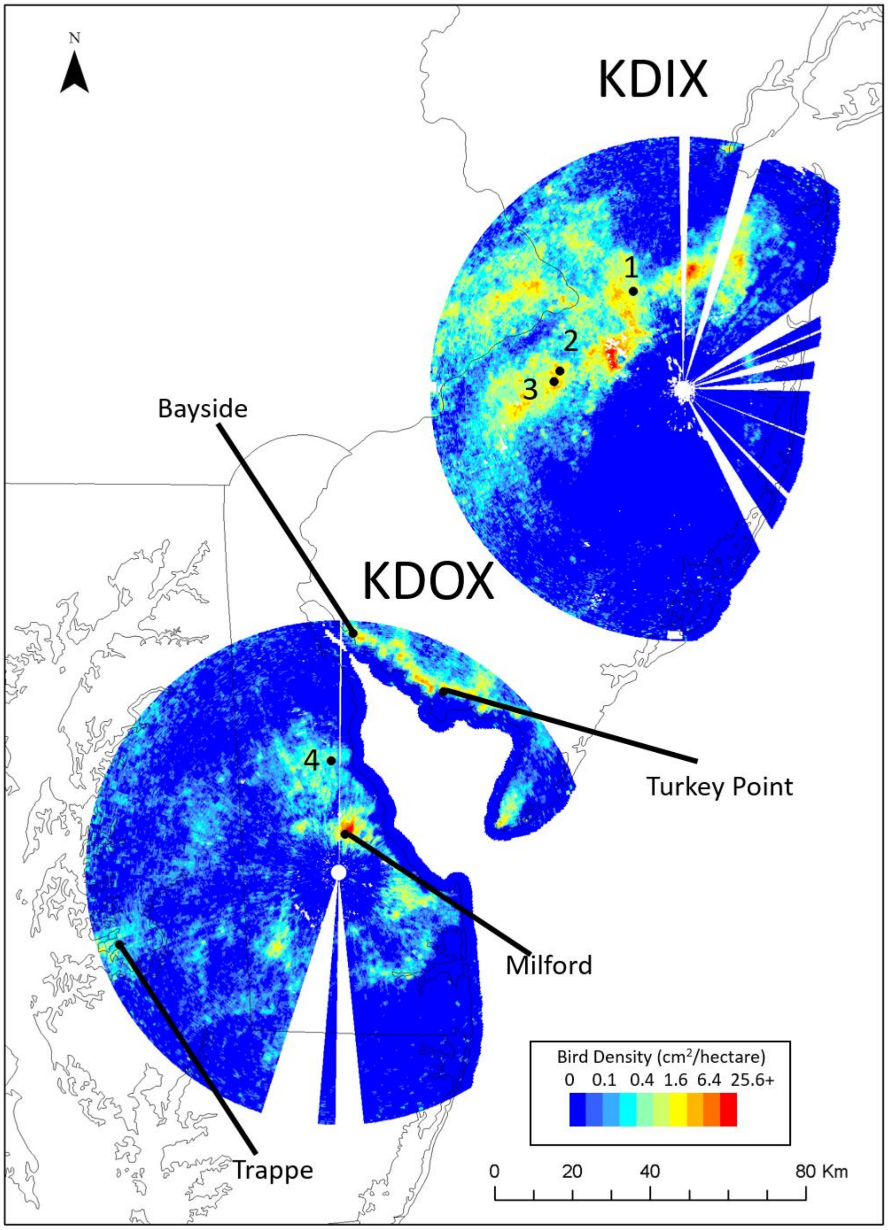

Figure 1 Study area and field sites across two radars identified by their call sign in the Mid-Atlantic. The four main field sites, identified by their names. Additionally, I performed a single survey at four other sites for presence of communal roosting activity: 1. Allentown, NJ 2. Iron Works Park, NJ, 3. Ashbrooke Elementary, NJ, and 4. Dover, DE. Bird density measured from radar reflectivity for years 2008-2015 at sunset. Blue areas represent low bird density and increase towards red areas with high bird density

I visually screened radar images from each night, dropping from further analysis nights contaminated by precipitation or clutter around the time of sunset. During screening, it was noted that the exodus of birds did not always happen after sunset as is frequently seen. Instead, on certain nights near the end of October reflectivity would increase just before sunset. Because of this I placed all remaining nights into three categories based on the intensity and timing of bird flight: a ‘sunset exodus’ when the first onset of bird flight was initiated around sunset, a ‘standard exodus’ when the first onset of bird flight was initiated 20 minutes or more after sunset, and ‘no exodus’ when no noticeable evening bird activity was observed. Nights with a sunset exodus often had a second pulse of reflectivity 20 to 30 minutes after sunset, however, the sunset exodus precluded analysis of this second pulse because the targets at sunset were still present on radar 20 to 30 minutes after sunset. There were no nights in the study period when birds moved north, as is seen occasionally in this region (Baird and Nisbet 1960).

These radars are Weather Surveillance Radar-1988 Doppler (WSR-88D) radars with a 10cm wavelength beam. Radar measures the return signal from a reflected pulse of energy off a target (i.e., reflectivity) in units of Z. WSR-88D radars are run in two modes: clean air mode where scans are taken every 10 minutes at 5 beam elevations (0.5°, 1.5°, 2.5°, 3.5°, and 4.5°), and precipitation mode where scans are taken every 2-5 minutes. The smallest unit of reflectivity is termed a ‘sample volume’ which is the volume of space in the atmosphere above a polygon on the ground.

In order to correct for the radar beams increasing elevation with increasing distance from the radar, I calculated vertically integrated reflectivity (VIR) of sample volumes using methods from Buler and Diehl (2009). This calculates a single measurement for each pulse volume that incorporates the approximate distribution of birds in each sample volume. This method starts by creating a vertical profile of the reflectivity (VPR) using data from multiple elevation angle sweeps. The absence of birds in many regions of the radar domain produces many sample volumes with no reflectivity (i.e., many zeroes in the data). Because of this, I calculated VPRs only using sample volumes with raw reflectivity greater than 1 Z (indicating the airspace contained birds) at the lowest beam elevation (0.5°) and at ranges between 5 and 50 km from the radar. I converted units of Z to cm^2/hectare in the manner of Dokter et al (2011) and refer to this metric as ‘bird density’. VIR represents the cross-sectional area of returned radar energy. It can represent the number of birds by applying a known radar cross-sectional area of a bird for a given radar wavelength. I spatially and temporally interpolated radar data to the same relative time point with respect to sun elevation angle by using a time weighted mean reflectivity in-between sampled radar scans that accounted for varying sun elevation across the radar range (sensu Buler and Dawson 2014). I computed radar data at time points separated by one degree of sun elevation that ranged from +4° to -4° below the horizon. The time it takes the sun to rise or fall one degree in elevation varies depending on the time of year, but during this time of the season is about 5 minutes. Data from each interpolated radar scan was fit to a common spatially-referenced polar grid.

Field Surveys

In autumn 2015, I selected sites to conduct field surveys of birds in areas where the radar observed consistent high-density concentrations of birds moving at sunset. I wanted to choose sites that were downstream of the flight path of birds seen on radar rather than at ground point sources to discern whether birds were moving towards or away from habitat. I chose four main sites, all within the sampling range of KDOX. The sites contained a variety of dominant habitat types including agriculture (Trappe, MD), urban development (Milford, DE), and wetland (Bayside Drive, NJ and Turkey Point, NJ. I ran surveys from October 15 to November 20, and rotated sites as when weather allowed. Additionally, I ran a single survey at Iron Works Park, New Jersey, Allentown, New Jersey, and around Ashbrooke Elementary in New Jersey to check that bird species composition of bird aloft in central New Jersey matched that in Delaware. On some nights I used a FLIR Guardsman HG-307 Pro thermal infrared camera with a 7° field of view and 320 x 240 pixel resolution to check that I was detecting birds flying at higher altitudes. Bird flight activity detected using this camera correlates most strongly with radar flight activity between 200 and 500m altitude (Horton et al. 2014), and should thus be a reliable method for checking the observer detected birds up to 500 m altitude within the cameras viewing range.

I conducted visual surveys from 30 minutes before sunset until 30 minutes after sunset or until it became too dark to visually detect birds in the air. I recorded every bird that passed within 250 meters of me in all directions, identified each to the lowest taxon, noted the time of detection, and the approximate flight direction of the bird. In order to compare with radar measurements I only included birds that flew at a height of at least 50 meters AGL assessed using local structures of known height. Radars typically do not sample under 50 meters AGL, and routinely sample higher than this at farther distances from the radar. I assumed that no bird lower than 50 meters was being sampled by the radar.

To quantify the habitat use of birds across the radar range, I used the 2011 National Land Cover Dataset (mrlc.gov/nlcd2011.php). The data set contains 20 categories of land cover at a spatial resolution of 30 m x 30 m (Homer et al. 2015). The resolution of the land cover was finer than a sample volume, so I calculated the proportion of bird density in each land cover type within every sample volume. I reclassified the land cover classes by summing the land cover types in each sample volume into six broader categories Agriculture (type: 81 & 82), Developed (type: 21, 22, 23, & 24), Upland Forest (type: 41, 42, 43, & 43), Emergent Wetland (type: 95), and Forested Wetland (type: 90) using the ‘zonal statistics’ tool in ArcGIS.

Analysis

For each nightly survey I summed total counts of birds within sun elevation angles between 4° before sunset until 4° after sunset, this is approximately 40 minutes in total for each survey. I calculated sun elevation of each observation using the “SZA” function in the package “RAtmosphere” in R 3.2.3 (R Core Team 2015). In order to measure change in reflectivity through the survey at each site, I determined the mean reflectivity of sample volumes within a survey sites weighted by area within the 250m radius circle for each interpolated angle on each night from sunset ±4°.

Mapping the terrestrial distribution of birds as they initiate migratory flight requires taking a scan from radar at a very specific time in order to maximize spatial accuracy. If the sampled time is too early then birds have not begun to take off from habitats and sample volumes at farther distances from the radar may not yet contain migrants within the radars beam. If the sampled time is too late then birds will have moved away from the habitats they emerged from which introduces error from spatial dispersion. I wanted to use knowledge gained during field surveys along with radar reflectivity through the 60-minute survey to choose a sampling time that represented the moment when birds began flying away from sites. I interpolated radar reflectivity to 0.5° increments between ±4° from sunset. using the ‘W2Birddensity’ function in the Warning Decision Support System–Integrated Information (WDSS-II) software (Lakshmanan et al. 2006). This function interpolates radar data within each sample volume to a specified sun angle across the radar domain. I then georeferenced the interpolated data within ArcGIS software. I used the observations from the ground surveys and interpolated radar scans to estimate an appropriate sampling time (i.e., sun angle) for mapping bird distributions near the ground with the radar data (discussed in detail later). I interpolated all clear nights across the six radars to this specified sun angle. I filtered out sample volumes that contained significant ground clutter, or were over water, or were outside the ranges between 5 km and 60 km. I calculated the average reflectivity at each radar across nights when birds initiated flights at sunset by weighting VIR measures by the two-dimensional area of sample volumes. I then calculated the geometric mean VIR across all sample volumes at all radars.

Unlike the ubiquitous distributions of birds during the peak migratory time period in this area (September – October), late season bird distributions were much more sparse and concentrated at relatively discrete locations with many areas with no birds. To reduce bias in mean bird density from areas with no birds and allow comparison of discrete areas, I quantified ‘high use areas’ among sample volumes at all radars. I categorized a sample volume as ‘high use’ if the VIR was at least one standard deviation above the mean within the radar domain. I then computed the proportion of each land cover class in high use areas.

Results

I conducted 17 evening surveys among 16 days, and I counted 15,397 birds among the surveys (fig 2). Species observed were primarily communally roosting species: 3,681 Common Grackles (*Quiscalus quiscula*), 3,172 American Robins (*Turdus migratorius*), 1,061 European Starlings (*Sturnus vulgaris*), and 813 Red-winged Blackbirds (*Agelaius phoeniceus*), these species accounted for 86% of individual birds detected during evening surveys. There were 5,345 birds I identified as passerines but not to the species level, due to the high frequency of birds flying overhead into roost sites on certain nights. The majority of the birds identified only as 'passerine' were likely the top four species. I did not feel I could reliably estimate the individual species numbers of these passerines. I estimate less than 1% of unidentified passerines were smaller passerines like American Goldfinches (*Spinus tristis*), Yellow-rumped Warblers (*Setophaga coronata*), or Cedar Waxwings (*Bombycilla cedrorum*). Numbers of birds and dominant species varied among study sites. Milford contained mostly communally roosting species (Common Grackles, American Robins, European Starlings), while Turkey Point and Bayside Drive contained largely American Robins and gulls. Nights with no flights after sunset occurred for 67% of nights (n=11). Bird counts on these nights were characterized by high counts of birds aloft prior to sunset, followed by an abrupt drop just after sunset (Fig. 3). Species composition on these nights consisted mainly of Common Grackles, American Robins, and European Starlings. Trappe Landing contained a large aggregation of Canadian Geese (*Branta Canadensis*) at nearby agricultural fields, and geese were seen at all surveys at this site, but counts peaked just prior to sunset. Radar reflectivity on these nights generally matched the same pattern of bird counts where reflectivity was highest before sunset and then abruptly declined (Fig. 4).

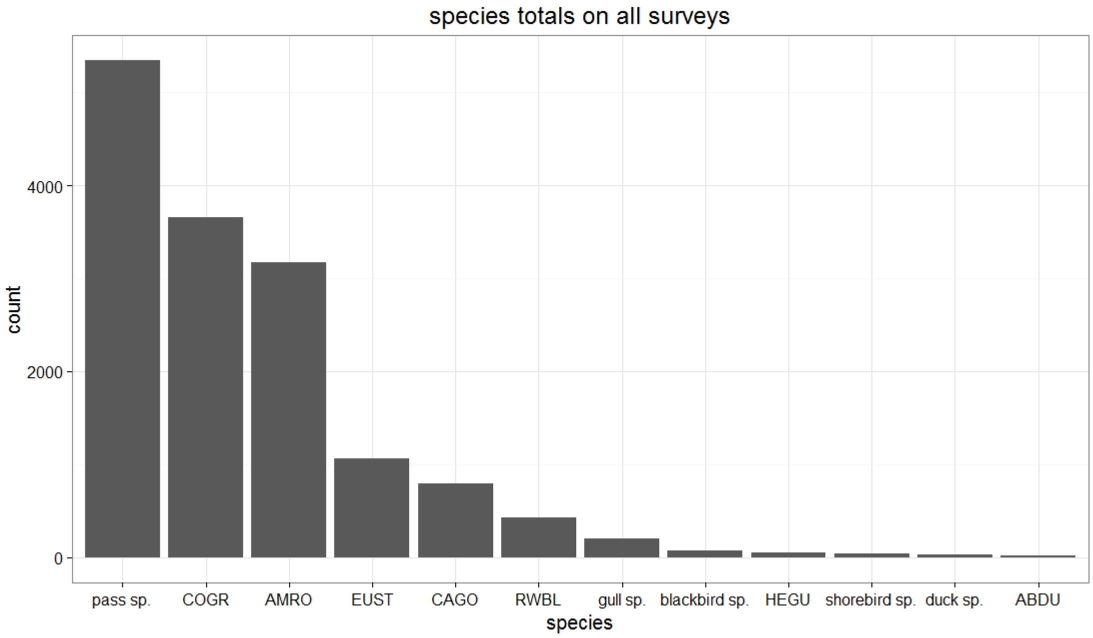

Figure 2 Total species at survys. Individual birds counted by species among 14 surveys. Species are identified by four letter AOU code (COGR – Common Grackle, AMRO – American Robin, EUST – European Starling, CAGO – Canada Goose, RWBL – Red-winged Blackbird, HEGU – Herring Gull, ABDU – American Black Duck).

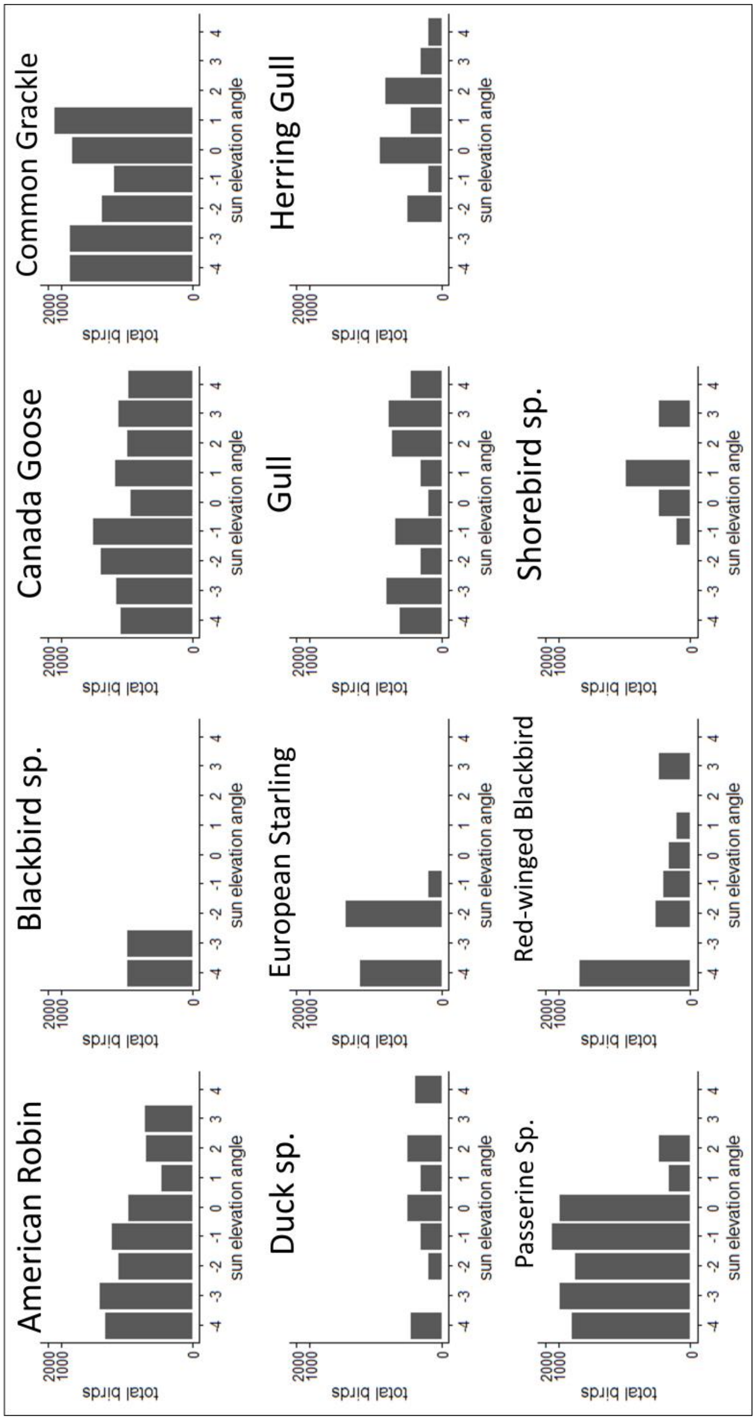

Figure 3 Total bird counts and average reflectivity on nights with no sunset exodus (n=11). Species are identified by their four letter banding code. Common Grackles were by far the highest count species across all surveys.

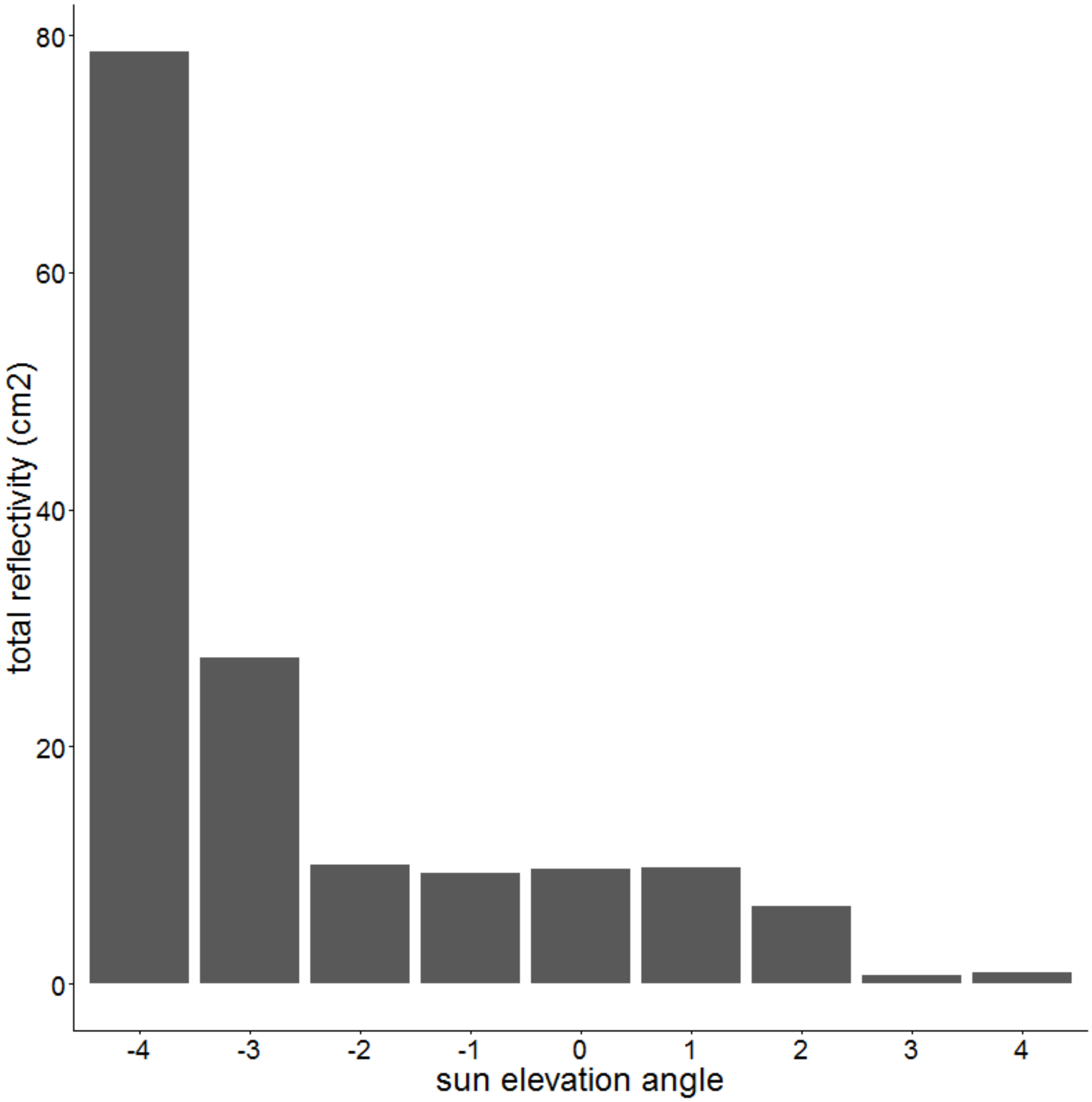

Figure 4 Mean reflectivity at four field sites measured from radar on nine total nights. Two nights could not be calculated due to range detection issues. Sun elevation angle is measured as the elevation before sunset. One sun elevation at this time of year and location approximately equals 5 minutes.

Among nights we surveyed, nights with birds aloft after sunset were relatively rare (n=3); this does not include two nights with sunset flights that were excluded because the FLIR camera detected birds flying at a high elevation that were not detected on ground surveys. Bird counts on the nights with birds aloft after sunset conformed roughly to a normal curve with peak counts at 1° before sunset (Fig. 5). Bird counts on these nights consisted primarily of American Robins, Common Grackles, European Starlings, and Red-winged Blackbirds. At Milford, species composition was similar to nights without post-sunset flights, including a drop in numbers of birds after sunset. Low numbers of birds were seen flying south on this night at this location. The other two nights were more similar to each other than at Milford. The major species counted on these two surveys was American Robins. Only two species were seen flying south, American Robins and Canada Geese. American Robin numbers peaked 2° after sunset, and were seen in large numbers at both sites - Trappe Landing (November 8) and Bayside Drive (November 20). I observed similar behavior by American Robins during these surveys. Approximately at sunset, Robins began to leave from vegetation within habitats and gain altitude. They then crossed the study site starting approximately at 1° after sunset flying WSW in loose groups. These congregations continued for approximately 10 minutes by visual observations, though the FLIR at Bayside Drive confirms that this flock likely continued to stream overhead until the end of the survey time. The reflectivity increased rapidly after sunset, approximately matching the field surveys (Fig. 6). At Milford, neither I nor the FLIR detected any birds flying south after sunset. The majority of birds were flying ENE and landing in trees just outside the survey area as they did on nights without a sunset exodus.

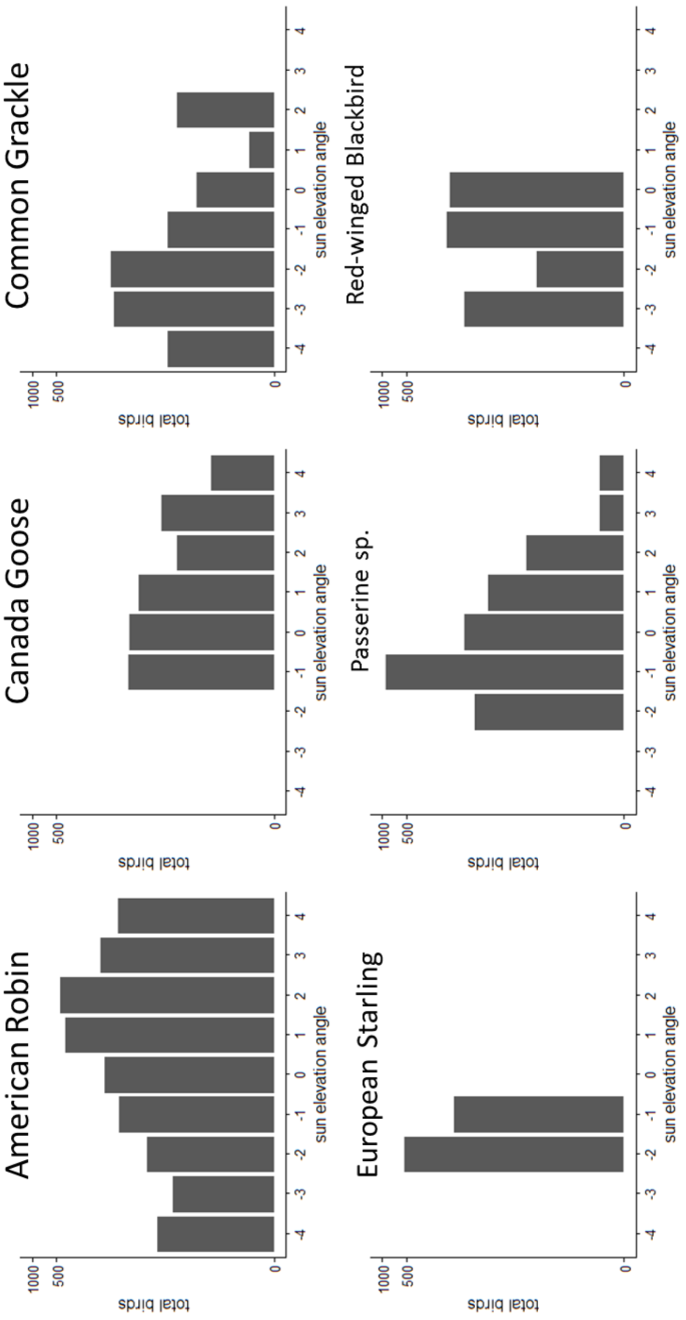

Figure 5 Total bird counts and average reflectivity on nights with a sunset exodus (n=3). Species are identified by their four letter banding code.

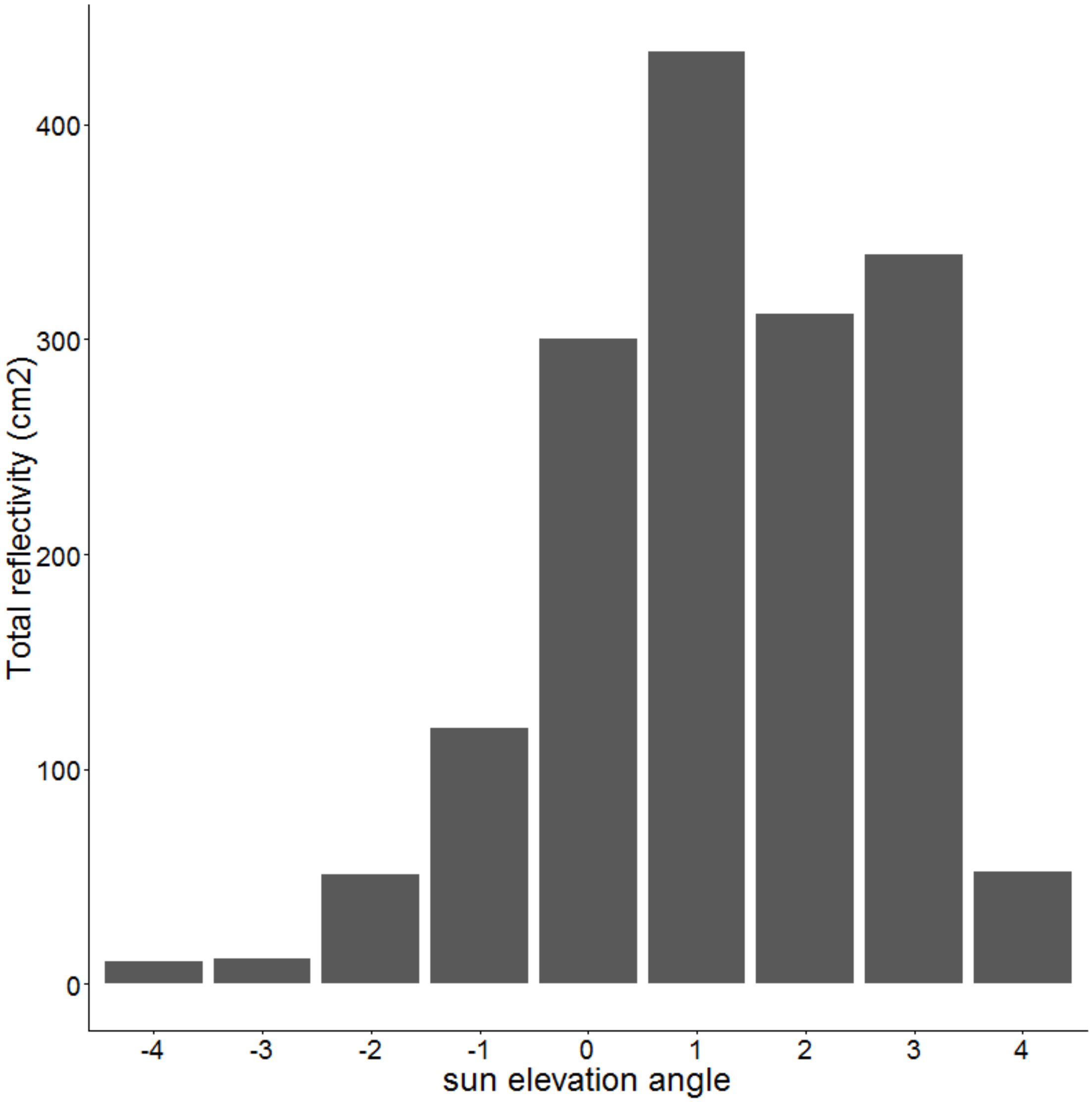

Figure 6 Total reflectivity derived from radar scans at 3 survey sites on nights when radar detected birds leaving habitats at sunset. Sun elevation angle is measured as the elevation before sunset. One sun elevation at this time of year and location approximately equals 5 minutes.

I screened 2,029 radar nights from October 15 to November 30 for 2008 to 2015 at the six radars. Of those nights 1231 (60%) were not included in analysis because they contained precipitation, anomalous propagation, or clutter. Of the remaining 798 nights about half contained no measurable exodus (426 nights), while 187 contained a sunset exodus and 175 contained an exodus at a time after sunset. Only 39% of these nights with a standard exodus were after October 31, while 85% of sunset exodus nights occurred after October 31. 70% of these nights with a sunset exodus were found at three radars KOKX, KDIX, and KDOX (43, 43, and 45 nights respectively) (Fig. 7.). Sunset movements peaked in the two week period between October 27 and November 10, and then declined until November 30. I did not check nights into December, but from the generally decreasing radar signature in late November I do not expect high frequency of nights with sunset movements in December.

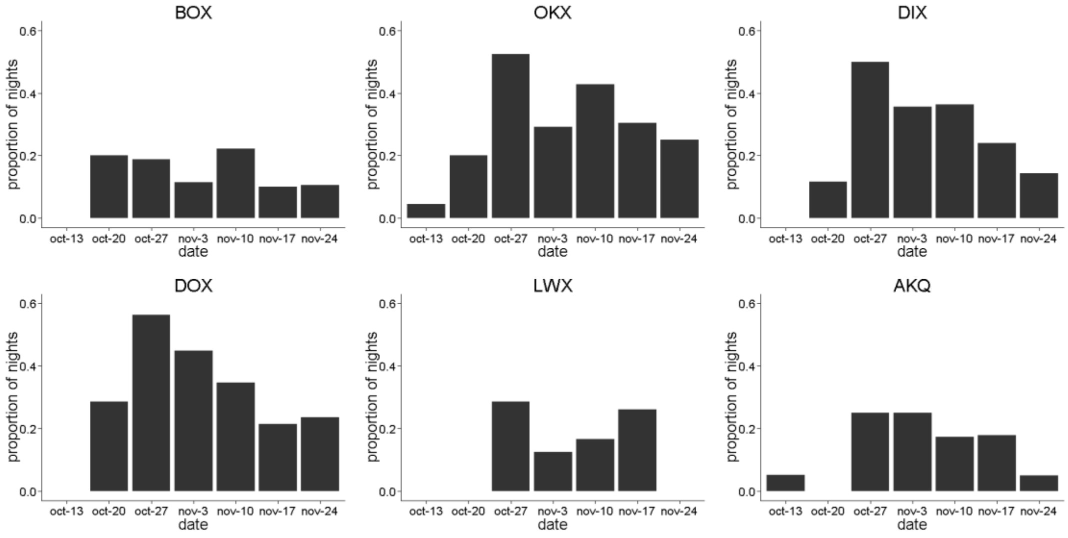

Figure 7 Average reflectivity on nights with a sunset exodus identified from October 15 – November 30, 2008 – 2015.

The surveys at Bayside Drive and Turkey Point detected birds taking off from the forests prior to crossing over the marsh and therefore could be used as a marker for the moment when birds begin moving laterally on radar. On nights with bird flights beginning at sunset, birds first emerge on radar over the inland forest of these two sites before moving over the emergent marsh. I chose 89.5° as an appropriate sampling time for mapping bird distributions because this time point represented the point at which average reflectivity increased over the upland forests at these sites but before it began shifting southwards into the emergent marsh (Fig. 8). I interpolated all nights (regardless of exodus time) to 89.5° for subsequent analysis.

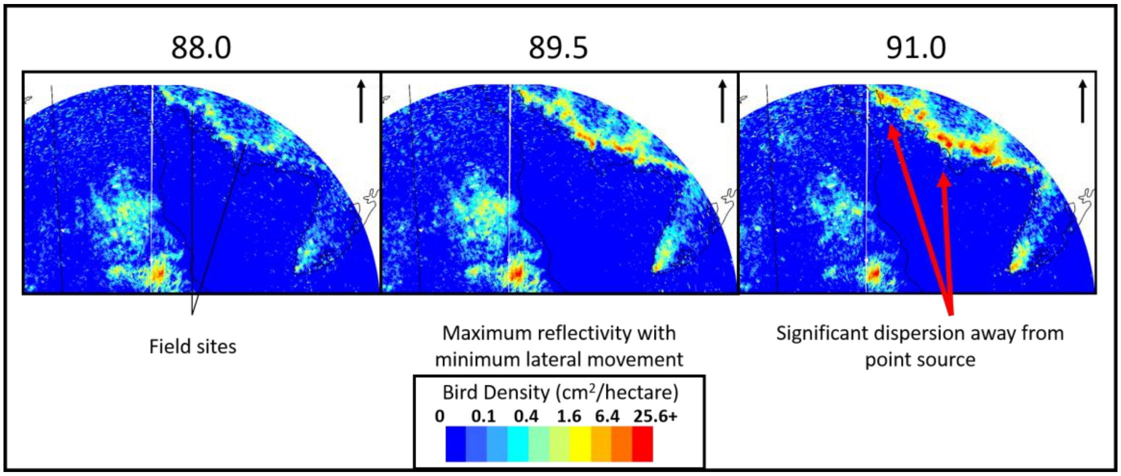

Figure 8 Interpolated reflectivity mapped along the Delaware Bay for 2015. Bayside Drive and Turkey Point field sites are along the bay shore in emergent marsh with forest just inland. Reflectivity increases at forested sites inland and shifts laterally over emergent marsh starting at 91°, which are corroborated by field surveys showing American Robins leaving forested habitats. After 91° reflectivity is over emergent marsh where field surveys reported birds after birds left the forested edge inland.

Bird density on nights with a sunset exodus was highest in Delaware, Maryland and New Jersey. Despite the high number of sunset exodus nights, KOKX averaged the lowest bird density (Fig. 9). Nights with no sunset exodus (regardless of whether they contained a later exodus) were pooled as their bird density at 89.5° did not differ largely. High use areas on nights without a sunset exodus were either in agricultural areas or developed areas with abundant forest cover, including areas outside New Bedford, MA and suburban areas outside Philadelphia, PA, and Trenton, NJ (Fig. 10). High use areas on nights without a sunset exodus were rarely in areas of forested wetland and emergent marsh. Nights with and without a sunset exodus generally shared high use areas, but nights without a sunset exodus covered less total area. High use areas on nights with a sunset exodus contained more upland forest and forested wetland cells than nights without one. Certain areas on nights with a sunset exodus varied from those without a sunset exodus. These areas were generally adjacent to a water body (e.g. Delaware Bay, Long Island Sound, coastal Rhode Island, and the James River) (Fig. 11-13).

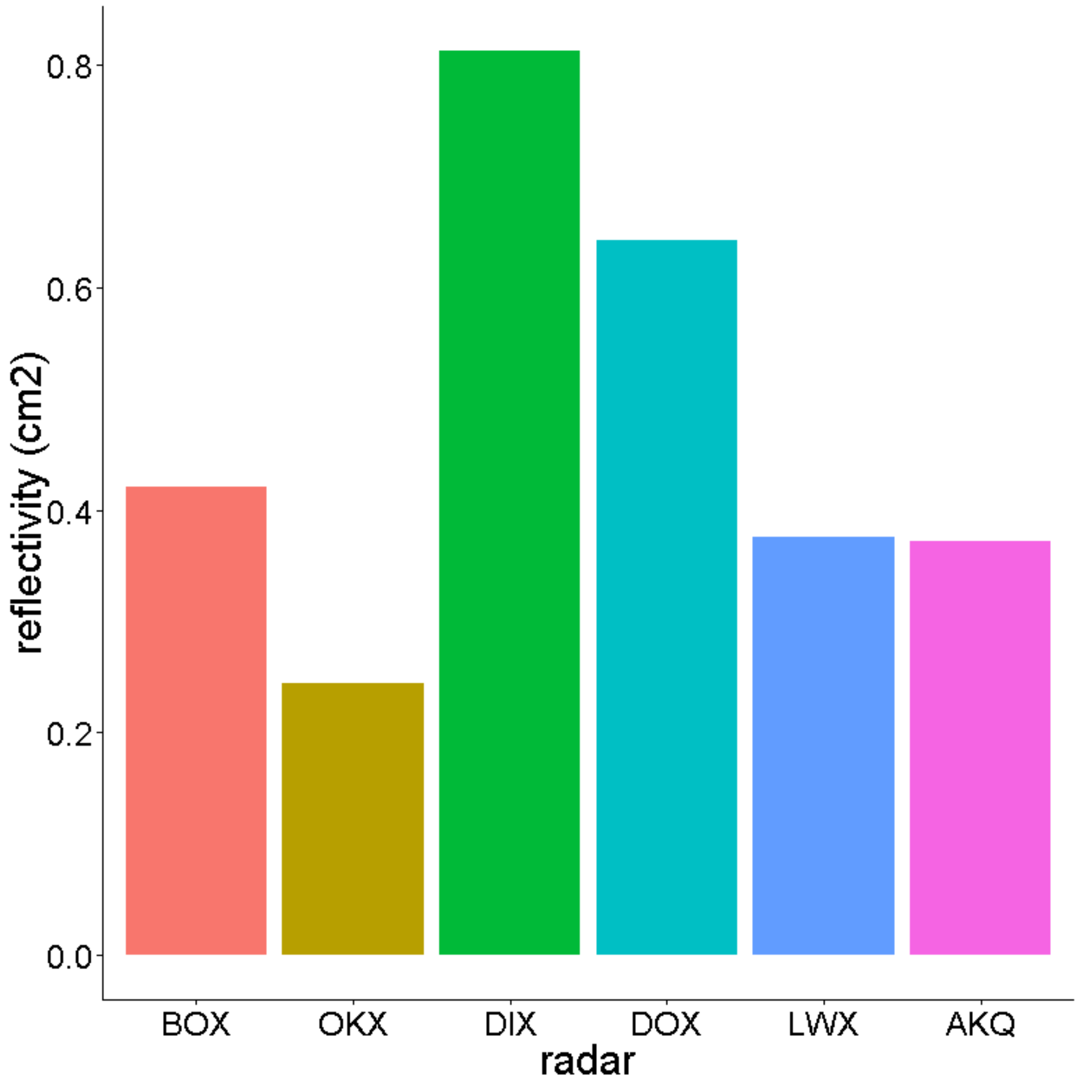

Figure 9 Average reflectivity on nights with a sunset exodus identified from October 15 – November 30, 2008 – 2015.

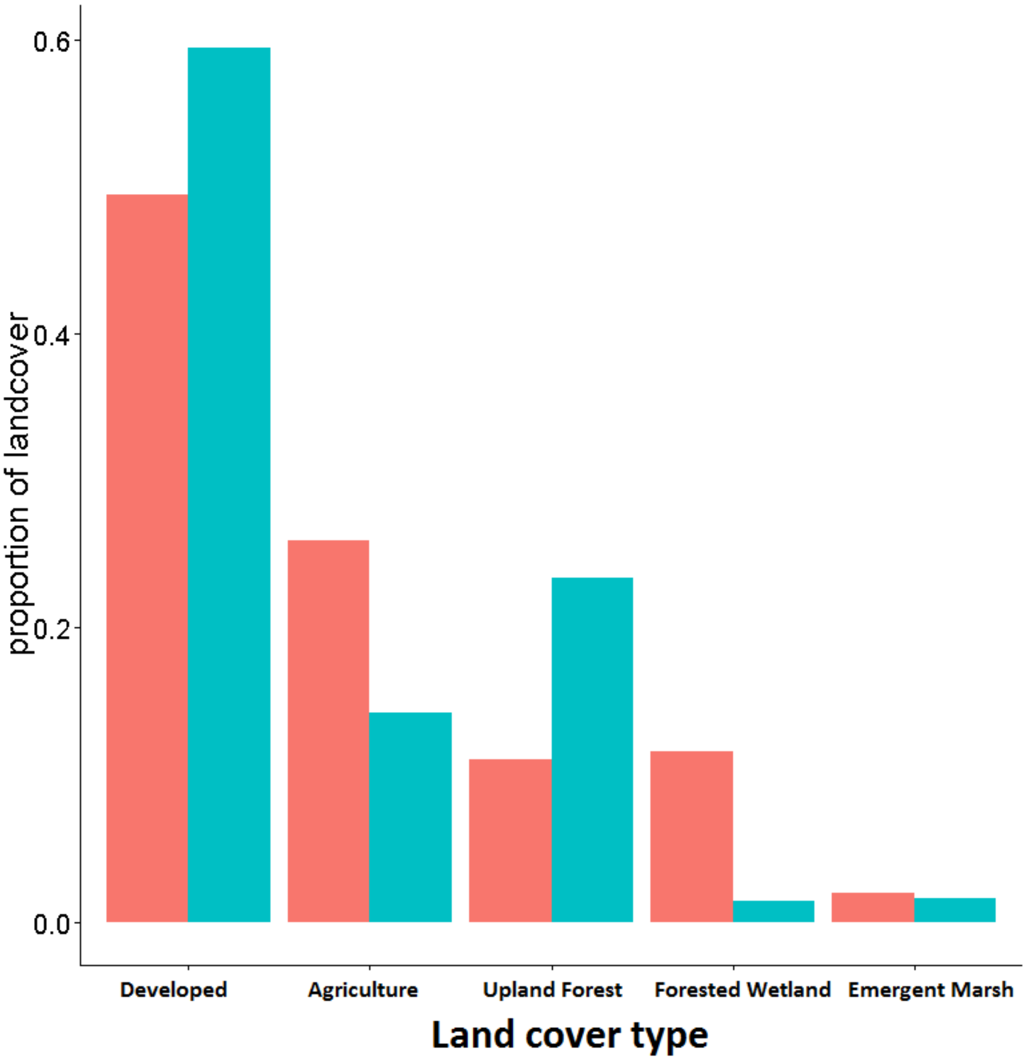

Figure 10 Proportion of each land cover type in 'high use' areas on nights with a sunset exodus and without one. High use areas on nights without a sunset exodus are primarily (+60%) developed cover type followed by agriculture.

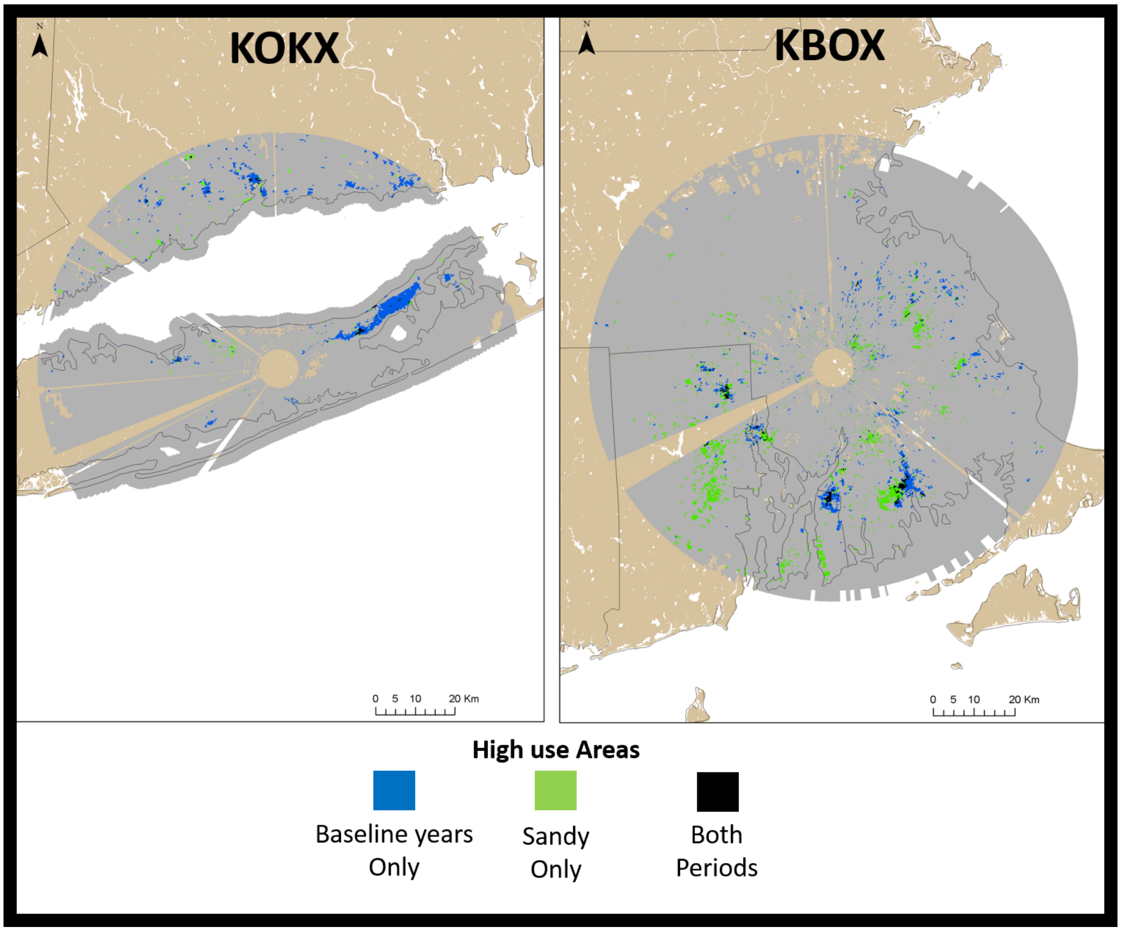

Figure 11 Identified ‘high use’ areas on nights with a sunset exodus and without at KOKX (Long Island, NY) and KBOX (Boston, MA). High use areas are sample volumes which are one standard deviation above the mean.

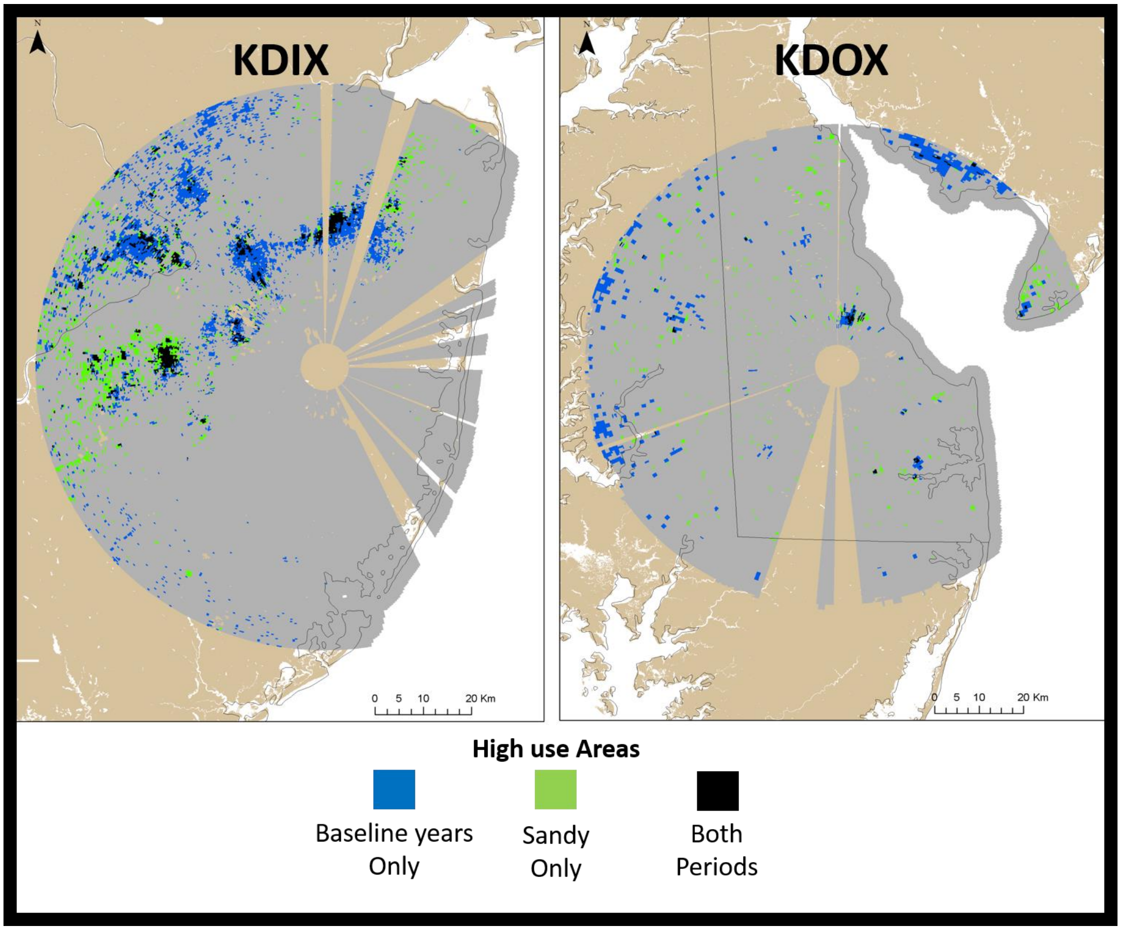

Figure 12 Identified 'high use' areas on nights with a sunset exodus and without at KDIX (Mt. Holly, NJ) and KDOX (Dover, DE). High use areas are sample volumes which are one standard deviation above the mean.

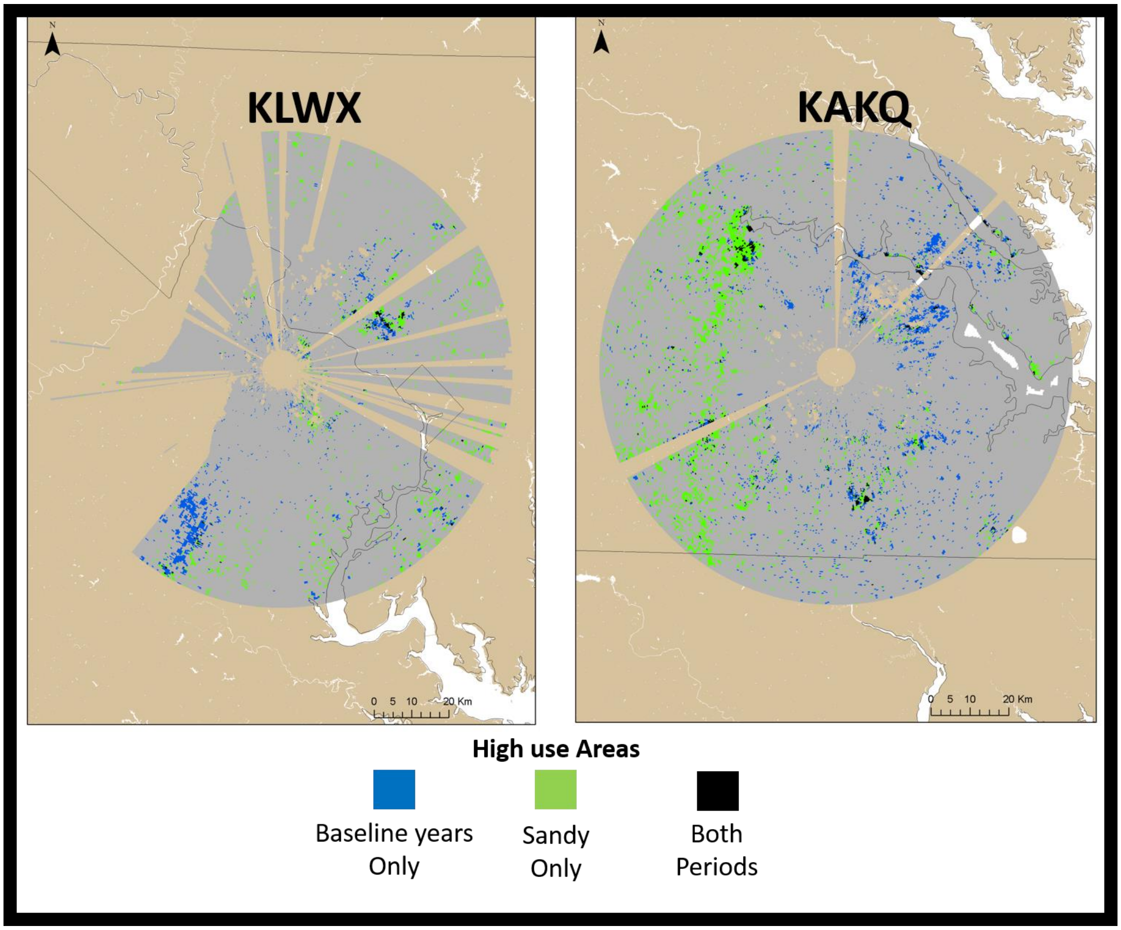

Figure 13 Identified ‘high use’ areas on nights with a sunset exodus and without at KLWX (Washington D.C.) and KAKQ (Norfolk, VA). High use areas are sample volumes which are one standard deviation above the mean.

Discussion

The field surveys detected large numbers of American Robins leaving habitats at sunset, gaining altitude, and flying to the WSW. This pattern matches the signature of radar targets seen on radar in late October and November when bird density increases abruptly at sunset and begins moving SW through the Mid-Atlantic. On nights where these patterns are seen on radar I detected largely American Robins making southern flights. At Trappe Landing and Bayside Drive, Robins were the only birds flying south after sunset, and were seen streaming out of habitats at densities high enough to match radar signatures. I did detect Canada Geese flying south periodically at Trappe Landing, however, this also occurred on nights without a sunset exodus and numbers peaked prior to sunset not after sunset.

Despite the American Robins large population and ubiquitous range, their migratory habits are rarely studied. Robins are thought to be diurnal migrants, which contrasts with this finding. This paradigm likely first came about from observations of Robins moving south during the day time. William Brewster first mentioned Robins as diurnal migrants while studying autumn migration at a lighthouse in the Bay of Fundy (Brewster 1886). He reported that diurnal migrants often crossed the Bay mid-morning flying south (a category he defines later as including Robins), and was the first person to pen them as ‘diurnal’; however, he noted that Robins will occasionally migrate nocturnally when crossing a barrier. Though not explicitly stated, he concludes this likely from nightly kills at the lighthouse on foggy nights. Baird and Nisbet (1960), summarizing morning flight studies across the North East noted Robins flying across the Chesapeake Bay in the morning when other species typically are flying north back to land. These flights are typically made by small nocturnal migrating passerines that reorient themselves northward at sunrise, presumably after finding themselves over water at daylight. American Robins also were seen making these flights northward that are similar to reorientation flights, so Baird and Nisbet (1960) considered Robins to be both diurnal and nocturnal migrants. Eiserer (1979, 1980), was less convinced of the dual migratory strategy of Robins. In his studies of captive Robins and their ‘roosttime restlessness’ he found evidence that Robins become restless at dusk and then again in morning. He cautioned to not consider the dusk restlessness as proof of nocturnal migration as it is found throughout the Robins annual cycle. Counter to this, he found that Robins will stop feeding and drinking prior to dusk in migration, and occasionally become active at night, actions which are very similar to nocturnal migrants. In the end he states: ‘The present observations, then, are consistent with the conclusion that Robins are primarily diurnal but occasionally nocturnal migrators.”. To date, I can find no study that has concrete evidence of Robins migrating primarily during the day or night. This study is the first to present data on Robins actively migrating at night.

The Robins I observed flying south were about to cross a large water body (the Delaware Bay or Chesapeake Bay). Passerines will ‘build up’ along edges of large water crossings (Diehl et al. 2003, Buler and Moore 2011) and deserts (Fransson et al. 2008). Brewster (1886) noted that Robins will fly at night to cross large barriers, but he does not present evidence to explain the conclusion. I think this explanation insufficient to fully explain the phenomenon I observed. While the Delaware Bay and Chesapeake Bay represent significant barriers, as seen by the morning flight activity at these locations, radar derived bird density was the highest among all radars around Philadelphia where no over water flight is imminent. Although, this may explain some of the activity, it cannot explain the motivation for all of the flights seen by the radar. Perhaps then American Robins make facultative movements in respect to the time of day they migrate. Analysis of morning reflectivity as birds leave roosting sites during this time of season shows large reflectivity increases that radiate in all directions out from concentrated sites much like other roosting species seen on radar (Bridge et al. 2015). It is difficult to discern whether some of these signatures are birds initiating migratory flight or traveling to feeding areas. But it remains possible that Robins could be initiating diurnal or nocturnal flight depending factors like time of season, barriers, location, winds, or conspecific interactions.

To test idea that these signatures are primarily made up of American Robins migrating through the region, I downloaded presence data from eBird.org for the years 2008 to 2015 for five regions at various latitudes within the known American Robin range (Newfoundland, CA, Massachussets, New Jersey, South Carolina, and Florida). eBird is a citizen science repository for the species lists of individual birders, and available data are expressed as the percentage of lists with that species reported (http://ebird.org). American Robin presences peak during autumn at increasingly later dates the farther south you go (Fig. 14). Robins begin decreasing in presence in Newfoundland in the third week in October. Around this moment Massachusetts and New Jersey begin increasing in recorded presence of Robins and decrease throughout the month of November. Starting in the first and second week in November, American Robin presences begin increasing in South Carolina and Florida, their presumed wintering locations. This means presence of Robins begin increasing in New Jersey at approximately the same week that I began to observe nights with a sunset exodus in the core of my study area (New York, New Jersey, and Delaware).

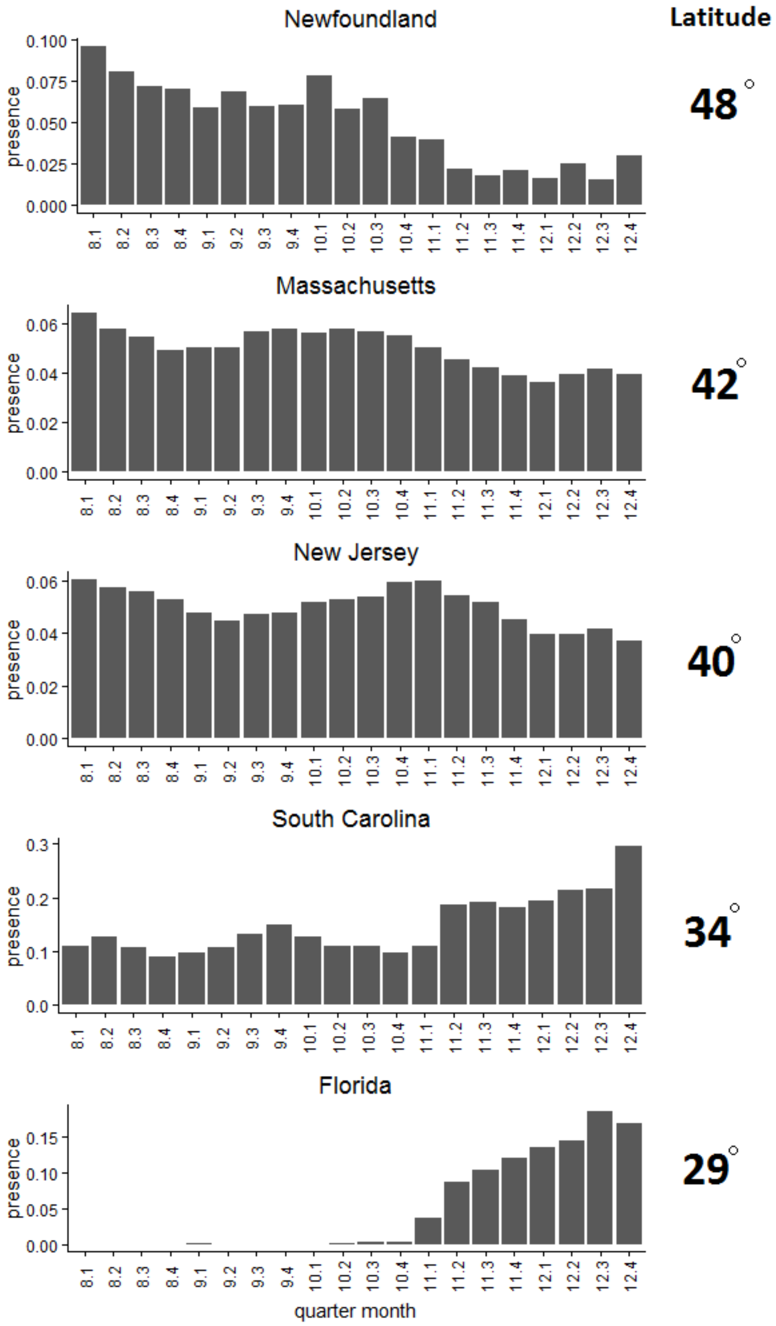

Figure 14 Presence of American Robins on individual checklists taken from eBird.org at five locations decreasing in latitude. Presences are the proportion of checklists that entered at least one American Robin.

The timing of these movements from late October through November does not completely match other studies on Robin migration. Caccamise and Fischl (1985) working in northern New Jersey, found roost densities peaked on September 8 and they recorded no Robins after November 1. However, their study did not extend beyond November 7, when they presumed most species were now wintering, and they did not consider the possibility that Robins might switch roosts. These timings were similar to those reported by Brewster (1890), although neither study focused on migratory Robins locally but mainly breeding Robins. Purely migratory Robin roosts tend to increase at the moment Caccamise and Fischl (1985) describe breeding roosts declining in early November, though studies are sparse (Widmann 1895, Black 1932). Brewster (1890) did note that, after presuming all roosts were abandoned in Massachusetts he stumbled upon a new roost of hundreds of Robins on November 6 which matches the peak in prevalence of sunset movements that I observed. He theorized these are migrants from the north filling in after their breeding birds left. In my study, the early movements rarely appeared earlier than the last week in October, and frequently not until November. If migratory Robins switch to different roost sites after breeders have left, it may appear that a roost is abandoned and Robins migrated south. Once breeding birds leave, a new cohort of Robins from farther north may migrate through the area, explaining the disparate timing of studies. It is therefore, necessary to study in greater detail the timing of autumn migration and the relation to timing and their chosen breeding latitude.

American Robins roost in tall marsh vegetation or riparian wetlands typically adjacent to food sources like agricultural areas or urban areas with urban lawns and parks. This habitat use matches the general pattern of habitat composition of high use areas seen at all radars, and would explain why high bird density is seen in suburban areas, where the density of nocturnal migrants at stopover sites is typically low to moderate. Robins frequently exploit ever increasing urban and suburban habitats around the United States (Beissinger and Osborne 1984, Morneau et al. 1995). From high bird density and the prevalence of nights containing a sunset movement in November, it seems that Long Island, New Jersey, and Delaware are important areas for American Robins and other communally roosting species in late autumn. Birds appear to concentrate in large numbers over a relatively narrow window of weeks and then move out of the area by the end of November.

On nights with no migratory movement, I saw movements of other communal roosters including Common Grackles, European Starlings, and Red-winged Blackbirds. I regularly observed these species flying into roost around Milford, Delaware. Even on a survey night when other portions of the radar-observed area around KDOX had targets flying south at sunset, the survey at Milford observed no southern flying birds. This site is likely a year round roosting area for a variety of species and contains high reflectivity seen on radar regardless of migrant movement elsewhere on the radar. Reflectivity seen on nights without a sunset exodus could also be reflectivity signatures of birds coming to roost. To test the hypothesis that some of these sample volumes on nights with no migration were birds coming into roost sites, I checked four separate locations around KDIX and KDOX (Ashbrook, Allentown, Iron Works, and Dover) for evidence of birds roosting in large numbers. I checked each site for sizeable aggregation of birds flying into a site to roost at night, or for birds flying out of a site in the morning (Fig. 15). At all sites I found congregations of birds coming into roost, primarily of four species: Common Grackles, American Robins, European Starlings, and Mourning Doves. These locations approximately matched areas of high bird density on the radar. These four species commonly roost together during migration and the winter (Caccamise and Fischl 1985, Morrison and Caccamise 1990). Radar studies typically use radar scans as birds leave roosts in the morning to locate and track the population trends of roosting birds. (Russell et al. 1998, Bridge et al. 2015). They use morning scans because birds tend to fly low into roost sites, and high when leaving roost sites. While more research is needed on these reflectivity signatures, I believe that evening reflectivity can also be used to locate the approximate location of communal roosts within 50m.

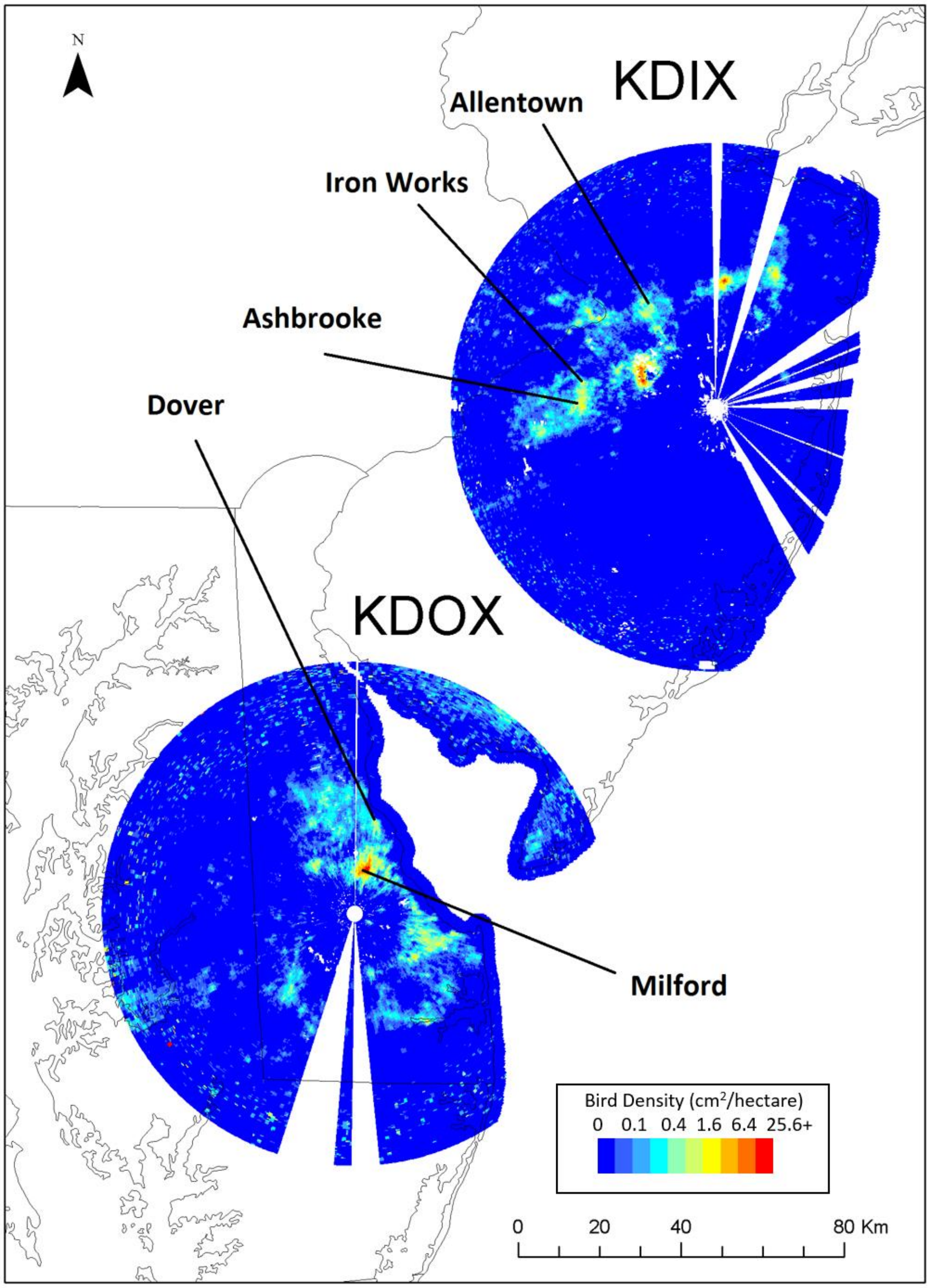

Figure 15 Average reflectivity for all nights with no discernible exodus from October 15- November 30 2008 - 2015. Points are locations where I confirmed the presence of a roosting site used by American Robins, Common Grackles, and European Starlings. All sites were checked either with evening surveys (visually tracking birds as they entered a roost) or morning sites (visually tracking the location as birds left a roost).

Reflectivity during this time period (late autumn) seems to sample a mixture of birds embarking on migratory flights and birds moving to or from roosts. In fact, this may be one reason why this observation has remained a mystery until now. Many birds seen gathering at night might be assumed to be roosting. Remote discernment of whether sample volumes contain migratory or roosting movements remains a challenge, but would be helpful to track changes in migratory movements irrespective of sample volumes containing large roosts (like Milford) or migratory birds. This study is significant because it presents evidence that American Robins will make nocturnal migratory movements. Additionally, roosting migrants like American Robins use the Mid-Atlantic in late October and November, before vacating the area, presumably for areas farther south. Weather radar proved to be a useful tool in identifying these targets, and allows for the continual monitoring of site use by migratory Robins, as well as communal roosting species such as Common Grackles and European Starlings.

While I present evidence for Robins making nocturnal migrant movements, I cannot say that they only migrate at night. Anecdotal observations frequently report Robins moving in large groups during the day, though whether these are local or migratory movements is unclear. Studies that track individual American Robins through migration are needed to parse out at what time of the day Robins migrate and perhaps why they choose to migrate at that time. Common Grackles share a similar migration phenology with American Robins, and are also poorly studied in migration. Research is needed on all communally roosting species and the dynamics of roost occupancy from breeding to wintering months. I hope this research will guide future work studying migratory roosts using weather radar, and give cause for scientists to rethink long accepted paradigms.

Chapter 2

THE EFFECT OF HURRICANE SANDY ON STOPOVER DISTRIBUTIONS OF MIGRATING LANDBIRDS IN THE NORTHEASTERN UNITED STATES

Migratory birds face a myriad of obstacles during migration including collision with buildings (Loss et al. 2014), high energetic demands (Yong and Moore 1997), predation (Dierschke 2003, Cimprich et al. 2005), unknown landscapes (Cohen et al. 2012, 2014), and threats of severe weather (Newton 2007). This stage in a birds annual cycle is important because it experiences the highest rate of mortality compared to breeding and wintering stages (Sillett and Holmes 2002), and impacts during one portion of the cycle can carry over and effect fecundity and survival in another (Rushing et al. 2014). Of these potential threats, severe weather can impact birds at the largest scale. Severe weather can cause mass-mortality events that number in the thousands of individuals (Newton 2007). Hurricanes are the largest scale sever weather event, affecting areas up to thousands of kilometers wide. The major cause of mortality from hurricanes is over-exposure due to drowning or exhaustion if a bird is forced out to seas in a storm. More often birds will ‘weather’ a storm by seeking shelter near the ground or in dense bushes (Sutton 1945, Cely 1993). Once a storm has passed, birds will their shift their foraging tactics and habitat use depending on the resulting habitat changes. Open areas created from high winds (windfall gaps) create novel habitat types that may change the composition of the habitat for years. Wunderle (1995), working in Puerto Rico, showed that changes in bird species composition after Hurricane Hugo were related to the displacement of habitat and fruit production and local structure changes. Initial captures on new windfall gaps increased as canopy dwelling birds were displaced by understory and early successional species.

Barrow et al. (2005), analyzed the effects on migrating land birds of Hurricane Katrina, a category 3 hurricane that made landfall on the northern Gulf of Mexico coast in late August of 2005. They used data from weather surveillance radars to quantify and map the spatial distribution of birds that emerged from daytime stopover sites at the onset of nocturnal migratory flight in the days before and after Katrina's landfall. High winds from the storm defoliated deciduous trees within bottomland hardwood forests. Barrow et al. (2005) used Normalized Vegetation Index (NDVI) measures, an index of vegetation greenness, from the MODIS satellite sensor to identify vegetation damage from the storm. They found that birds stopped using damaged areas and shifted their use to the lower-quality adjacent pine forests that were less-damaged. Two weeks later, as trees began to leaf out again, migrating birds shifted their distributions back to the higher quality river bottomland hardwood forests.

Hurricanes may also blow migrating birds far off their intended course. For example, following the exceptional 2005 hurricane season, numerous migrant songbirds, atypical in the region at that time, were reported in the eastern Caribbean (Faaborg and Gauthreaux 2010), while following Hurricane Wilma that same year was followed by unusual sightings of Chimney Swifts in the maritime provinces of Canada (Dionne et al. 2008). Frequently, hurricanes can affect the timing of migration, stalling birds or shifting their migratory phenology (Fisk 1979, Thurber 1980, Wunderle 1995). Occasionally under the right conditions, hurricanes may cause early arrival of migrants into regions or at numbers much higher than normal due to high and favorable winds (Fisk 1979).

Hurricane Sandy was a major hurricane that made landfall at Brigantine, New Jersey, on 29 October, 2012. It was the widest hurricane in the Atlantic and the second most costly behind Katrina (Blake et al. 2013). Sandy formed in the southwestern Caribbean Sea on 23 October, becoming a hurricane on 24 October just before landfall in Jamaica. It strengthened and subsequently crossed over Cuba as a Category 3 hurricane on 25 October. After passing Cuba, it weakened and moved north along the Atlantic Coast. On October 28, it passed by North Carolina, and then shifted its path west towards the Mid-Atlantic region of the U.S. Just prior to landfall, Hurricane Sandy was downgraded to a post-tropical depression with winds up to 90 mph. After landfall, Sandy turned west-north west and eventually merged with a low pressure system over eastern Canada (Blake et al. 2013).

At landfall, heavy winds added to a high-tide caused significant storm surge into coastal areas and wetlands measuring as high as 12 meters on Long Island. While damage to coastal wetland and dune habitats was considerable, tree damage was generally minor with relatively low numbers of overturned trees, although saltwater intrusion into near coastal forested areas caused local die offs (Blake et al. 2013). Inland habitats experienced relatively little damage. Sandy produced significant rain (up to 12 inches) in Delaware and Maryland and heavy snowfall in the mountains of West Virginia (Blake et al. 2013).

Few hurricanes make landfall into November (Elsner and Kara 1999), so Sandy was a late season storm. This timing coincides with the tail end of the autumn migration of passerine birds at this latitude (Bennet 1952). At that time of the season, the majority of Neotropical migrants had likely already moved through the Mid-Atlantic region, while some species of late season temperate migrants (e.g. Dark-eyed Juncos, American Robins, and White-throated Sparrows (*Zonotrichia albicollis*)) likely were likely at their peak densities (Allen and Peterson 1936, Baird 1980).

In Chapter 1, I showed that scans taken at sunset by weather surveillance radars in Delaware and New Jersey in late October and November were composed primarily of four species: American Robins, Common Grackles, European Starlings, and Canada Geese. On nights where migratory movements were seen at sunset on radar, large numbers of Robins aloft were seen flying south on field surveys. These movements originated in suburban and agricultural areas with the highest bird densities in New Jersey and Delaware. The prevalence of these movements was highest during late October and early November, within the same time window that Hurricane Sandy made landfall. American Robins migrate through the northern United States during October and November en route to wintering areas in the southern United States (Aldrich and James 1991), and congregate in large roosts during the migratory season (Caccamise and Fischl 1985). They frequently feed in agricultural areas and suburban lawns usually within 3km of their nightly roosting site (Caccamise and Morrison 1986, Morrison and Caccamise 1990).

In this chapter, I used data from weather surveillance radars to measure how late season migrants changed their spatial distribution in the wake of Sandy. I wanted to compare these changes in distribution to three measures predicted to be important factors relative to hurricane damage: 1) the distance from the path of Sandy. I predicted that areas closest to the path of Sandy were more likely to be damaged and therefore lead to the largest decreases in bird distribution. 2) The distance from the coast. I predicted that areas closest to the coast are more likely to be hit the hardest by winds and storm surge, and therefore lead to decreases in bird distribution. And 3) Changes in vegetation. I predicted that areas that were damaged from winds and storm surge would negatively affect the vegetation which would lead to decreased bird distribution at those sites. Finally, in order to better understand patterns in the change of bird distribution I compared bird distribution among different habitat types before and after Sandy's passage.

Methods

I downloaded level II data from the National Centers for Environmental Information for six WSR-88D radars across the northeastern US region for the 30 October – 30 November for the years 2008 to 2012: KBOX (Boston, MA), KOKX (Upton, NY), KDIX (Mt.Holly, NJ), KDOX (Dover, DE), KLWX (Sterling, VA), and KAKQ (Norfolk, VA) (Fig. 16). I considered 2008 – 2011 to be the baseline years, with 2012 the year of Hurricane Sandy. I chose these radars because they cover the area where Hurricane Sandy's effect on birds may have been the largest. These radars encompass approximately equivalent areas north and south from where Sandy made landfall, and are approximately the width of the storm (~1000km). I used UCAR/Unidata's Integrated Data Viewer (unidata.ucar.edu/software/idv) to visually screen data, and removed nights that contained precipitation, clutter, or anomalous propagation around sunset within the radar range that may bias reflectivity measurements.

These radars are Weather Surveillance Radar-1988 Doppler (WSR-88D) radars with a 10cm wavelength beam. Radar measures the return signal from a reflected pulse of energy off a target (i.e., reflectivity) in units of Z. WSR-88D radars are run in two modes: clean air mode where scans are taken every 10 minutes at 5 beam elevations (0.5°, 1.5°, 2.5°, 3.5°, and 4.5°), and precipitation mode where scans are taken every 2-5 minutes. The smallest unit of reflectivity is termed a ‘sample volume’ which is the volume of space in the atmosphere above a polygon on the ground.

Migratory movements of American Robins are identified by the sudden appearance of reflectivity on radar generally emanating from coastal or urban sites approximately at sunset. These birds quickly move away from point sources on radar. I classified all remaining nights into three categories based on the intensity and timing of bird flight: a ‘sunset exodus’ when the first onset of bird flight was initiated around sunset, a ‘standard exodus’ when the first onset of bird flight was initiated 20 minutes or more after sunset, and ‘no exodus’ when no noticeable evening bird activity was observed. Nights with a sunset exodus often had a second pulse of reflectivity 20 to 30 minutes after sunset, however, the sunset exodus precluded analysis of this second pulse because the targets at sunset were still present on radar 20 to 30 minutes after sunset. I only used nights with a sunset movement in the analysis presented here.

I calculated a vertical profile of reflectivity (VPR) for each scan in 10m height bins from 0km to 3km above ground level (AGL) (Buler and Diehl 2009). I calculated VPR using sample volumes within 5km to 60km and used sample volumes that contained at least 1Z in the lowest beam tilt (0.5°). I used the VPRs to calculate a correction factor for each sample volume, which gave us a standardized single measurement of vertical integrated reflectivity (VIR: which I will refer to as ‘bird density’ for the remainder of the chapter). This measurements incorporates the approximate distribution of birds at all altitudes in each sample volume into a single measurements for each sample volume. I then converted measurements of reflectivity from units Z to cm^2/km^3 from equations derived by Dokter et al. (2011). I interpolated reflectivity scans to a sun elevation angle of 0.5 degrees above the horizon (i.e. just prior to sunset) by calculating a time weighted mean of scans that accounts for variability in sun elevation across the landscape using the ‘W2Birddensity’ function in the Warning Decision Support System–Integrated Information (WDSS-II) software (Lakshmanan et al. 2006). This function interpolates each sample volume to a standardized sun angle with respect to varying sunset times across the radar range. At this time of year and day, 5 minutes approximately equals the time for a change in 1 degree of sun elevation. I then summarized VIR within all sample volumes at the lowest beam tilt (0.5°) as a measure of relative bird stopover use.

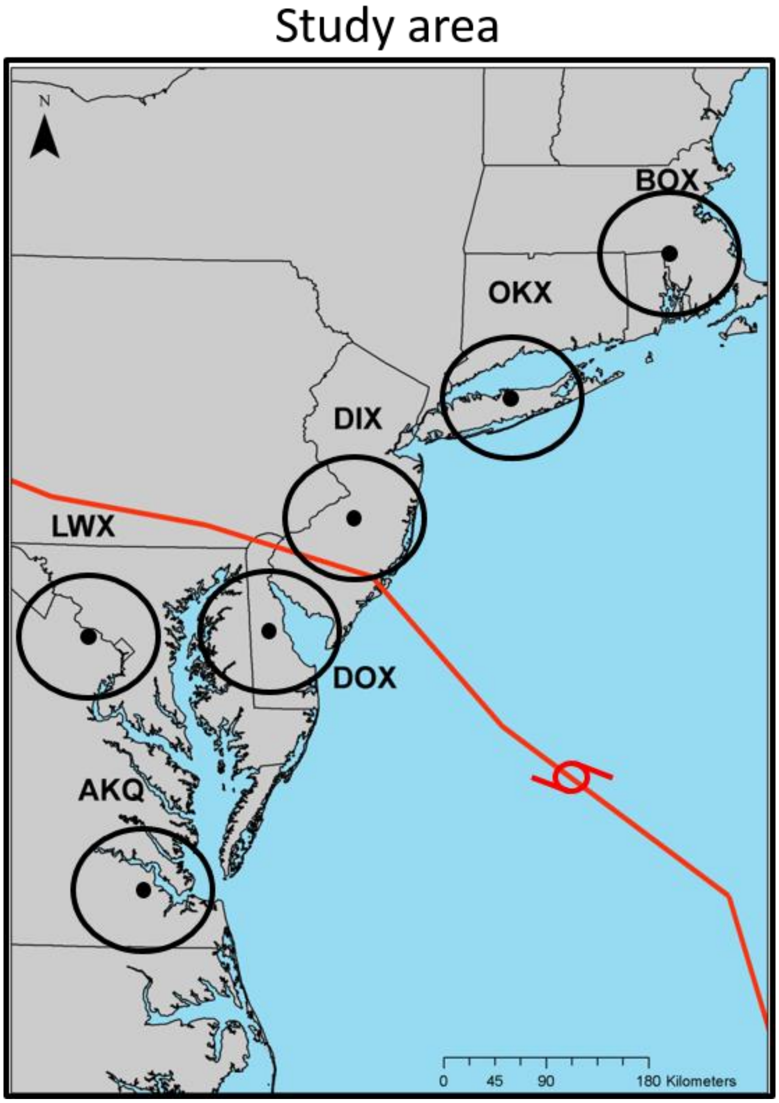

Figure 16 The six radars identified by their call sign along the Atlantic coast in the northeastern United States. Hurricane Sandys path is indicated by the red line.

Unlike the ubiquitous distributions of birds during the peak migratory time period in this area (September – October), late season bird distributions were much more sparse and concentrated at relatively discrete locations with many areas of with no birds. To reduce bias in mean bird density from areas with no birds and allow comparison of discrete areas, I quantified 'high use areas' among sample volumes at all radars if the VIR was at least one standard deviation above the mean across all radars.

To quantify the land cover of the radar-sampled areas, I used the 2011 National Land Cover Dataset. The data set contains 20 categories of land cover at a spatial resolution of 30 m x 30 m (Homer et al. 2015). The resolution of the land cover was finer than a sample volume, so I calculated the total of each land cover type within every sample volume. I reclassified the land cover classes by summing the land cover types in each sample volume into six broader categories Agriculture (types: 81 & 82), Developed (types: 21, 22, 23, & 24), Upland Forest (types: 41, 42, 43, & 43), Emergent Wetland (types: 95), and Forested Wetland (type: 90) using the 'zonal statistics' tool in ArcGIS. I downloaded the path for the eye of Hurricane Sandy from the International Best Tracks Archive from NOAA National Center for Environmental Information (www.ncdc.noaa.gov/ibtracs). I used the 'Near' tool in ArcGIS to calculate the nearest distance to Sandy's path and distance to the coast for each sample volume. To test for changes in vegetation I used the Normalized Difference Vegetation Index (NDVI) derived from MODIS satellite measurements of reflectance. Changes in the NDVI metric, which is measured at 16 day intervals, coincide with change in 'greenness' of a landscape (Carroll et al. 2004). I obtained NDVI measurements from modis.gsfc.nasa.gov for the years 2008 to 2012 for the 16-day interval that encompassed the time period immediately after Sandy's land fall (Julian day 304). I constructed an average baseline NDVI by taking the average NDVI across the four baseline years.

Analysis

I calculated the difference in bird density during 2012 (Sandy year) compared to previous years by subtracting the average bird density for each sample volume during baseline years from the average bird density during the Sandy year. To compare changes in bird density within different land cover types between years, I calculated the area of each cover type within each sample volume, then multiplied these values by the average bird density for the Sandy and baseline years to derive bird abundances within habitat types. I then calculated the average bird abundance within each cover type. I then divided these bird abundances by the total bird abundance across all cover types, which resulted in the proportion of bird abundance across each cover type for baseline and Sandy years.

I resampled the NDVI to the larger spatial resolution of the sample volumes by taking an area-weighted mean of the NDVI at each sample volume using the 'zonal statistics' tool in ArcGIS. I then subtracted the NDVI from the Sandy year from the baseline NDVI to measure changes in NDVI after Sandy. The resulting NDVI data showed 95% of the NDVI differences were between -0.1 and 0.1. I wanted to identify areas that had large changes in NDVI as these were most likely damaged areas from Sandy, so I calculated the average change in bird density across 10 NDVI categories in 0.2 bins from -1 to 1 at all radars.

In order to calculate the average change in bird density relative to the distance from Sandy, I calculated the average change in bird density of all sample volumes in 50km bins from 0km to 450km north and south of Sandy's path. I did the same analysis but for average distance from the coast using 10km bins from 0 km to 80km from the coast.

I wanted to model how change in bird density was related to changes in NDVI, distance to the coast, and distance from Sandy. Visual inspection of the data showed discrete spatial patterns that were likely auto correlated. I used a Lagrange Multiplier test to test for spatial dependence using the ‘lm.LMtests’ function in the ‘spdep’ package using R 3.2.3 (R Core Team 2016) using only the change in bird density values in the calculated ‘high use’ sample volumes for the baseline and Sandy years. This test showed significant spatial dependency ($p<<0.01$). I then fit two models, a spatial lag model and spatial error model, using the same subset of data with change in bird density as the dependent variable and NDVI, absolute distance from Sandy’s path, and distance to the coast as independent variables. The spatial error model assumes the errors contain a correlated structure while the spatial lag model is a spatially autoregressive technique using spatially lagged values to control for autocorrelation (Plant 2012). I fit these models using the ‘lagsarlm’ and ‘errorsarlm’ function in the ‘spdep’ package using R. I then chose the model with the lowest Akaike Information Criterion (AIC).

Results

Of the 911 radar-nights I downloaded, 416 nights were clear of rain, clutter, and anomalous propagation. Of these nights 138 (33%) contained a migratory movement, while 278 (66%) contained no significant exodus of birds within the first 3 hours of the night. This high amount of nights with no significant exodus is reasonable because the time period represents the end of autumn migration for the majority of passerines that move through the area. Of the nights with migration, 91 (66%) contained a movement at sunset versus 47 (34%) which had the first movement 30 minutes or more after sunset. The majority of these later movements was within the first week of November, and only occurred during the Sandy year at two radars (twice at KDOX and three times at KLWX).The results presented here are based only on nights with sunset movements. The majority of radars had at least four nights in 2012 with a sunset movement, KBOX had only two nights. KOKX did not have data for the 15 days between November 15 and November 30, but had four nights prior to November 15th with a sunset exodus so I included it in analysis.

Stopover use differences between baseline and Sandy years varied between and within the radar ranges. Over all, bird density in the Sandy year was lower than baseline years at radars nearest to Sandy's landfall (0.35 and 0.32 cm^2/ha at KDIX and KDOX respectively), and higher at the radar farthest south of Sandy (0.60 cm^2/ha at KAKQ) (Fig. 17). KDIX had the largest decrease in bird density compared to baseline years (-1.21 cm^2/ha change in bird density). KAKQ was the only radar that was significantly higher than baseline years (0.12 cm^2/ha). Bird density at KDOX and KDIX generally decreased across the radar sampling range (Fig. 18-20). Certain areas in the sample range increased in bird density after Sandy that were located adjacent to areas that were high use areas in baseline years (e.g. Areas around New Bedford, MA, Fall River, MA, and Rock Creek Regional Park, MD). Other radars had a relatively large spatial shift in bird density after Sandy (Fig. 21-23). At KOKX, bird density increased in suburban areas around Coram, NY and decreased in bird density in the agricultural fields west of Mattituck, NY. KAKQ had higher bird density in the Sandy year compared to baseline years. Agricultural and wetlands areas near the coast at KAKQ decreased in bird density while upland forest and urban areas west of I-95 increased in bird density. Across all radars, birds increased their use of developed and upland forests and decreased their use of agricultural and wetland cover types after

Hurricane Sandy compared to previous years (Fig. 24). KDOX did not see a decrease in bird density in agricultural areas likely because the area around Milford, DE at KDOX contains significant agricultural cells. Emergent wetlands around the Delaware Bay had significant decreases in bird density and were essentially not used for the remainder of the Sandy year. This area received high flooding and storm damage due to its proximity to the storms landfall.

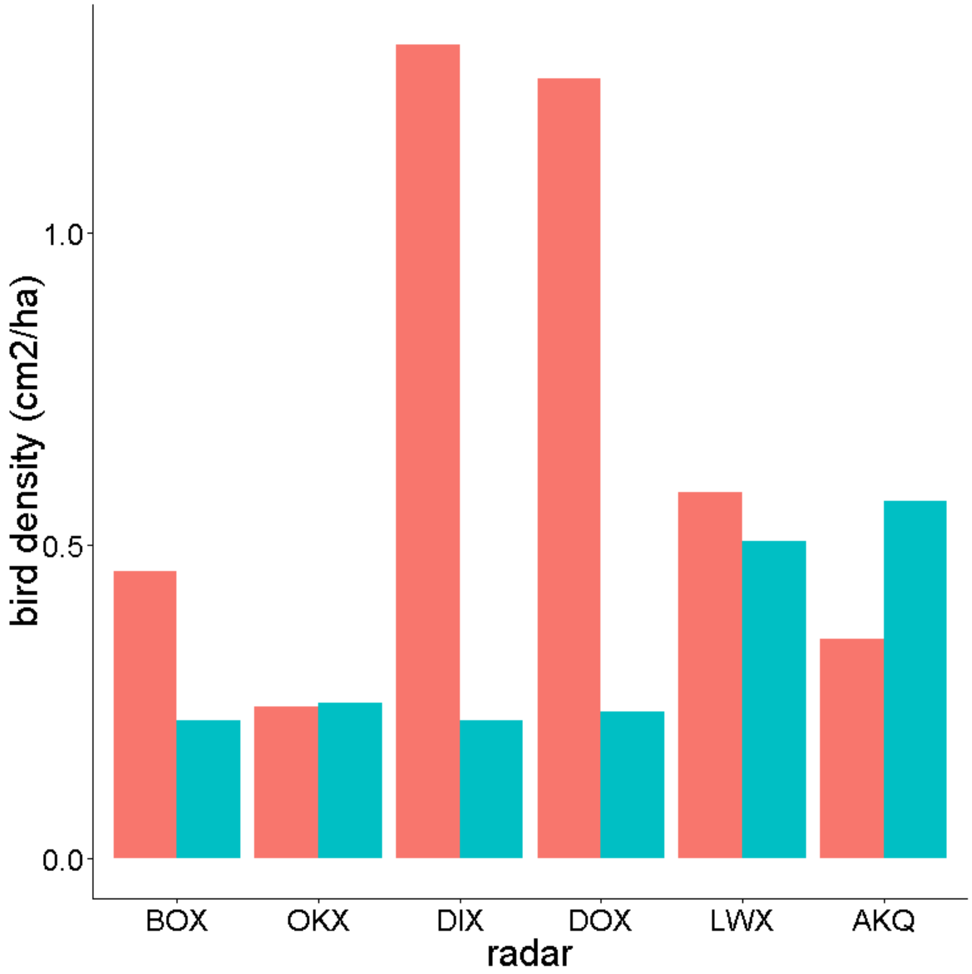

Figure 17 Mean bird density of sample volumes with > 75% of a single cover type at six radars. Red is baseline years (2008 – 2011) and blue is the Sandy year (2012).

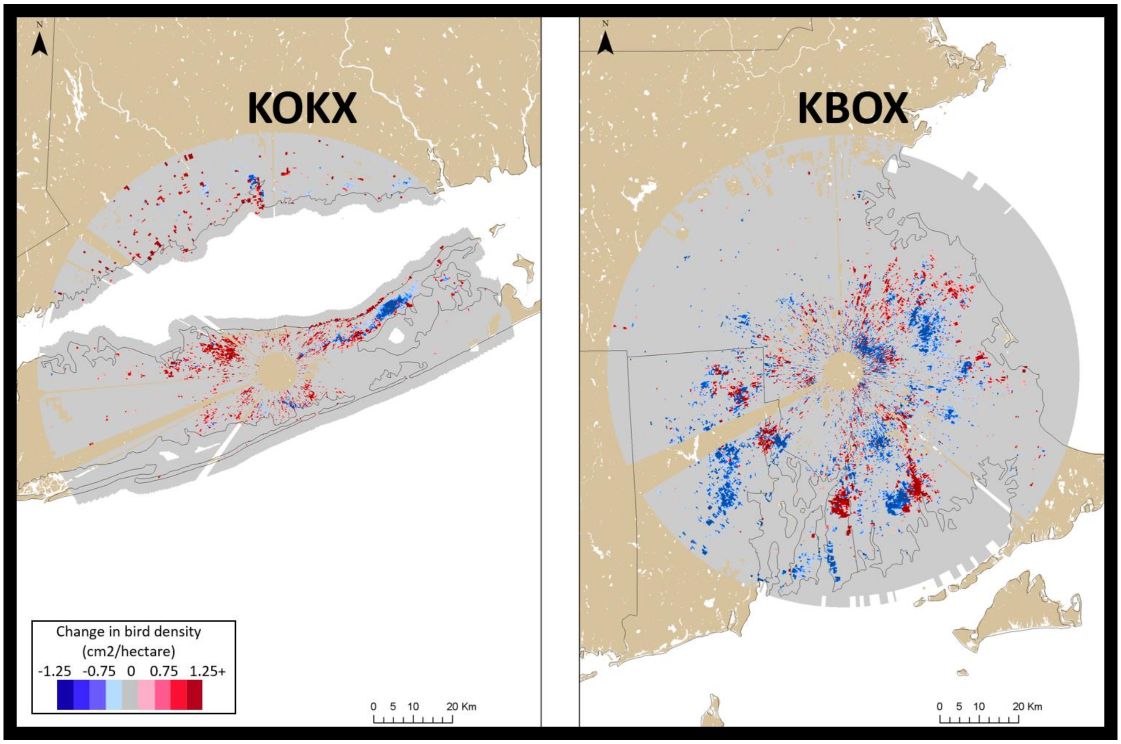

Figure 18 Change in bird density at KOKX (Long Island, NY) and KBOX (Boston, MA) after Sandy compared to baseline years. Decreases in bird density in blue and increases are in red.

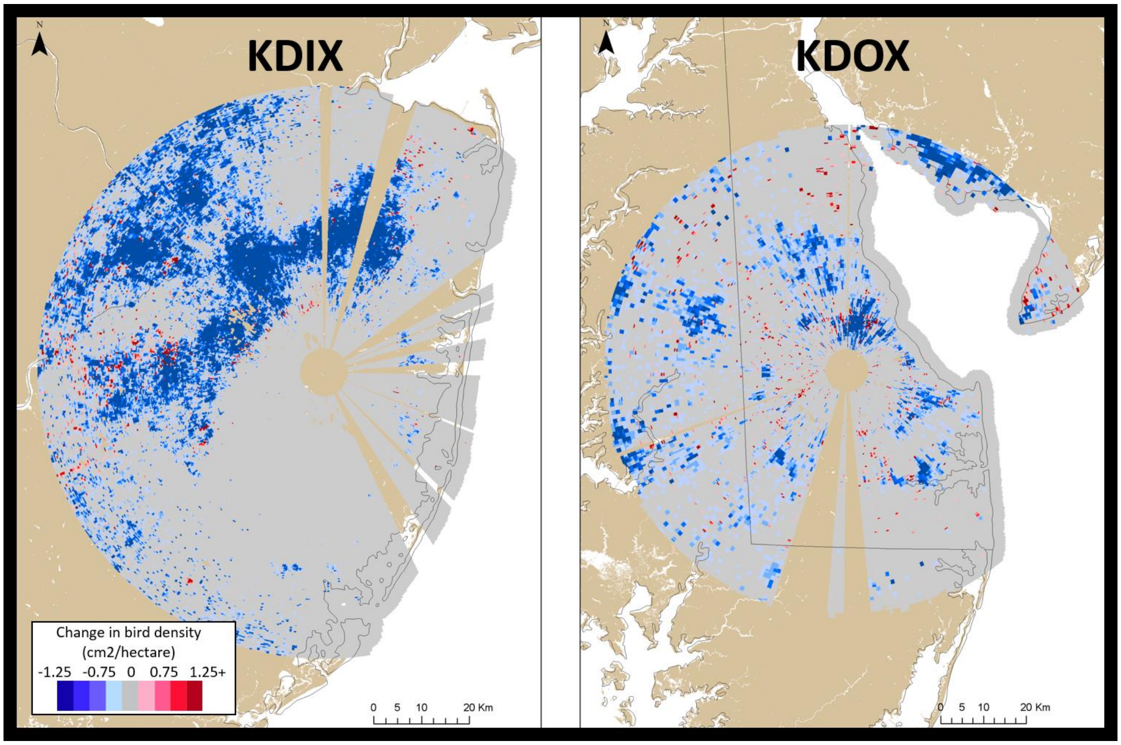

Figure 19 Change in bird density at KDIX (Mt. Holly, NJ) and KDOX (Dover, DE) after Sandy compared to baseline years. Decreases in bird density in blue and increases are in red.

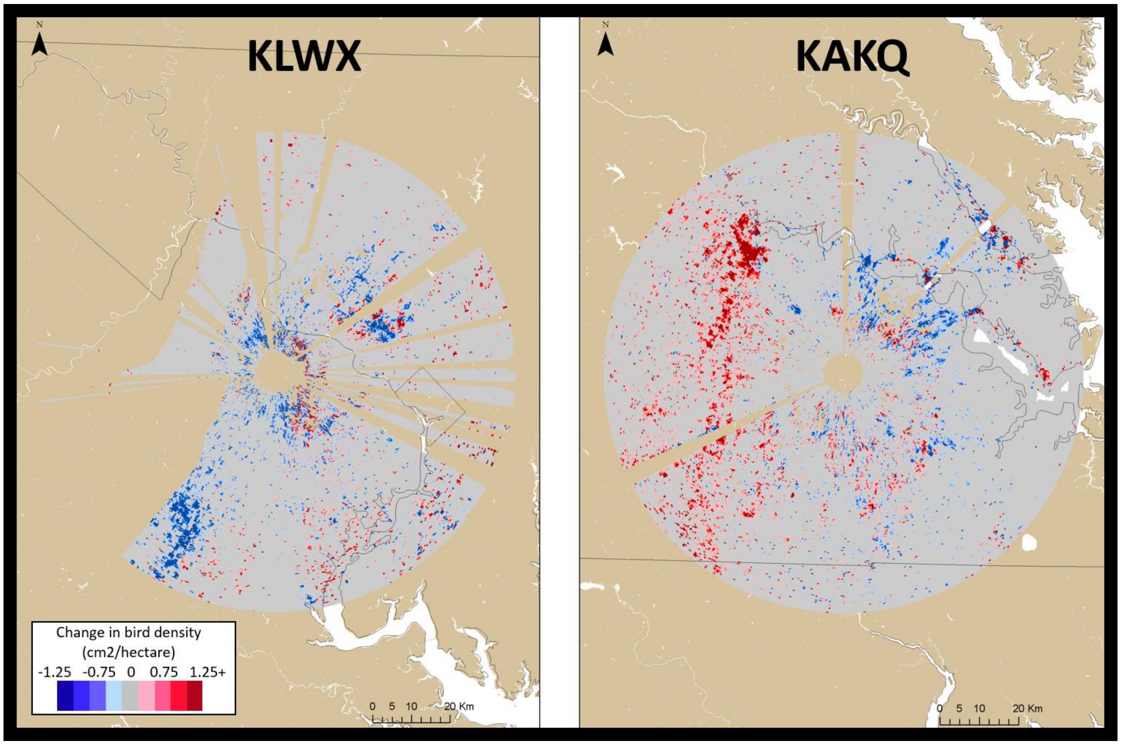

Figure 20 Change in bird density at KLWX (Washington D.C.) and KAKQ (Norfolk, VA) after Sandy compared to baseline years. Decreases in bird density in blue and increases are in red

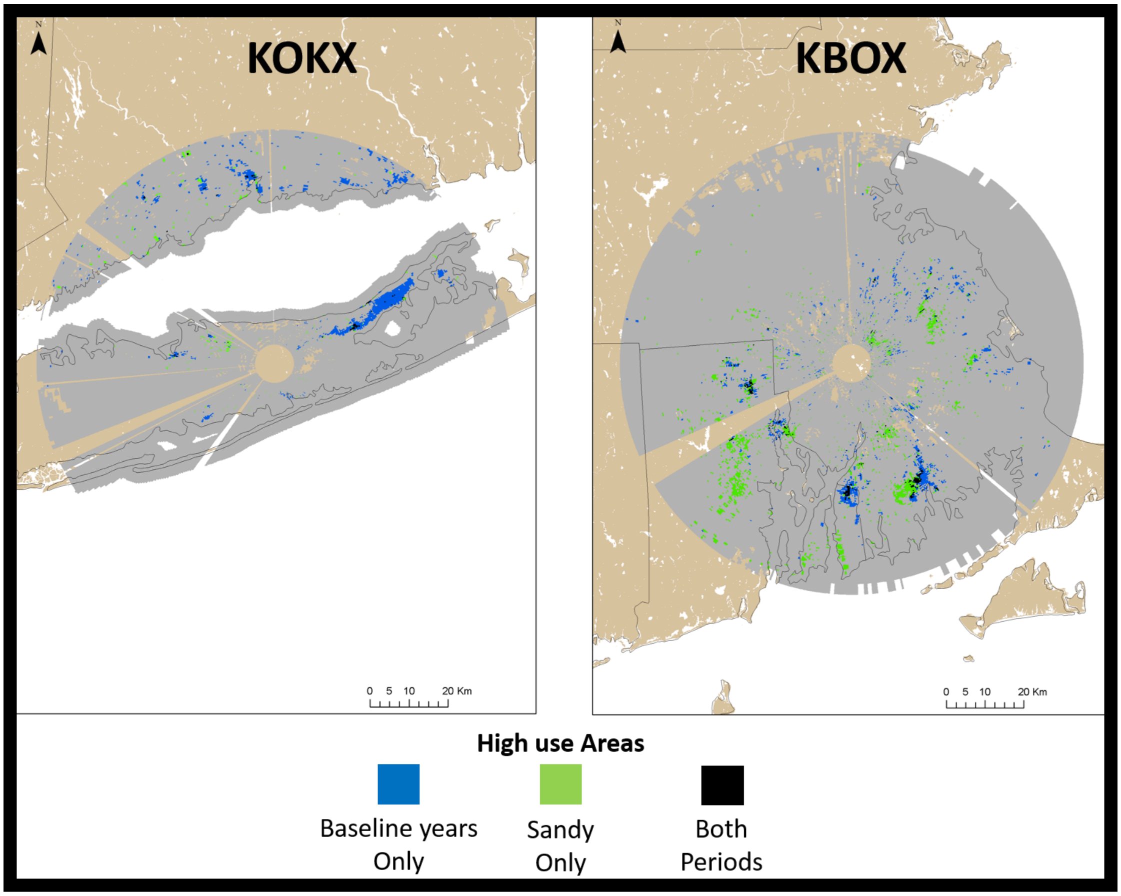

Figure 21 Maps of high-bird-use areas measured during November of baseline years 2008-2011 (blue), after Hurricane Sandy in 2012 (green), or during all years (black) at KOKX (Long Island, NY) and KBOX (Boston, MA). Sample volumes were categorized as 'high use' if it was greater than one standard deviation above the mean bird density.

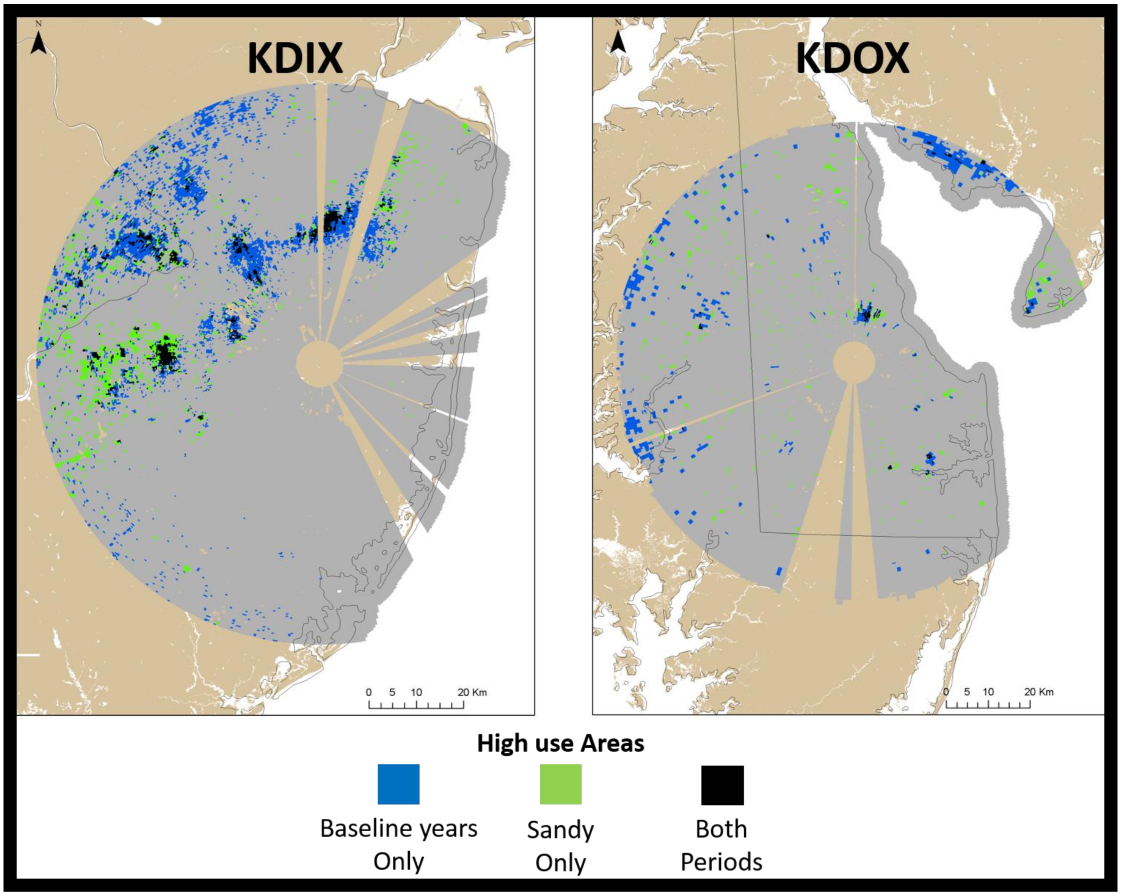

Figure 22 Maps of high-bird-use areas measured during November of baseline years 2008-2011 (blue), after Hurricane Sandy in 2012 (green), or during all years (black) at KDIX (Mt. Holly, NJ) and KDOX (Dover, DE). Sample volumes were categorized as ‘high use’ if it was greater than one standard deviation above the mean bird density.

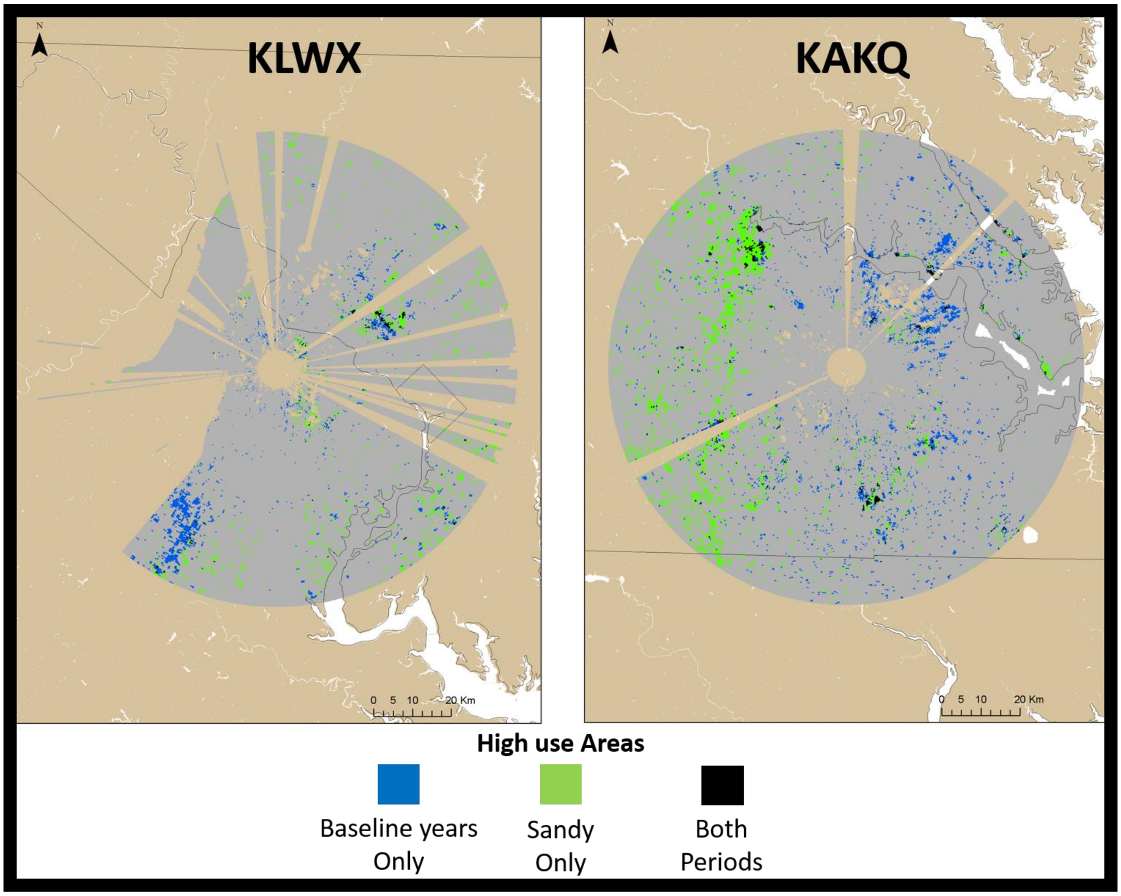

Figure 23 Maps of high-bird-use areas measured during November of baseline years 2008-2011 (blue), after Hurricane Sandy in 2012 (green), or during all years (black) at at KLWX (Washington D.C.) and KAKQ (Norfolk, VA). Sample volumes were categorized as 'high use' if it was greater than one standard deviation above the mean bird density.

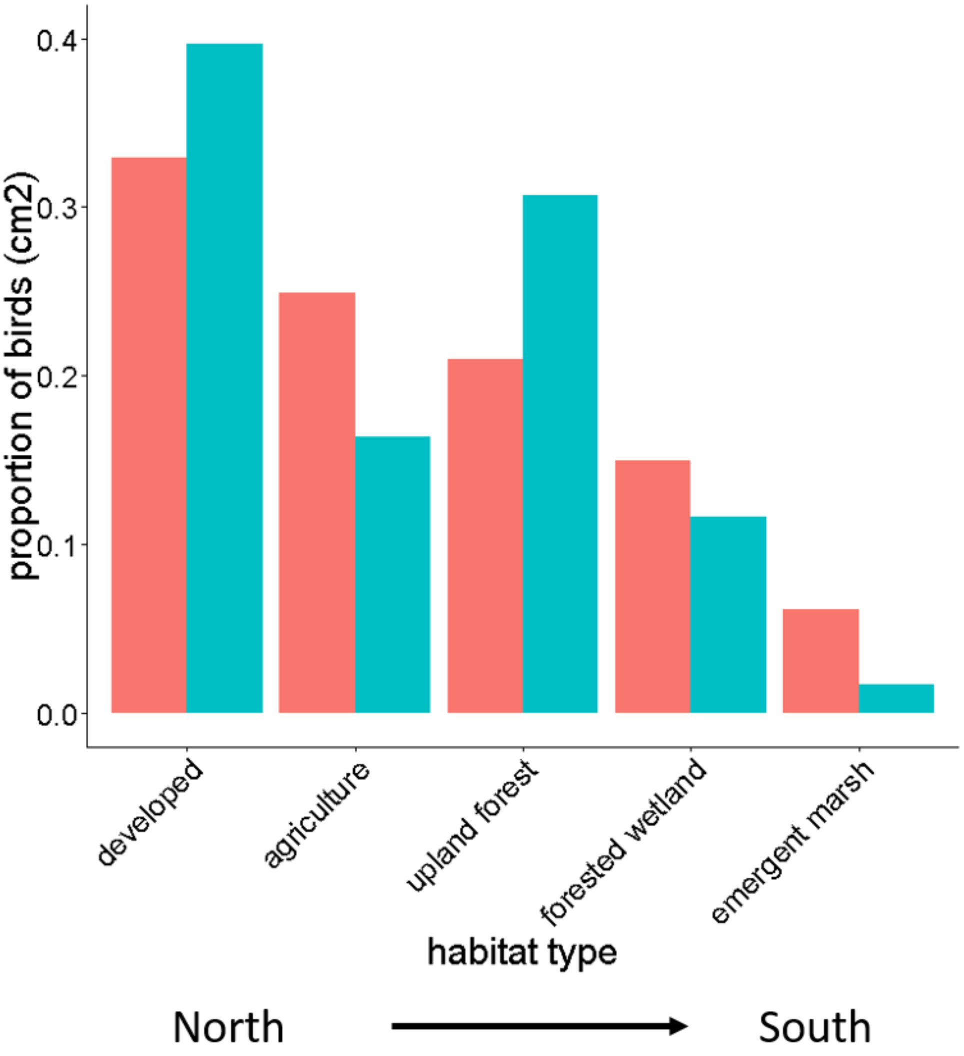

Figure 24 Composition of habitats used by late-season migrants across all radars during the month of November of 2012 in blue (after Hurricane Sandy) and baseline years in red (2008-2011).

Bird densities were lower than in previous years at areas closest to Sandy's path up to 150km away. North of Sandy's path, average differences in bird density relative to previous years oscillated from negative to positive and back to negative within 150km (Fig. 17). The higher bird density corresponds with scattered areas on Long Island that had higher bird densities after Sandy. South of Sandy, the differences in bird densities followed a logarithmic curve, with no change in bird density after 250km from Sandy's path.

Average bird density was lower during 2012 compared to previous years at all distances from the coastline except the farthest bin (80km)(Fig. 18). The largest decrease in bird density occurred at 35km inland from the coast, likely due to the decrease in bird density in suburbs around Philadelphia, PA and Trenton, NJ. Differences in bird densities did not correspond positively to differences in NDVI (Fig. 19). Sites which showed little change in NDVI also averaged lower changes in bird density. 95% of all sample volumes had an NDVI between -0.1 and 0.1 signaling very little change across the region after Sandy relative to baseline years. NDVI changes greater than this threshold did not show a consistent pattern and standard error frequently was within those values within -0.1 and 0.1.

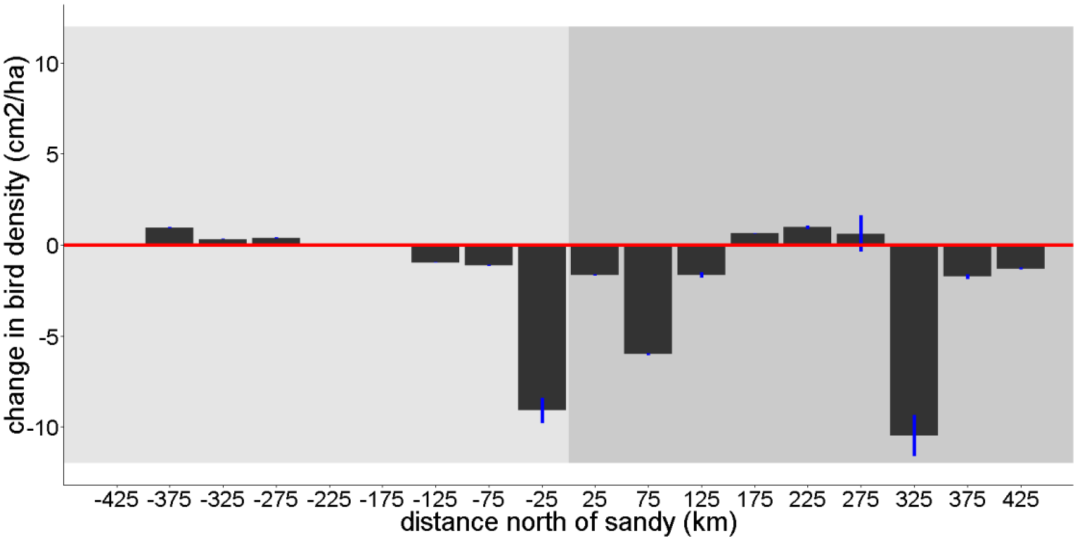

Figure 25 Difference in average bird density at the onset of evening flights during November between 2012 and previous years (2008-2011) as a function of distance north (dark gray) and south (light gray) of Sandy's path. Error bars are standard error.

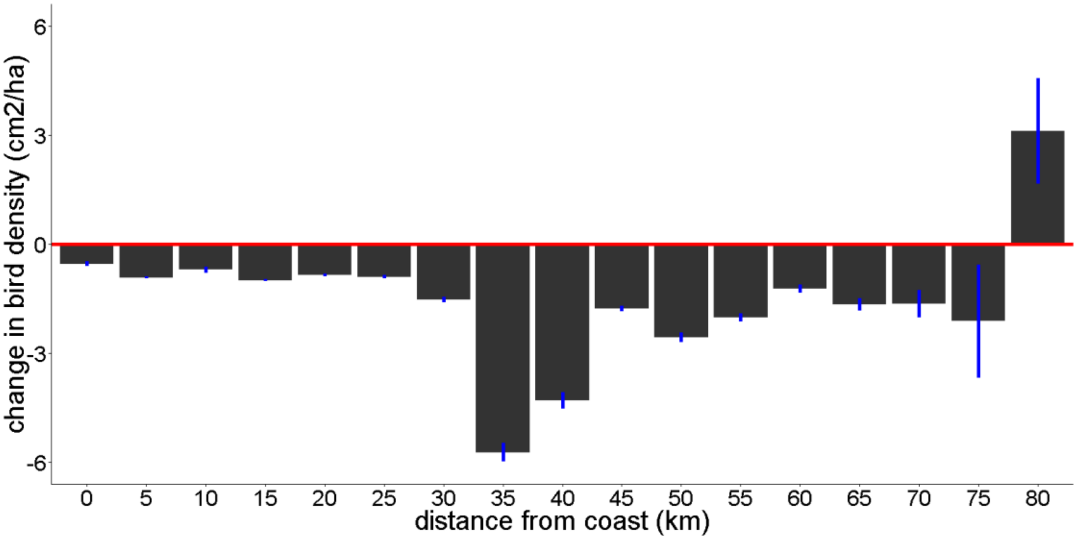

Figure 26 Difference in average bird density at the onset of evening flights during November between 2012 and previous years (2008-2011) as a function of distance from the coastline. Error bars are standard error.

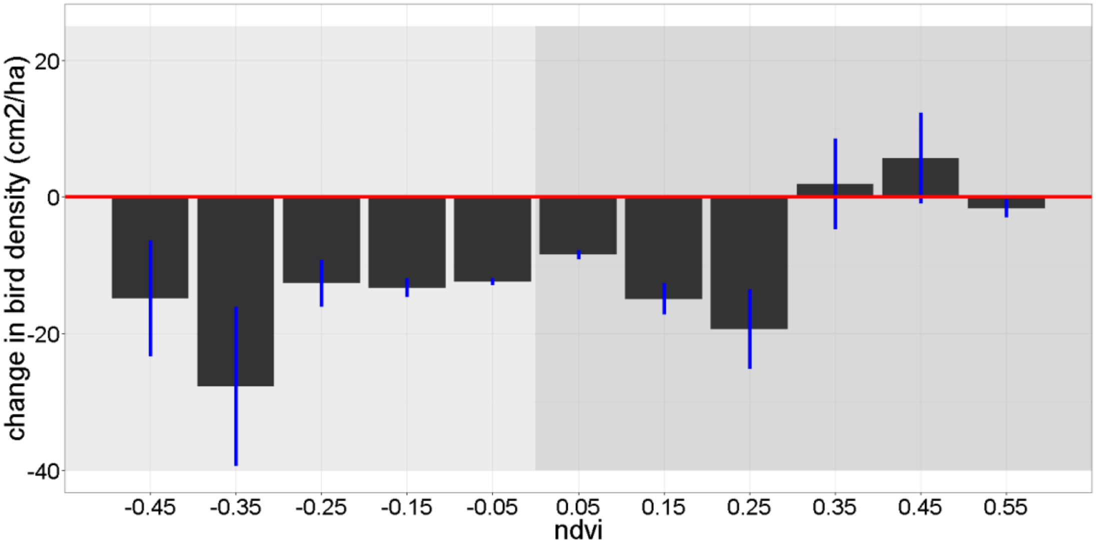

Figure 27 Difference in average bird density at the onset of evening flights during November between 2012 and previous years (2008-2011) as a function of change in NDVI (greenness) after Sandy's landfall. Dark gray are positive changes and light gray are negative changes. Error bars are standard error.

The AIC weights of both the spatial lag model and spatial error model were similar (AIC = 26549 and 26538 respectively), and they were both lower than the spatial independent model (AIC = 28236). I chose the spatial error model because it had the lowest AIC value. Only distance to Sandy was significant in the spatial error model, and had a positive relationship with change in bird density (table 1.). NDVI and distance to coast had negative relationships but were not significant.

Parameters	**Estimate**	**Std. Error**	**Z value**	**P**	
Intercept	-0.6402	0.2228	-2.874	0.0004	*
NDVI	-0.0009	0.0096	-0.094	0.9254	
distance from Sandy	0.6476	0.1833	3.532	0.0004	*
distance to coast	0.0328	0.0357	0.9202	0.3573	

Table 1 Model estimates from the spatial error model explaining change in bird density after Hurricane Sandy from 15,000 observations. (*) denote if the parameter estimate was significantly different from zero in the model.

Discussion

After the passage of Hurricane Sandy, bird densities decreased in areas that were closest to the storm (New Jersey) and areas known to have experienced high winds and storm surge (e.g. regions around Long Island). South of Sandy, birds were seen at higher concentration than typically seen in other years. Relative bird use was lower in agricultural areas and wetlands and higher in developed areas across the study range after Hurricane Sandy. This behavior may be related to ‘sheltering’ during the storm. During hurricanes, birds will seek shelter particularly near buildings (Cely 1993). This may also explain why open habitat types like agricultural lands and wetlands tended to have the highest relative decrease in use by birds. High proportions of this cover type might represent habitat that is more open and therefore not sheltered from the high winds. Developed cover types generally increased in bird density. Birds may have sheltered in the more suburban areas where buildings may help to decrease winds, though this would likely be short term, whereas the pattern continued for the month of November. Suburban areas, particularly those not adjacent to the coast received relatively little flooding. It’s possible that birds foraged less in agricultural areas that may have been flooded by rains from Sandy, and shifted use to lawns and trees in urban areas. This may be practical for species that frequently use both agricultural and suburban areas like American Robins and Common Grackles. In migration, these species will shift their distribution as local fruit abundances change. (Baird 1980). Similarly, birds frequently shift their distribution after a hurricane to match the new food availability and habitats. Parrots in Jamaica were seen foraging in agricultural fields after montane regions were heavily damaged by Hurricane Gilbert (Varty 1991), while Prairie Warblers increased in mangroves which they normally used infrequently after the same Hurricane (Wunderle et al. 1992). In Delaware, this likely did not occur because areas around Milford, DE remained relatively constant in bird density between the Sandy years and baseline years (see Chapter 1). This is likely a site of a large communal roost used by American Robins, Common Grackles, and European Starlings. Very large roosts like this are seen on radar, and are visible on nights when there was migration nearby. Radar shows this is likely one of the larger roosts in the region and likely buffered from changes.

NDVI did not change significantly after Sandy across the study region relative to baseline years, likely because at this time of the season leaf senescence is ending (Arora and Boer 2005). This does not mean damage to vegetation did not occur across the study area. Large decreases in NDVI were seen along the Potomac River in

Maryland, however, this region typically records almost zero bird density when sampling radar at sunset this late in the season. NDVI measures the green reflectance from vegetation, and likely does not measure significant losses in fruit or mast from trees and shrubs. High winds from hurricanes can blow fruit and mast off trees or shrubs (Wiley and Wunderle 1993), this in turn can affect the spatial distribution of birds. Shifts from agricultural areas to developed areas may be signaling a shift in available resources after winds from Sandy destroyed local fruit production. There is unfortunately no data on fruit distribution before and after Sandy.

The most significant increase in bird density after Sandy was seen in Virginia west of I-95. This region generally had the lowest bird density across the study area. One possible explanation for shift in bird density is that migrating birds were forced to make landfall due to encountering heavy rains during the storm. On October 27, the rain bands at the edge of the storm began to move over Virginia and Delaware. The edge of the storm covered the eastern portion of the KAKQ coverage area while the western half was largely clear. The radars showed that large movements of birds left habitats at sunset in Long Island and New Jersey, and appeared to hit this band of rain around Virginia, which likely grounded them. One week after the storm, as rains passed, there was a large increase in birds leaving habitats at sunset approximately in the western portion of Virginia which had increases in bird density after Sandy.

The study-wide decrease in bird densities may also have been caused by birds leaving the area either before the storm or directly after it. Sandy may have led to the acceleration of migration through the region. In typical years, bird stopover densities and migratory traffic rates are declining in November, until the average traffic rate through the region is near zero (Farnsworth et al. 2015). In analysis of Hurricane

Katrina stopover use, stopover usage mostly returned to average values four weeks after the storm (Barrow et al. 2005). If Sandy caused a momentary change to the flow of migration, I would expect stopover use in the area to return to average values after a couple weeks. Instead migration traffic rates were lower after the storm. Stopover analysis focuses primarily on nights when a migration flight occurs. For this analysis I only used nights where I could identify targets taking off at sunset and migrating south. Across the study area, after Sandy, I saw an increase in nights where no migration occurred compared to baseline years, particularly in the last two weeks of November. These nights would not be used in stopover analysis, but might show that migration accelerated through the region particularly before the storm, causing lower bird density in the region. Another explanation for this decrease in bird density may be that birds were killed during the storm. Measured mortality of small species like passerines is usually very low after hurricanes, however, mortality surveys may be heavily biased towards larger species (Cely 1993). The largest measured mortality tends to occur to waterbirds due to their proximity to flood waters (summarized in Wiley and Wunderle 1993). Reports have not surfaced of any large mortalities due to Sandy. Birdwatchers flocking to the Northeast after Hurricane Sandy and reporting on online forums reported many vagrant birds but very few if any dead passerines (unpub). Due to this lack of reports, I think it is unlikely that the decrease in overall bird density was due to mass mortality events.

Birds are flexible in their habitat use, especially after hurricanes (Wiley and Wunderle 1993). Migrants might be particularly flexible at this because they spend a quarter of their life cycle in a variety of habitats over their migration routes. This study shows that late-season communally-roosting land bird migrants dominated by

American Robins shifted their distribution for at least a month after a major severe weather event, and that the distance over which hurricanes can affect migration is wide. Significant decreases in bird density were seen out to 300km to the north of the center of the Sandy's path and 150km to the south. Additionally, birds shifted from agricultural to developed areas up to a month after the storm. Without data on fruit distribution before and after Sandy it is difficult to tell if the shifts in habitat use I documented were due to a shift in food resources or a function of an overall decrease in stopover through the area.

The increasing severity of future hurricanes due to increased sea surface temperatures caused by climate change is theorized to occur (Goldenberg et al. 2001, IPCC 2014), though decadal fluctuations that complicate interpretation of patterns (Knutson et al. 2010). If the severity of storms increases, this may add another hurdle for migrant birds to overcome, many which are already in decline. The 'storm hypothesis' posits that increased severity of storms may be a cause of decline (Butler 2000), due to either weather encountered during migration or damage to wintering areas. Any change during one part of the season can cause carry over effects, whether from severe weather (Brown and Brown 2000) or cyclical changes in weather (Paxton et al. 2014). This study shows that migratory birds exhibit spatial plasticity that may buffer discernible large scale effects from a hurricane. Not insignificant is the energy expended while birds relocate to new areas, and what cost this may incur at subsequent life stages. There's much we don't yet know about how birds behave after a storm, particularly in migration, or what lag effects may remain. Hurricane effects on wildlife suffer from the lack of baseline data to compare values. Weather radars allow for the detection of migratory patterns over large geographic area, and archived data make it possible to look back at the response of migrating birds to storms since the mid-1990s. When coupled with new technologies that allow individual birds, even small passerines, to be tracked during migration, and the field observations of citizen scientist’s in repositories like eBird, scientists now can test new questions when rare events live severe weather affects areas.

Chapter 3

ANALYSIS OF MIGRANT TRAFFICE RATES BEFORE AND AFTER PASSAGE OF HURRICANE SANDY IN THE NORTHEASTERN UNITED STATES

Annually millions of birds undergo long distant migration to breeding and wintering areas, many which may be thousands of kilometers away. This perilous journey can be the period of greatest risk to mortality in a birds life cycle (Sillett and Holmes 2002). Enroute, they face challenges from high energetic demands (Yong and Moore 1993), predation (Dierschke 2003, Cimprich et al. 2005), refueling in unknown landscapes (Cohen et al. 2012, 2014), and threats of severe weather (Newton 2007). A successful migrant that navigates these threats will arrive at their breeding or wintering ground with a significant advantage over those that arrive in poor condition or late (Marra et al. 1998, Smith and Moore 2005). It is therefore likely that adaptive strategies exist to minimize many of these risks. Of these, severe weather events are stochastic processes that can impact large geographic areas, making mitigation likely very important for affected migrants. Mass mortality events due to severe weather can kill hundreds of thousands of birds in a single event from sudden freezing temperatures, tornadoes, or drowning from extended periods of rain over water (Newton 2007). Some of these events may limit entire populations (Barry 1968), and may cause delayed effects to fecundity (Brown and Brown 2000, Butler 2000).

The successful ‘optimal’ migrant minimizes energy while maximizing migration speed (Alerstam and Lindstrom 1990). In spring, male birds may forego energy demands to increase their speed to reach breeding grounds early to establish territories. Females under less constraint for speed typically arrive later, but must minimize the risk of arriving too late and accepting lower quality foraging areas or nesting substrates (Drake et al. 2014). Migrants in the autumn are thought to be under less pressure to migrate quickly through a region, particularly temperate migrants who have a long time period to travel a short distance. During autumn, many migrants are choosier on the winds they take, and will migrate only on nights of favorable winds (Liechti and Bruderer 1998). If this is not possible, they will migrate at altitudes with the most favorable winds (Wainwright et al. 2016). This 'sit and wait' strategy may not be useful if the winds do not shift with high enough periodicity, and may depend on regional synoptic patterns (Alerstam et al. 2011).

In North America the annual autumn migration of birds coincides with peak season of hurricanes. These large scale synoptic systems are stochastic events that are difficult for animals to predict because the storms originate thousands of kilometers from their landfall. Winds and rain are often the first warning that a storm is approaching, and these may enter regions only a day or two in advance of the storm. By the time these events occur many migrants are often grounded and do not engage in migratory flights until heavy precipitation subsides after the storm (Richardson 1990). Dangers from hurricanes depend on how a bird interacts with a storm. As hurricanes make landfall, they can trap birds in the relatively mild 'eye wall' (Freeman 2003, Van Den Broeke 2013). If the eye moves back over water, birds that cannot land on the water are forced to stay in the wall until the storm makes landfall again. During this time, birds may become exhausted and fall into the water to die. While some cases have been documented recently using polarmetric weather radar data (Van Den Broeke 2013), the number of hurricanes this happens in is largely unknown. More commonly, birds may be displaced by strong winds from the edge of the hurricane. If a bird flies near the edge of a storm, it may become entrapped in the high counter clockwise blowing winds, and be forced into strange directions. In the Atlantic, this mechanism has been thought to cause the arrival of unseasonable migrants in the Maritime Provinces and Northeast United States in the autumn (Wiley and Wunderle 1993). In less extreme cases, hurricanes have been blamed for increases in uncommon migrants sometimes hundreds of kilometers away from their typical range (Fisk 1979, Thurber 1980, Faaborg and Gauthreaux 2010). The strong shift in winds and long periods of rain may also stall migrants and delay their subsequent migration. This migratory pause happens after many days of rain and is a significant factor in the intensity of migrants aloft (Ernii et al. 2002). Birds will choose to not migrate on nights of even lite rain, and instead forego migration until weather clears (Richardson 1990). A majority of studies on the effects of birds in relation to hurricanes are often small scale, reporting, for example, on results from a single site in the wintering range (see Wiley and Wunderle 1993 for an exhaustive list). Few studies have quantified the effect of hurricanes on birds at a scale of hundreds of kilometers that is equivalent to the hurricane itself.

Hurricane Sandy was a major hurricane that made landfall at Brigantine New Jersey on October 29, 2012. It was the largest hurricane (by width) ever recorded in the Atlantic and the second most costly behind Katrina (Blake et al. 2013). Hurricane Sandy formed in the Caribbean Sea on October 23. It became a hurricane on October 24 just before making landfall in Jamaica. It strengthened to a category 3 hurricane just before passing over Cuba on October 25. At this point it turned north into the cooler Atlantic waters and weakened in strength. On October 28, it passed by North

Carolina, and then abruptly shifted its path west towards the Mid-Atlantic states. Just prior to U.S landfall, Hurricane Sandy was downgraded to a post-tropical depression with winds up to 90 mph. At landfall, heavy winds added to a high-tide that caused significant storm surge into adjacent coastal areas and wetlands measuring as high as 12 feet on Long Island (Blake et al. 2013). Measured tree damage remained low with relatively low numbers of overturned trees, although saltwater intrusion into near coastal forested caused local die offs. After landfall, Sandy turned west-north west and eventually merged with a low pressure system over eastern Canada (Blake et al. 2013). Sandy was a remarkable in the late timing of a storm of its size. Very few hurricanes typically make landfall in November (Elsner and Kara 1999). While damage to coastal wetland and dune habitats were significant, relatively little damage was reported to inland habitats and forests. Sandy produced significant rain in Delaware and Maryland with a peak total of 12 inches in Maryland and heavy snowfall in areas of West Virginia (Blake et al. 2013). The timing of Sandy into the northeast United States coincided with the tail end of autumn migration for most small land birds. At this moment, the majority of Central and South American wintering passerines had moved through the area, and the latest temperate migrants began moving through the area (Allen and Peterson 1936, Bennet 1952, Newton 2008).

In the wake of Hurricane Sandy, vagrant birds were reported by bird watchers across the eastern United States, including seabirds at inland locations and songbirds normally found in the Caribbean at this time of the season (eBird.org, unpub data). Prior to the hurricanes landfall, on the night of October 27, winds shifted towards the southwest, thus coinciding with the general direction of migratory flight through the region. The next day the storm would encompass the entire region with precipitation before making landfall. After five days of rain, Sandy left the region, allowing migration to resume. In Chapter 2, I analyzed data from weather surveillance radars and documented large decreases in stopover use along the Atlantic Coast in the weeks after Sandy relative to baseline years. The largest changes in bird density, were within 150km from the site of landfall in Brigantine, NJ. At radars south of the path in Virginia, days after passage of the storm, uncharacteristically large measurements of birds leaving habitats were measured on radar. One explanation of this pattern is that birds migrated through the region prior to Sandy's landfall, causing a decline in post-Sandy stopover use by birds. At this latitude, passerine migration intensity declines through November as the majority of land bird migration has ceased. Radar intensity also decreases during November and nights without migration are more frequent (Farnsworth et al. 2015). It is possible birds used the strong beneficial winds in the outer bands of the storm to migrate out of the region in advance of the storm. This would cause an abrupt decline in migrant traffic rate through the region compared to previous years as migration essentially ends earlier. Therefore, local decreases in stopover use may be related to birds advancing their migration timing through the region rather than avoiding the region because of storm damage to stopover habitats. Local increase in migration rate can occur after bouts of rain, as birds arriving from outside the area are grounded (Richardson 1990, Ernii et al. 2002). If weather is marginal, and birds decide a 'sit and wait' strategy, then they may choose to gain additional fat and take off as weather becomes more beneficial for migration. Few studies have reported on the effect of hurricanes on migrants, likely because of the difficulty in collecting appropriate baseline data (Wiley and Wunderle 1993). As such, information on flight patterns and traffic rates before and after a storm is lacking.

Weather radar has been used for the last five decades to study movements of flying animals (Chilson et al. 2012). It is an effective tool for studying broad scale migratory movement (Gauthreaux et al. 2005, Chilson et al. 2012). In the United States the National Weather Service maintains a network of over 150 radars archived and publically available for download. Measurements of reflectivity correlate with density of birds aloft (Gauthreaux and Belser 1998, Buler and Diehl 2009). Radar is a useful tool for measuring migrant traffic rate (MTR), the measure of the amount of birds per hour traveling across an area (Horton et al. 2014, Van Doren et al. 2015). These measurements can give us an idea of the approximate migration intensity in a region, and can be used to compare a change in total birds in an area.

My objective was to use Weather Surveillance Radar to measure the intensity of migratory bird flight in the evenings before and after the passage of Hurricane Sandy through the northeastern United States. I tested the hypothesis that Sandy altered the timing of migration in the area compared to previous years. I predicted that 1) Birds left in large numbers on the evening prior to landfall of the storm and thus produced high migration intensity compared to previous years, 2) That immediately after the storm large increases in migration rate would be seen around areas near the storms landfall, and 3) In the days following the passage of the storm, there would be a measurable decline in migratory flight intensity compared to previous years.

Methods

I downloaded data from the National Weather Service for the time period October 7 – November 30th 2008 – 2012 for six radars: KBOX (Boston, MA), KOKX (Upton, NY), KDIX (Mt.Holly, NJ), KDOX (Dover, DE), KLWX (Sterling, VA), and

KAKQ (Norfolk, VA) (Fig. 28). I chose these radars because they are adjacent to the coast where the largest effect to traffic rates likely occurred. These radars cover approximately equivalent areas north and south from where Sandy made landfall, and are approximately the width of the storm (~1000km). I used Integrated Data Viewer software to screen radar reflectivity data from each night, and deleted from further analysis nights with precipitation, which bias measurements of traffic rate Of the remaining nights I took six volume scans, one at sunset, and then a volume scan each hour after to sunset up to three hours. To correct for the radar sampling increasingly higher elevations with farther range, I calculated a vertical profile of reflectivity (VPR) for each scan in 10m height bins from 0km to 3km (Buler and Diehl 2009). A typical radar volume scan includes five elevations: 0.5°, 1.5°, 2.5°, 3.5°, and 4.5°. I chose to create VPR's using the 1.5° beam and above to allow comparison across nights with anomalous propagation of the beam or clutter that occur primarily at the lowest tilt. I calculated VPR using sample volumes within 5km to 20km of each radar, as these ranges correlate highest with birds aloft (Buler and Diehl 2009). For density measurements of birds aloft I used reflectivity measurements from all sample volumes in the 1.5° degree tilt. I used the VPRs to calculate a correction factor for each sample volume, which gave us a standardized single measurement of vertical reflectivity (Vertically Integrated Reflectivity). I then converted measurements of reflectivity from units Z to cm2/km3 from equations derived from Dokter et al (2011).

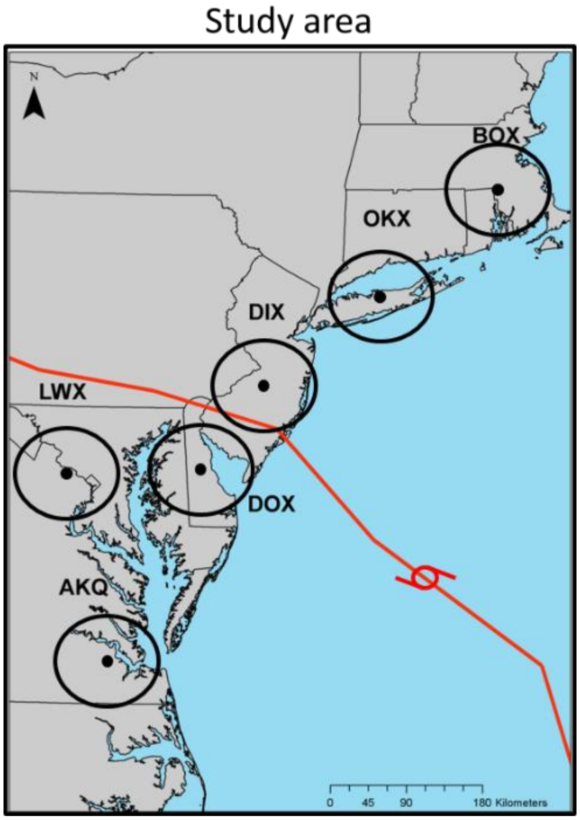

Figure 28 The six radars identified by their call sign along the Atlantic coast in the Northeast United States. Hurricane Sandys path is indicated by the red line

Calculating traffic rates require a measurement of the speed birds are travelling through the airspace. Radial velocity is the radar measurement of the ground speed of targets towards (negative values) or away from the radar (positive values). During migration, these values can be used to determine the collective mean speed and direction of birds over the ground within the radar domain. I took radial velocity measurements from the sweeps, and converted them to U and V vector components by fitting a sine wave function to the annulus of the radial velocity measurement for each range distance (Browning and Wexler 1986). To incorporate only the ground speeds at heights birds were migrating in I weighted the ground speeds by the derived VPRs. I then multiplied the mean vertically integrated reflectivity within 65 km of the radar by the ground speed to derive the Migration Traffic Rate (MTR) (Gauthreaux and Belser 1998, Black and Donaldson 1999). The resulting units are in cm^2 per km per hour, I then divided by 17.5 cm^2, the average cross-sectional area of a songbird (Diehl et al. 2003), which resulted in a measurement of birds per km per hour (which I refer to as MTR).

Analysis

I calculated MTR for each hour after sunset for twelve hours after sunset, for the night of October 27, 2012, and then calculated the mean variability of the traffic rate on a log scale across each hour for the night. I calculated 90% confidence intervals for baseline years for each hour segment. In order to calculate the average seasonal traffic rate over time I calculated the average of the nightly traffic rates for seven temporal bins on a log scale (Oct 7 – Oct 14, Oct 15 – Oct 21, Oct 21 – 27, Nov 1- Nov 7, Nov 8 – Nov 15, Nov 16 – Nov 21, Nov 22 – Nov 30) for the baseline years and Sandy year. I was most interested in migration traffic rates of birds within the local region surrounding radars and wanted to limit the amount of birds sampled which originated from habitats outside each radar. I used observations during the first three hours of the night, because this is the time when the majority of birds initiate migration (Åkesson et al. 2002). I did not include the four days when rain covered the entire study area during Sandy's landfall (Oct 28 – Oct 31). I calculated a 90% confidence interval for baseline years for each temporal bin.

Results

I analyzed data from 516 nights out of 1390, which were clear of rain, clutter, and anomalous propagation. On the evening of October 27 (two nights prior to landfall of Sandy), rain encroached in portions of the study area and I discarded time periods where rain was within 65km of the radar range, as this was the range I calculated average reflectivity of birds in flight. KAKQ contained rain within the radar sampling range at all time periods of the night, while KDOX, KDIX, and KLWX had rain enter the sampling range at 23:00, 01:00, and 02:00 UTC respectively. The remaining two radars, KOKX and KBOX contained no significant precipitation within 65km of the radar sampling range. Traffic rate was generally higher in the Sandy year than baseline years at all radars except for KDOX (Fig. 29). KBOX, increased initially and then declined in traffic rate five hours after sunset. Radars that were along the edge created by precipitation were higher in traffic rate. KOKX, KDIX, and KLWX peak traffic rates were three times higher than their corresponding baseline rate.

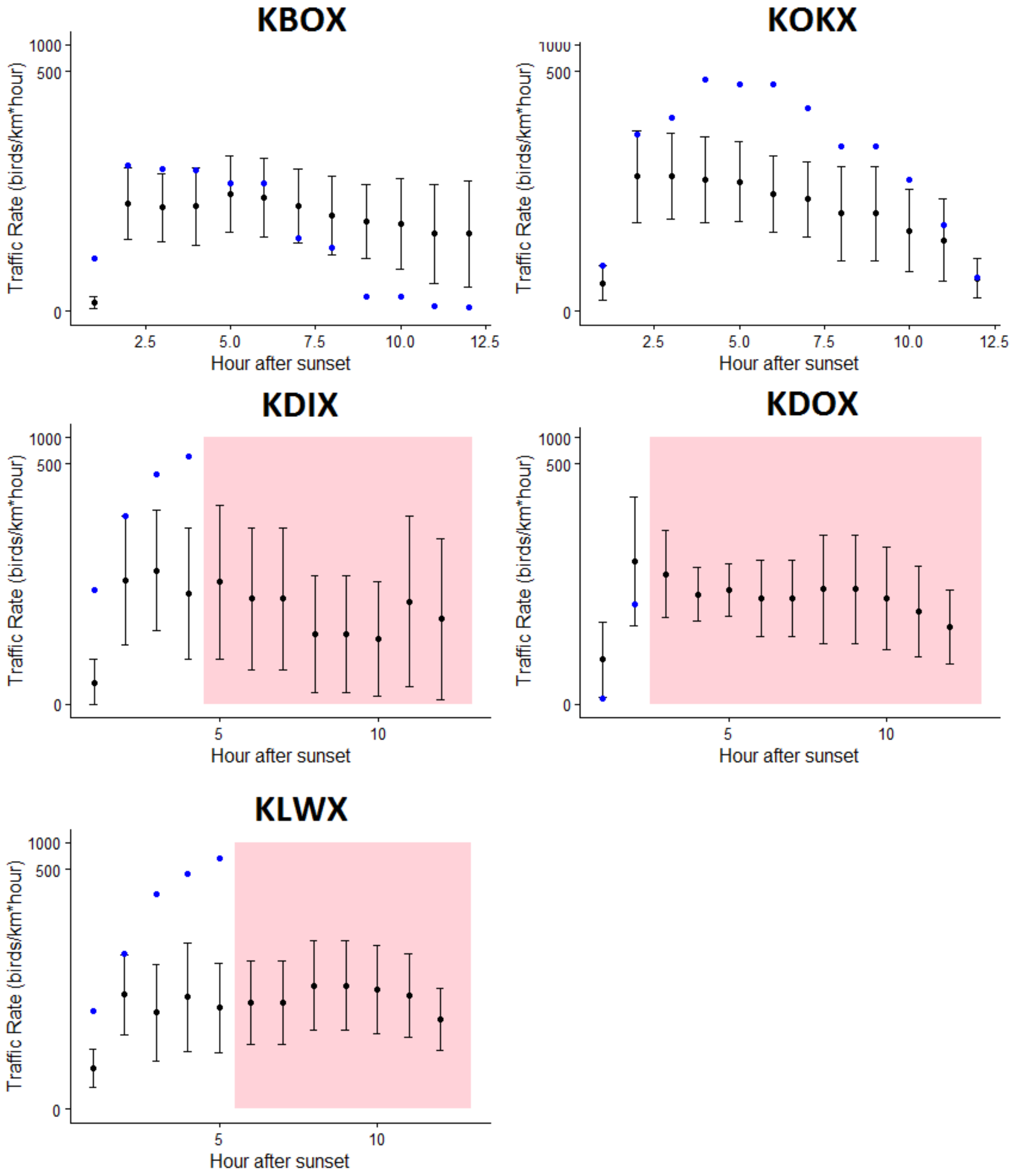

Figure 29 Migration Traffic Rate (MTR) on October 27, 2012 (blue) prior to Sandy through the first three hours of the night at five radars across the northeastern United States compared to baseline years (black) during the similar time period (October 25 – October 30). Pink areas are those where rain from Hurricane Sandy interfered with calculation of traffic rate. Bars are 90% confidence intervals calculated for every temporal segment during baseline years.

Temporal traffic rate at all radars were within the baseline confidence intervals except one week after Sandy. At this time, all radars averaged a significantly higher traffic rate in the week after Sandy than in the same week in baseline years (Fig. 30). These traffic rates were highest at KAKQ, where the traffic rate was twice as high as any other radar during that time period. Overall radars averaged 430% higher than baseline values during the week after Sandy. Two weeks after Sandy all radars declined in traffic rate compared to the first week, however KAKQ remained higher than baseline years. Three and four weeks after Sandy all radars averaged traffic rates that were generally lower than baseline years, although only KDOX and KAKQ were significantly lower. Three and four weeks after Sandy were lower than baseline years at four out of the six radars, while KLWX was similar to baseline years.

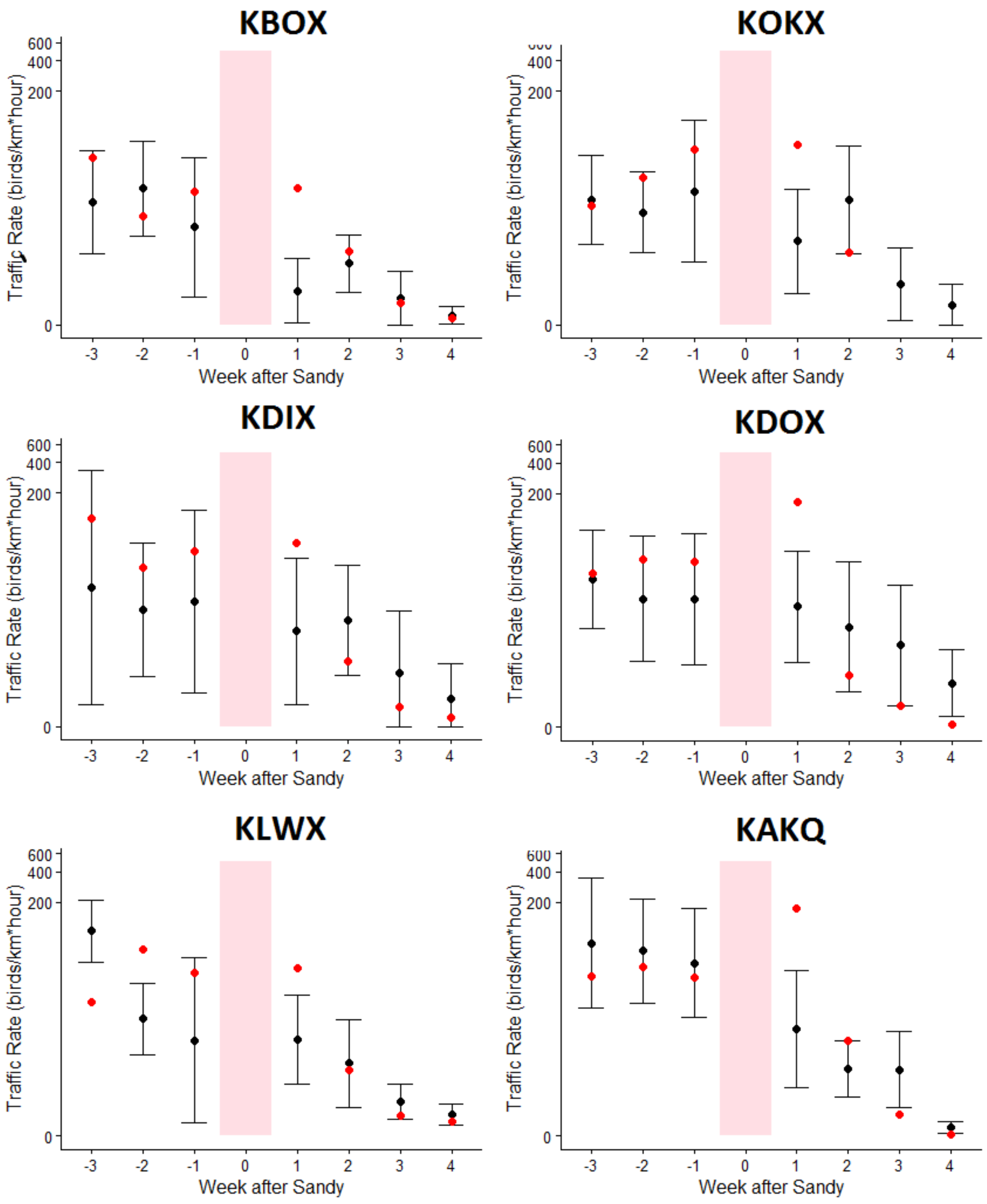

Figure 30 Migration Traffic Rate (MTR) at six radars in the Northeast United States before and after passage of Hurricane Sandy. Pink areas are those where Hurricane Sandy dominated the region with high winds and rain. The Sandy year is in red and the baseline years are in black. Bars are 90% confidence intervals calculated for every temporal segment during baseline years.

Discussion

Hurricane Sandy’s abnormally large width, orientation, and timing made it an unavoidable storm for many migrant birds in the region. My results suggest that on the night before the hurricane entered the Mid-Atlantic region, birds left en-masse from areas near the coast, at migration intensities much higher than normal for that time of the week. After wind and rain from the storm passed, the migration traffic rate was higher throughout the region. In the last half of November, traffic rates remained lower overall. The extensive strong winds and rain during Sandy likely caused a broad-migratory pause for several days. The higher than average traffic rates one week after Sandy followed by lower than average rates in the last two week of November suggest that this pulse of migrants was likely more than just a migratory pause from wind and rain caused by the storm. Instead an advance in the tail end of migration may have occurred as birds migrated quicker through the region than they normally would. I suggest two possible explanations for this pattern. One migrants spent at least four to five days with significant wind and rain during the storm. Birds typically do not migrate during inclement weather for fear of disorientation or death from overexposure while flying. This time period is a significant portion for a migrant to refuel, and might have meant more birds than average were refueled for migration, causing an increasing in migrants ready to leave once rain cleared the area. The main damage to habitat from Sandy was flooding from storm surge and rainfall, which was focused primarily in coastal zones. In Chapter 2, I showed little change in vegetation greenness after Sandy, largely because autumn senescence is near completion at this moment (Arora and Boer 2005). However, the dominant food type for migrants in late autumn is typically fruits (Baird 1980), which may not be accurately assessed by NDVI measurements, which measures change in green reflectance. Two birds, having experienced a traumatic event, may be more inclined to leave an area that is now less productive or is damaged. Studies in the Caribbean show that birds typically shift their distribution based on food availability, sometimes foraging in areas where they are rarely reported (Wiley and Wunderle 1993, Barrow et al. 2005), though these shifts are never on the scale I'm reporting. It is possible birds left the northeastern US quickly as food sources were either destroyed. American Robins and Grackles commonly shift their distribution through the migratory season in response to declining fruit availability (Baird 1980), and may move out of areas entirely if the fruit crop is destroyed. I know of no before and after studies that documented a storm related decline in fruiting and mast production after Sandy, so it is not possible to say whether this happened.

As birds left on October 27, prevailing winds likely brought birds in contact with the edge of the storm where they might have been forced to land in eastern Virginian and Maryland where the largest portion of rain was on this night. This may partly explain why the largest increases in traffic rate were in eastern Virginia a region that was covered in rain on this night. Across all radars, the migration traffic during the week before Sandy was on average higher than normal, in large part because of the high traffic rate on October 27.

Studies on phenology of migratory birds and weather have shown a link to shifting spring temperatures (Gordo 2007), and precipitation on the wintering grounds (Paxton et al. 2014), but rarely hurricanes (though see Fisk 1979, Thurber 1980). The results suggest a peak in migration rate occurred immediately after Sandy, after which point radars closest to Sandy's landfall (around New Jersey and Delaware) averaged lower than baseline years (though not always significantly). The last weeks in

November are generally low in traffic rate, as most migration through the area has ceased by this time (Farnsworth et al. 2015). Because of this, there are increased nights where migration traffic rate is essential zero. I attempted to address the highly varying traffic rates by calculating values on a log scale; however, this still may not adequately address the power near zero values can have on traffic rates (ex. KDIX confidence intervals three and four weeks after Sandy include zero). Based on visual assessment of radar three and four weeks after Sandy, radars were generally devoid of migration, which matches the traffic rate analysis. The night before rain from Sandy entered the region, winds were in a direction that matches the migratory direction. On this night, extraordinarily large number of birds migrated through the area. Hurricanes have been attributed for unusually high rates of birds capture at mist nets (Fisk 1979, Thurber 1980), and often blamed for causing vagrancies of birds, possibly from birds being 'sling-shotted' around a storms strong counter-clockwise winds (Wiley and Wunderle 1993). The results indicate this may be the mechanism for the large traffic rate on October 27, 2012, as the winds shifted towards the southwest in advance of the incoming storm. Birds travelled on the edge of the rain band, and then were possibly grounded in Virginia and Maryland where they then took off as soon as the weather cleared. The pulses in abundance of late season migrants may be difficult to observe on the ground because the migrants are likely common winter species like American Robins, Dark-eyed Juncos, and Common Grackles. Attempts at detecting these pulses using citizen science eBird presences was difficult because calculations of abundance from this data source remain elusive (Callaghan and Gawlik 2015).

Although long term decadal cycles in hurricane intensity complicate the pattern (Knutson et al. 2010), climate scientists expect that increasing sea surface temperature will cause an increase hurricane intensity in the future (IPCC 2014). Some effects have already been recorded, like the shifting poleward of the point of hurricane maximum intensity (Ramsay 2014). Increased prevalence of hurricanes likely means that migrating birds will increasingly come in contact with these dangerous storms. The results suggest that birds are relatively plastic to their timing before and after a storm, and that local decreases may not be due to declines or mortalities from individuals but shifts in migratory timing. This may suggest that the effect of hurricanes may be buffered by the high mobility of migrants. However, any extra energy demand such as switching food sources, weathering a violent storm, or migrating too early may add to the already high energetic demands of migrants by increasing extraneous movement. Little is known how detrimental even indirect disturbances may effect a migrant’s survival and carryover fitness, but it is postulated that storm severity may be linked to declining bird populations (Butler 2000). More studies are needed on the effects of severe weather on birds specifically their switching of food sources and body condition at stopover sites in route to wintering areas. With this we can begin to predict how increasing severity of weather due to climate change may affect migrant bird populations.

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