



University of Illinois
Institute of Natural Resource Sustainability
William Shilts, Executive Director

ILLINOIS NATURAL HISTORY SURVEY
Brian D. Anderson, Director
1816 South Oak Street
Champaign, IL 61820
217-333-6830

Modeling Waterfowl Migration Using Radar Imagery

Benjamin J. O'Neal,
Joshua D. Stafford,
Ronald. P. Larkin,
and
Richard E. Warner

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Executive Summary

Research from the last two decades has elucidated the importance of migration and stopover in the annual life-cycle of waterfowl. However, conservation goals and objectives for migrant waterfowl in the mid-continent have often been based on antiquated data or conjecture, and significant information needs remain with respect to the migration ecology of ducks. Length of time spent at stopover sites and factors that affect departure probability are among the key uncertainties that have eluded us due to the innate difficulties of studying movement events that most often occur at night over large-scales.

Weather surveillance radar is one tool with the potential to overcome these challenges and reveal new insights into migration. Although the technique has been useful in studying bird movements at broad spatial and taxonomic levels, it has not yet been applied to quantitative questions related to waterfowl due to the challenges of target classification and the calibration of radar echo to bird density. In the fall of 2008, we used a thermal infrared camera (TIR) to ground-truth duck movements on weather radar. Our field estimate of the mean radar cross section of all dabbling ducks (112.5 cm^2) aligned well with the one published estimate for mallards (120.0 cm^2). We also found a strong relationship between TIR estimates of duck density and corresponding measures of echo on radar ($R^2 = 0.91, n = 8$).

Joint Ventures (JVs) rely on mid-continent focus areas such as those in the Illinois River valley (IRV) to provide the energetic requirements of ducks throughout fall migration. However, ducks arrive and depart these wetlands throughout fall, resulting in considerable turnover in fall populations. Site surveys can reveal the overall magnitude of use, but the actual number of birds using a site and length of time they spend at these stopovers is largely unknown.

We examined 8 years of data (1996-1998, 2003, and 2005-2008) from the KILX radar in Lincoln, Illinois to identify and enumerate ducks emigrating from a known stopover site. To estimate the mean stopover duration for each year (days/duck), we divided aerial inventory estimates of total use-days for the site by the estimated number of ducks seen departing on radar. The overall mean (10.1 ± 2.8 days [SD]) differed greatly from the current value used by JVs in energetic carrying capacity models (28 days). Because our estimates of stopover duration varied substantially between years, we explored the role of habitat quality as a potential driver of these fluctuations. A regression analysis revealed a positive, linear trend and a strong relationship ($R^2 = 0.58$).

We also developed a comprehensive database of duck departures throughout these seasons to examine the relationship between departure timing and exogenous weather conditions. This approach substantially improves those of previous studies of this question by identifying explicit cases of departure and non-departure. We used biologically-justifiable covariates related to wind direction and speed, visibility, cloud height, temperature, and pressure to construct a discrete set of competing models intended to explain variation in daily emigration. We will employ an information theoretic approach and evaluate competing models according to complexity and parsimony.

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Disclaimer

Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the U.S. Fish and Wildlife Service or Illinois Department of Natural Resources.

Objectives

- 1) Determine efficacy of identifying and quantifying duck movements on WSR-88D
- 2) Estimate stopover duration of migratory ducks at a major stopover in Illinois
- 3) Model waterfowl emigration in relation to environmental covariates

Determining efficacy of identifying and quantifying duck movements on WSR-88D

The aerial movements of birds have implications for cross-seasonal population effects, disease transmission, climate change, habitat management, behavioral ecology and aviation conflicts (Akesson and Hedenstrom 2000, Marra et al. 2005, Mehlman et al. 2005, Zakrajsek and Bissonette 2005, Newton 2006). However, these movements are difficult to detect, classify, and quantify because they often occur over large spatial extents, at high altitudes, and at night (Alerstam 1990).

Radar is one technique capable of overcoming these challenges and providing insight into the key movements of birds (Bruderer 1997, Gauthreaux and Belser 2003, Larkin 2005). Among the many types, weather surveillance radar (WSR) has received substantial use due to its inherent capacity to study movements over large-spatial extents. There are 154 weather radars throughout the United States, and they are known as WSR-88D (Weather Surveillance Radar 1988 Doppler)

or NEXRAD (NEXt Generation RADar). The operational details of these radars and technicalities regarding application to avian research are well documented (Crum 1993, Gauthreaux and Belser 2003, Diehl and Larkin 2004). However, sources and formats of data and software to analyze these data have developed rapidly in recent years. Therefore, an update and overview of contemporary methods of data acquisition and processing available to avian researchers is warranted.

In addition to the ongoing technological developments, WSR is inherently complex: data are collected remotely, their interpretation is not immediately intuitive, and the radars' operation involves subtle assumptions. In spite of the efforts by pioneering radar biologists to describe and demonstrate the utility of radar, biologists have generally been slow to apply WSR to the quantitative study of specific taxonomic groups. Apart from Russell and Gauthreaux's study (1999) on purple martins (*Progne subis*), WSR has primarily been employed to examine broad-scale movements of general taxonomic groups, such as migrating songbirds (*Passeriformes*; Gauthreaux 1970, Gauthreaux and Belser 1998, Koistinen 2000, Diehl et al. 2003). Previous authors have substantially informed our understanding of how bird densities relate to radar echo, but we contend that a strong, quantitative relationship between densities of known targets and WSR echo has yet to be documented (Gauthreaux and Belser 1998, Diehl et al. 2003, Farnsworth et al. 2004).

Indeed, the development of techniques to identify and quantify specific avian taxa captured on WSR would provide a valuable tool for investigating questions regarding the ecology of birds aloft. Therefore, we endeavored to synthesize current components of WSR work, explore the potential to classify WSR targets based on natural history-related patterns, and investigate the potential to verify and quantify WSR targets using an independent ground-

truthing method. Our specific objectives were to: 1) Evaluate WSR data sources, formats, and software; 2) Estimate heights of WSR targets using portable radar; 3) Examine spatial and temporal patterns of movements captured on WSR during falls 2006 and 2007, and classify based on the natural history of potential target taxon (i.e., dabbling ducks [tribe Anatini]); 4) Test this classification using a thermal infrared (TIR) camera to observe physical characteristics, enumerate targets, and estimate RCS values, and; 5) Investigate the potential to use this estimate of RCS to quantify the number of ducks in WSR echoes across a spectrum of migration intensities.

Methods

WSR-88D data sources, format, and software—WSR generates three data fields: 1) reflectivity, which is a measure of the amount of energy returned to the radar by a target; 2) radial velocity, which is a measure of target motion toward or away from the radar, and; 3) spectral width, which is a measure of the variation in radar velocity during the radar's sampling period. All three data moments may be useful when classifying targets captured by WSR, but for this study we focus solely on reflectivity. Reflectivity is presented in units of Z, which describes the amount of echo caused by distributed targets such as birds, but because Z varies greatly depending on the size and number of targets, it is often presented logarithmically as dBZ.

There are multiple sources of these data, each of which distribute WSR files in a unique way. In order to acquire thousands of files in the most efficient fashion, we evaluated the primary WSR data sources including the real-time weather database operated by the University Corporation for Atmospheric Research's National Center for Atmospheric Research (<http://www.rap.ucar.edu/weather/radar/>), the NEXRAD data inventory hosted by National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC;

<http://www.ncdc.noaa.gov/nexradinv/>), and the HDSS Access System hosted by NOAA's National Environmental Satellite, Data, and Information Service (<http://has.ncdc.noaa.gov/pls/plhas/has.dsselect>).

In addition to variation among data sources, several data formats were available to choose from. The simplest was Level III (1-km cells in North/East [Cartesian] coordinates); the more comprehensive was Level II, which encodes more spatially accurate spherical-coordinate data in higher reflectivity resolution (0.5 dB increments). Beginning in 2008, many WSR-88Ds began to collect and archive a new super-resolution Level II data, with 4X the former range resolution in reflectivity data and 2X the former azimuthal resolution for both reflectivity and velocity data (Torres and Curtis 2007). Both Level II formats result in larger file sizes which may have deterred biologists from using this format when storage requirements and processing power were more costly and restrictive. We compared Level III, Level II, and super-resolution Level II NCDC data for studying bird movements.

Several software packages existed that were potentially useful for examining bird movements on WSR. Thus, we evaluated the following software programs to determine which were best suited for examining bird movements: 1) GRLevel2 (Gibson Ridge Software 2005); 2) Integrated Data Viewer (IDV) 2.6 (Murray et al. 2003); 3) Weather and Climate Toolkit 2.2 (Ansari 2008), and; 4) ArcMap 9.3 (ESRI 2008).

Patterns of movement on WSR—While surveying WSR reflectivity data for bird movements in general we detected discrete patches of echo emerging from major wetland areas in central Illinois and hypothesized that they were migrating dabbling ducks. To test this hypothesis we needed to determine the prevalence and consistency of these events. Therefore, we downloaded data collected at the KILX radar in Lincoln, Illinois during the fall (September

1-December 31) migration periods of 2006 and 2007. WSR scans occur every 10 min when operating in the typical clear-air mode, often capturing birds in flight on multiple scans that may be viewed in sequence to create time-lapse depictions of movements (Fig. 2). We used IDV 2.6 to display reflectivity data and focused on the scan at the lowest elevation (0.5°), which extends from 159-940 m height above ground level (AGL) at the 45-km range of our ground-truthing field site. Assuming an estimated RCS of 120 cm^2 for mallards (*Anas platyrhynchos*; Houghton et al. 1975), we set a minimum reflectivity threshold of 6.3 dBZ within IDV 2.6 ($1 \text{ mallard}/\text{km}^3$), so as to reduce superfluous reflectivity from non-target sources. We identified all similar events within our study period, compiled a list of common characteristics, and classified the source of the echoes based on the natural history of potential target organisms (Diehl and Larkin 2004).

Estimating target heights—In order to be confident that the KILX beam was capturing most of the birds when elevated at 0.5° , and that our ground-truthing technique was capable of detecting nearly all of these targets, we first needed information on target heights. Literature estimates, range-finders, portable radars of many kinds, and even WSR itself can be used to estimate these heights when targets fly overhead. In fall 2007 we conducted field observations of ducks departing the Illinois River valley with a portable radar that had a much finer spatial resolution and shorter wave length than WSR. The field site for these observations was in the path of ducks departing the Illinois River valley ($89^\circ 51' 59'' \text{ W } 40^\circ 15' 2'' \text{ N}$). The radar had a beam width of 3 degrees and a resolution of 7.5 m in range; it operated with its antenna stationary, counting birds and measuring their ranges and other quantities with the antenna elevated to 30 degrees above the horizon (Larkin 1983, 2005). Using an A-scope and a real-time display of wing beat time series, we classified targets as “duck-like” (steadily flapping and a few multiple targets), “unknown” (difficult to classify), and “flap-coasting” (mainly small

passerines). The unknown category probably included insects, non-flap-coasting birds including waterfowl, and instances when two different kinds of flying animals passed through the radar beam simultaneously at the same range. We excluded from the analysis targets noted as “non-vertebrate-like” (insects and ground targets).

Ground-truthing—We selected a field site for our 2008 ground-truthing based on the location of echoes observed on KILX in 2006 and 2007 (Fig. 1). The majority of these echoes emerged from a complex of wetlands and backwater lakes along the Illinois River and traveled along a southeasterly track (Fig. 1). We selected a field site along the average departure track (155°) that was sufficiently distant from the source habitat that most targets within the group would have climbed to a height within the radar beam when elevated at 0.5° , but close enough that targets would be distinct from echoes coming from other areas (Fig. 1). Within that eligible zone we selected the point with the highest elevation to minimize the distance to flying targets ($89^\circ 51' 15''$ W, $40^\circ 10' 37''$ N).

We used a FLIR S-60 TIR camera (FLIR Systems, Inc., Boston, MA) mounted on a tripod and oriented vertically to observe and record flying targets at night. The S-60 detector has 320×240 resolution and a frame rate of 60/s. We collected TIR data between 30 and 70 min post-sunset to capture potential targets being simultaneously recorded on KILX. We conducted these observations every evening from 25 October-9 November 2008, weather permitting. We used a lens with a 12° wide \times 8° high field of view (FOV); however, the lateral edges of the TIR FOV had reduced contrast, so we truncated FOV to $8^\circ \times 8^\circ$, or $70 \text{ m} \times 70 \text{ m}$ at an average range of 500 m AGL. We used an IEEE 1394 (i.e., firewire) connection to transfer the live video feed from the TIR camera to a PC laptop where the video datastream was captured with ThermaCAM Researcher Pro 2.8 (FLIR Systems 2004). We transferred the 40 min of TIR video data (20 GB)

to a portable hard drive nightly. We later screened the data by eye on a PC desktop noting all flying targets within the FOV, and summing the number of targets each night to determine the total number of targets that passed overhead in a given sample. We classified targets taxonomically based on characteristics of surface temperature, size, speed, and flight trajectory.

We examined KILX reflectivity data from nights we recorded TIR data to help identify WSR targets based on the average amount of echo generated by each bird. We chose the one super-resolution KILX scan each night at the point immediately after the majority of the group had flown over the site. In order to accurately match our TIR sample of targets with the appropriate sample of KILX reflectivity, we used ArcGIS 9.3 to clip a swath of reflectivity that corresponded to the portion of the migrant mass that passed over our field site and through the FOV of our TIR camera each night (Fig. 2). The width of this swath was based on the mean width captured by the TIR camera (70 m) at 500 m range, the height (781 m) was based on the height of the 1° KILX beam at the 45-km range of our field site, and the length was based on the spatial extent of the entire group of ducks on KILX. These dimensions provided an estimate of the volume of airspace sampled each night, which we used to convert our TIR-based estimates of flux to a volumetric density. We aligned the azimuth of the clipped swath with the track in which the group was traveling. Using the antilog, we linearized the dBZ value for each pulse volume, and summed the amount of reflectivity in the entire swath (Z).

In addition to morphology and range, the orientation of a bird with respect to the radar (aspect), can also affect the reflectivity. However aspect was not an issue because our echoes shared a common source, traveled with a very consistent departure track and heading, and therefore presented a narrow range aspects (broadside $\pm 20^\circ$; Edwards and Houghton 1959).

Following Black and Donaldson (1999), we estimated the average radar cross section per bird each night using the following equation:

$$Z = (\text{bird density} \cdot \text{average radar cross section per bird}) / 28.0,$$

where density is birds/km³ and average radar cross section is cm²/bird. We calculated a grand mean of all targets across all nights and then checked the validity of our natural history-based classification by comparing this estimate with published estimates of RCS on comparable radars (Eastwood 1967, Houghton et al. 1975, Diehl et al. 2003).

Quantifying echo—Dense congregations of relatively large-bodied birds, such as migrating waterbirds yield a strong signal-to-noise-ratio on WSR that can be separated from common confounding sources of echo such as dust, insects, and ground clutter (Eastwood 1967, Larkin 2005). We hypothesized that flocks of ducks captured on WSR would behave as volumetric scatterers such that each individual bird's contribution would add equally to the total reflectivity (Eastwood 1967, Doviak and Zrnik 1993). If this were the case, an estimate of the RCS for an average individual from a group of targets could be used to convert the strength of echo on radar to a volumetric density of birds. To test this hypothesis, we regressed nightly mean reflectivity (Z) for ground-truthed KILX samples against the volumetric density of birds recorded on TIR and calculated the coefficient of determination (R²) to evaluate model fit.

Results

WSR-88D data sources, format, and software—Our evaluation revealed that data sources had clear advantages and disadvantages. We found NCAR to be a worthwhile source of data during our field season when screening data in near real-time. However, these data could not be downloaded for spatially-explicit analyses. NCDC's NEXRAD data inventory was a useful source of data for exploratory analyses, but was slow when seeking multiple days. When

downloading an entire season's data, we found NOAA's HAS mass storage system to be the most efficient because the server allowed us to request four months with a single command. Approximately 30 minutes after requesting data for our timeframe, we received a link to tar bundles on a web page. Download management software was nearly essential for mass downloading (e.g., GetRight 6.3, Headlight Software 2008).

We found Level III data useful for quick overviews. However, each field of data and antenna elevation needed to be loaded individually. Level II provided finer spatial resolution, and combined all relevant data for each scan (fields and elevations) in one file. The super-resolution Level II data that became available in 2008 offered substantially higher spatial resolution, and was used exclusively for 2008 ground-truthing. Our computer was equipped with a 3.0 GHz Intel Pentium® 4 processor, 2.0 GB of RAM, a 500 GB hard drive, and a 100 MB network connection and was capable of efficiently downloading, storing, and rendering both forms of Level II data.

Each of the four software programs we examined had useful features. GRLevelIII displayed Level II radar data quickly, but lacked the spatial mapping features necessary to study bird movements. GRLevelII could display super-resolution data, but required a free software patch. Unidata's IDV 2.6 was powerful for the display, mapping, and analysis of radar data, including super-resolution Level II, but was slow for screening and analyzing an entire migration period. NOAA's Weather and Climate Toolkit was slow at rendering and screening large volumes of data, but was the only platform that allowed reflectivity data to be exported to a shapefile format for geospatial analysis. ArcGIS 9.3 very usefully allowed quantification of groups of birds on radar by selecting explicit pulse volume polygons. Further, ArcGIS also

allowed us to empirically estimate reflectivity from the particular swath that passed over our TIR field site.

We used all of these programs in combination according to our objectives. We used GRLevelII to perform the raw screening of all scans within season, then analyzed all movements flagged in GRLevelII using IDV 2.6 to identify targets that were potential bird movements. Finally, we used Weather and Climate Toolkit to convert these radar data to shapefiles and imported them into ArcGIS 9.3 for spatial sampling and quantification.

Patterns of movement on WSR—We identified 21 and 24 potential migratory duck movements from our focal wetland complex in the Illinois River valley in 2006 and 2007, respectively. All potential movements shared the following characteristics: 1) events occurred between late-September and early-December; 2) events occurred on average 44 ± 6 (SD, $N = 45$) min after sunset; 3) echoes emanated from distinct wetland-habitat areas; 4) echoes covered geographic extents consistent with the source habitat (e.g., Illinois River valley wetland complex = 150 km^2); 5) echoes appeared under consistent weather conditions (cold, clear, northerly winds); 6) echoes exceeded 10 dBZ in strength; 7) echoes were temporally and spatially discrete; 8) echoes were smooth rather than irregular, and; 9) the center of the echoes had higher reflectivity than the periphery.

We compared each of the previous characteristics to the natural history of dabbling ducks, the most abundant taxa at our study site over the entire season: 1) dabbling ducks migrate through Illinois during this time frame (Havera 1999); 2) dabbling ducks emigrate at this time of day (Bellrose 1980); 3) dabbling ducks account for the majority of avian use-days at these wetland areas throughout the fall; 4) dabbling ducks are distributed throughout the complex of wetlands, whereas other species (i.e., red-winged black birds [*Agelaius phoeniceus*]) only occupy

portions of the source complex; 5) dabbling ducks emigrate from Illinois under these weather conditions (Havera 1999); 6) these echo strengths align with those expected theoretically for dabbling ducks and exceed those for insects (Diehl and Larkin 2004), and; 7-9) dabbling ducks are gregarious (Bellrose 1980).

Estimating target heights—Our portable radar detected no duck-like targets when KILX showed no ducks leaving the Illinois River valley. Each evening when KILX recorded patches of echo leaving the Illinois River valley the portable radar recorded a pulse of duck-like and unknown targets passing overhead as the patch of KILX echo passed the field site. Passage of birds over the portable radar varied little from night to night when KILX recorded a duck emigration from the IRV. Sizes (X-band cross sections) of duck-like targets on the portable radar were greater than passerines but heights were the same (Table 1). A proportion of unknown targets were almost certainly waterfowl judging by their similarity to duck-like targets. Flap-coasting passerines appeared at similar heights to waterfowl (Table 1) but averaged 20.2 minutes later than waterfowl.

Ground-truthing—We could readily detect targets in false color, both in real-time in the field, and on digital video on a PC monitor. Targets typically occupied 4-6 pixels, which at times was sufficient to distinguish wingbeats. In general, all targets had surface temperatures, sizes, speeds, and straight flight trajectories that were consistent with what could be expected from migrating birds at 400-600 m range.

We recorded 395 targets on the TIR camera over seven nights. Eighty-seven percent of targets were not flying in traditional diurnal flock formations, but were spaced apart from one another (Bellrose 1980). Target density ranged from 0.0-83.6 targets/km³ and averaged 30.8 ± 27.9 targets/km³ (SD; Table 2). The volume of airspace sampled by the TIR camera when the

group of targets passed overhead ranged from 1.0-2.1 km³ with a mean of 1.8 ± 0.4 km³ (SD). Mean reflectivity (Z) of the sampled swaths of WSR targets over all seven nights ranged from 2-232 Z ($\bar{x} = 118 \pm 72$ [SD]; Table 2).

Nightly average estimates of RCS ranged from 66.5-150.9 cm² and averaged 112.5 ± 30.1 (SD; Table 2), which was comparable to an expected value for the entire dabbling duck guild based on the published estimate of 120.0 cm² for a mallard on a radar with the same wavelength (10.0 cm) and polarization (horizontal; Houghton et al. 1975).

Quantifying echo—Mean target density (ducks estimated on TIR) explained 91% of the variation in WSR reflectivity (Z; Fig. 3).

Discussion

WSR has developed considerably even since the recent publication of summaries of radar ornithology (Gauthreaux and Belser 2003, Diehl and Larkin 2004, Larkin 2005). For example, this is the first study we are aware of that has used super-resolution Level II WSR data for wildlife research. Although we did not quantify the effect of increased spatial resolution in reflectivity data, there is no doubt that it improved our ground-truthing by more accurately capturing the distribution of scattered bird targets. When not restricted by computing capacity, biologists should find that this new data format increases their ability to address finer-scale questions with WSR and adds to the versatility of WSR as a technique for the quantitative study of bird movements.

We also addressed recent developments in WSR by evaluating and summarizing the most efficient data sources, formats, and software currently available. We suggest that a standard PC computer and internet connection, along with download management software, can be used to rapidly acquire large volumes of data from NCDC's HAS mass storage system. Further,

researchers can conduct simple analyses using a suite of free or inexpensive software that display and animate radar data. Although WSR is rather technical and requires careful application, our results indicate that this technique can be readily applied to the study of bird movements.

After identifying consistent patterns among movements, we found it valuable to compare these patterns with the natural history of species potentially present at source habitats during our study. Our primary source of WSR echoes was spatially isolated enough that targets could be distinguished from the targets originating from surrounding sources. Nonetheless, several other avian taxa (e.g., red-winged black birds [*Agelaius phoeniceus*], European starlings [*Sturnus vulgaris*], ring-billed gulls [*Larus delawarensis*], American coots [*Fulica americana*], and Canada geese [*Branta canadensis*]) were present at our primary site for portions of the fall migration period. In addition to our hypothesized taxa, dabbling ducks, it was necessary to understand natural histories of potential alternate taxa to reduce false classification. Overall, the spatial and temporal patterns we observed provided considerable evidence in support of our hypothesis that dabbling ducks were the source of the distinct echo type recorded on WSR during our study.

To move forward with the classification and quantification of these WSR targets, we needed information on the height at which they flew. With portable radar we determined that ducks and passerines flew at a similar and consistent height AGL (400-600 m) that was within both the height window captured by the 0.5° KILX beam and the functional range of TIR. The portable radar also provided supplemental support for the classification of duck echoes by confirming the absence of duck-like targets on nights void of duck movements on KILX and confirming the presence of a discrete pulse of unique duck-like targets on nights with duck movements on KILX.

After determining the height of our WSR targets, we endeavored to conduct targeted ground-truthing, which is a critical, but often lacking component in radar ornithology studies (Eastwood 1967, Bruderer 1997, Larkin 2005). First, we verified target classification using direct observation with the TIR camera. The sensitivity and resolution of the FLIR S-60 allowed us to easily detect and enumerate migrating ducks flying at night at groundspeeds of 30 m/s and ranges from 400-600 m. We could even detect subtle wingbeats of large-bodied ducks at short ranges (i.e., 400 m). Using TIR, we also observed individual ducks migrating with greater spacing than expected from diurnal flock formations. From these findings and those of others, TIR has great potential as a technique to learn about nocturnally-migrating birds (Gauthreaux and Livingston 2006).

The effectiveness with which TIR could observe ducks at night also enabled us to estimate the RCS of targets. We found the average RCS across all nights was highly similar to the published values for dabbling ducks (Houghton et al. 1975). In addition, we detected variation in average RCS estimates across nights that also aligned with the natural history of our target guild. We detected lower RCS on two nights, both of which occurred early in our study period (late October) when considerable numbers of smaller dabbling ducks (green-winged teal [*Anas crecca*] and northern pintail [*Anas acuta*]) were emigrating from our source wetland complex. In contrast, the three average RCS values estimated later in November were consistent, and appropriate for mallards, which was the dominant dabbling duck species present at that time. Overall, ground-truthing confirmed our natural-history based classification and provided strong support for our overlying hypothesis regarding the identity of our WSR echoes.

We also hypothesized that the density of ducks would be positively and linearly related to the reflectivity measured on radar (Eastwood 1967). Our field tests included a wide range of

duck densities and migration intensities, and the relationship between target density and average WSR reflectivity was strong ($R^2 = 0.91$). Our calculation of a reliable estimate of the RCS of migrating dabbling ducks may be used to quantify duck movements under comparable conditions at other WSR units. Further, our results indicate that techniques such as TIR can be used to estimate the RCS of other taxonomic groups of birds thereby broadening the application of WSR to quantitative study of other aerofauna (Ruth et al. 2005).

Estimating Stopover Duration of Migratory Ducks in Illinois

Every year the wetlands of the Midwest serve as critical stopover habitat for millions of migrating ducks (Bellrose 1980). Research from the last two decades has elucidated the importance of migration and stopover in the annual life-cycle of waterfowl (Haramis et al. 1986, Hepp et al. 1986, Heitmeyer 1988). However, conservation goals and objectives for migrant waterfowl in the mid-continent have often been based on antiquated data or conjecture, and significant information needs remain with respect to migrational ecology (UMRGLRJV Board 1998).

In 1986, the United States and Canadian governments endorsed the North American Waterfowl Management Plan (NAWMP) as a framework for continental waterfowl and wetlands conservation (NAWMP 1986). The NAWMP develops and implements habitat management programs called “joint ventures” that promote sustainability and growth of waterfowl populations at a continental scale through partnerships of federal, state and private conservation organizations (NAWMP 2004). The Upper Mississippi River and Great Lakes Region Joint Venture (hereafter, JV) develops and implements conservation strategies for waterfowl and wetlands in the upper Midwest.

The JV relies on migratory focus areas, such as the Illinois River valley, to meet foraging

requirements of 8.9-million waterfowl during a 30-day fall migration period (UMRGLRJV Board 1998). However, waterfowl arrive and depart Illinois wetlands throughout fall, resulting in considerable turnover in fall populations. The length of time spent at these stopovers is largely unknown, and represents a key uncertainty in conservation planning and an explicit target for evaluation (UMRGLRJV Board 1998). Indeed, the JV uses an energy-based carrying capacity strategy to guide conservation planning, but this strategy currently employs antiquated estimates of stopover duration to estimate the number of energetic waterfowl use-days required to attain population objectives (*sensu* Prince 1979, Reinecke et al. 1989). The most cited study was conducted over 40 years ago and used a banding method with a limited scope of inference (Bellrose and Crompton 1970). A more recent study of northern pintails has employed the powerful method of satellite telemetry, but the cost of this method limits findings to a small number of individuals of one species (Miller et al. 2005).

However, the dabbling duck guild includes several species that must be accounted for when planning and managing. Indeed, the JV manages all dabbling ducks comprehensively under its energetic carry capacity model due to similar habitat requirements across the foraging guild (Bellrose 1980, UMRGLRJV Board 1998). A method of studying stopover duration that captures the variation among species, gender, and age has thus far been unavailable. Improved techniques to estimate stopover duration for dabbling ducks in general at meaningful spatial and temporal scales should yield results beneficial to conservation planning and implementation. We believe weather surveillance radar (WSR) offers an effective means of addressing this need.

Unlike visual, telemetry, and local radar, WSR units have the ability to continuously monitor movement patterns of flying animals during an entire season (Gauthreaux et al. 2003, Diehl and Larkin 2004, Larkin 2005). When wetland complexes are sufficiently isolated, it is

possible to connect duck targets on WSR with their specific source habitat. Thus, images captured by this system offer the first means of approaching comprehensive, objective census of nearly all ducks departing discrete wetland complexes. Using these censuses we developed an empirical method of estimating stopover duration for the entire dabbling duck guild.

Methods

Study Site—We estimated stopover duration at a wetland complex that included Chautauqua National Wildlife Refuge (CNWR), Emiquon Preserve and the surrounding bodies of Clear Lake, Rice Lake, Big Lake, Goose Lake, and Duck Creek (Fig. 1). Located in Mason County, Illinois, CNWR is considered the most important waterfowl refuge in the Illinois River valley with respect to use, and has been designated a Globally Significant Bird Area (Havera 1999).

Aerial inventories—We compiled duck abundance data for eight falls (October-December 1996-1998, 2003, 2005-2008) for the CNWR complex from weekly aerial inventories conducted by the Illinois Natural History Survey. We characterized total stopover use as duck-use-days (DUDs), which we calculated by multiplying mean number of individuals observed on 2 consecutive censuses by number of days between those counts (Rundle and Fredrickson 1981).

Radar emigration survey—We analyzed Level II WSR-88D data collected at the KILX radar in Lincoln, Illinois and obtained from the National Oceanic and Atmospheric Administration's National Climatic Data Center to estimate the number of waterfowl emigrating from our study site throughout the eight fall migrations (October-December 1996-1998, 2003, 2005-2008). We estimated the size of departing flocks when total echo had stabilized, following the ascent of takeoff, and prior to dispersion or joining of flocks from other stopover areas (Diehl and Larkin 2004).

Height estimation—We used portable x-band radar, as described earlier, to confirm that the KILX beam was capturing most of the birds when elevated at 0.5° , and that our ground-truthing technique was capable of detecting nearly all of these targets.

Target discrimination and ground truthing—We discriminated ducks from weather, insects, bats and other birds based on spatial reflectivity signatures, circadian and circannual patterns, source habitat, and strength and distribution of echo (Russell and Wilson 1996). We used thermal infrared (TIR), as described previously to confirm that weather surveillance radar targets were dabbling ducks. We also used TIR to estimate the average radar cross section (RCS) for dabbling ducks, which was necessary to convert WSR reflectivity to numbers of ducks

Analysis—We estimated the average stopover duration across an entire migration by dividing estimates of total DUDs by the total number of ducks departing the same site as estimated by radar for each site and year. We compared annual estimates of stopover duration with an annual index of habitat quality to examine the relationship between local habitat quality and length of stopover.

Results

Estimated DUDs from aerial inventories ranged from 2,094,240 to 7,323,358 and averaged $4,017,438 \pm 1,741,252$ (SD; Table 3). Using WSR we estimated that emigrants from the Illinois River valley ranged from 299,993 to 648,093 and averaged $413,585 \pm 114,257$ (SD; Table 3). Average annual stopover duration varied considerably, ranging from 6.0 to 13.9 days with an average estimate of 10.1 ± 2.8 days (SD; Table 3). We detected a clear trend in the relationship between habitat quality and stopover duration, with our index of habitat quality explaining a substantial portion of the variation in stopover duration (Fig. 4).

Discussion

We suggest that average annual stopover duration among dabbling ducks in fall was substantially shorter during the years we examined (10 days) than was reported in earlier studies which examined stopover duration in the Illinois River valley from 1950-1970 (28-days). This substantial difference could alter current JV carry capacity models which rely on earlier estimates (Bellrose and Crompton 1970, UMRGLRJV Board 1998). We contend that the quality of local foraging habitat in the Illinois River valley appears to influence the amount of time that dabbling ducks stay in the region.

Modeling Waterfowl Migration Using Radar Imagery

One of the most fascinating components of migratory behavior in birds is the control of the timing of departures. It is clear now from field work, genetic analyses, and laboratory experiments that departure decisions are based on a suite of factors including endogenous circannual rhythms, energetics, and exogenous factors such as weather encountered en route and at the take-off point and destination (Berthold 2001). These factors likely interact to produce the variability in departure timing that exists among taxa, sex, age, body condition, and season.

Laboratory experiments have clearly demonstrated that endogenous factors play a great role in some species at some times of the year; however, there is evidence indicating proximate environmental cues such (e.g., weather) can be the dominant driver in some species at certain times of year (Richardson 1990, Zehnder et al. 2001). In general, the likelihood of departure is assumed to be affected in an additive way by responses to various distinguishable aspects of weather acting as proximate factors (Drury and Keith 1962). The magnitude of the effect of these specific weather factors on departure remains unknown for many avian taxa.

Wind has the strongest and most intuitive relationship with bird movements due to the dominant effect that it can have on the energetic costs of flight (Alerstam 1979). It is estimated

that birds migrating selectively on nights with favorable winds decrease their migration time by 30% (Liechti and Bruderer 1998). Many birds tend to takeoff in peak numbers when winds are following relative to their own flight direction (Lack 1960, Richardson 1990) with light speeds (Koistinen 2000). In addition to surface conditions, wind conditions aloft likely also play a large role in emigration probability (Schaub et al. 2004).

Many avifauna also respond to barometric pressure. A comprehensive study by Nisbet and Drury (1968) found low pressure to be an important predictor of the intensity of spring migration. In contrast, fall migration is more closely associated with high pressure (Danhardt and Lindstrom 2001). In general, both spring and fall movements have been shown to be more associated with pressure trend than pressure *per se* (Wege and Raveling 1983), with spring migrations often occurring with falling pressure, and fall migratory movements occurring with rising pressure (Ying 1985, Akesson et al. 2002).

Temperature also appears to play a role in the volume of migration occurring on a given day. Many studies have indicated that peak spring migration of birds in general tends to occur on warm days, and peak fall migration on cold days (Gauthreaux 1977, Zalakevicius 1990, Ying 1985). This behavior likely has direct selective advantages, with some birds responding directly to temperature cues when initiating flight. Alerstam (1978) found that the most consistent measure of temperature correlated with various bird groups was the trend in daily minimum temperature, while Able (1973) found it to be the 24-hour change in temperature.

There is also a strong relationship between migration intensity and precipitation. Studies employing visual observation of departures (Danhardt and Lindstrom 2001), capture-recapture (Schaub et al. 2004), radar (Gauthreaux 1977, Alerstam 1979, Hussell 1981), radio-telemetry (Wege and Raveling 1983), and release of birds aloft at night (Demong and Emlen 1978) have

shown a strong negative relationship between precipitation and bird migration. For this reason, precipitation is likely second only to wind in determining the intensity of migration (Alerstam 1981). Mechanisms for the negative relationship between bird migration and precipitation include: disorientation, increased weight, and heat loss (Richardson 1978).

Like other weather factors, cloud cover is highly correlated with precipitation, but for many species overcast conditions alone are not sufficient to reduce birds aloft (Richardson 1978). Some studies indicate that some birds are capable of migrating under solid overcast with little disorientation (Emlen and Demong 1980, Able 1985), but overcast conditions are generally believed to be unfavorable for bird movements (Richardson 1990). This may be due in part to the importance of visual celestial cues in nocturnal orientation (Akesson et al. 2001). Similarly, horizontal visibility can also negatively affect the number of animals aloft (Koistinen 2000).

Waterfowl are one family of birds whose specific interaction with weather has been examined for decades with great interest. Nonetheless, quantitative estimates of factors influencing migratory movements by most waterfowl have generally eluded biologists. There is little doubt that weather variables such as cold temperatures and wind play critical roles in stimulating departure of waterfowl from staging areas, but few research efforts have successfully estimated the effect-size of such environmental factors on egress of waterfowl (Rowan 1929, Hochbaum 1955, Bellrose and Sieh 1960, Bellrose 1973, Owen 1968, Erskine 1971, Blokpoel et al. 1975, Richardson 1978, Blokpoel and Gauthier 1980).

Bellrose (1973) modeled waterfowl migration movements in relation to 33 weather-related covariates over 21 years. However, the departures in his study were derived indirectly

from changes in abundances among weekly counts of ducks, making it difficult to discern egress if birds departed and arrived simultaneously.

Beason (1978) modeled waterbird migration events in relation to weather variables in the southwestern U.S. using visual observation and L-band radar. Migration events were well correlated with weather variables during spring, but poorly so during fall (Beason 1978). However, inclement weather is rare in the southwestern U.S. during fall and low variability of independent variables resulted in low prediction power. Furthermore, these findings were based only on 2 years of migration (Beason 1978).

Cox and Afton (2000) developed models that predicted well interregional movements of radio-marked northern pintails in Louisiana, thus showing that high-resolution data on waterfowl movements could yield models with high predictive ability. However, they could not discern a consistent effect of weather-related variables on winter movements among 3 years. Furthermore, transmitters may cause birds to migrate abnormally (Miller et al. 2005).

In spite of the many attempts, few studies have isolated strong relationships between weather and migratory movements. This could be attributed in many cases to a lack of data demonstrating explicit departure events. The advent of modern weather surveillance radar has provided a tool that captures definitive migratory events and provides novel insight into the timing of departure relative to environmental covariates.

Methods

Study Site —We examined departure events from a major wetland complex in Illinois that included: Chautauqua National Wildlife Refuge, Emiquon Preserve and the surrounding bodies of Clear Lake, Rice Lake, Big Lake, Goose Lake, and Duck Creek (Fig. 1)

Radar Data Analysis—We examined Level II WSR-88D data collected at the KILX radar in Lincoln, Illinois from October 1-December 31, 1996-1998, 2003, 2005-2008 to determine the timing of dabbling duck departures. Details on target discrimination are described above.

Weather Data Collection—We explored all of the weather data available within the region of our study site and compiled a database of surface weather observations collected in Peoria, Illinois including: wind direction and speed, cloud cover, visibility, temperature, barometric pressure, precipitation, snowfall and snow cover. In addition to these raw variables we also calculated barometric pressure and temperature trends. The wind conditions at migratory altitude may be more relevant to departure probability, so we compiled wind aloft data for 600 m elevation from the radiosonde database collected at KILX, Lincoln, Illinois.

Statistical Analysis—We constructed a set of competing biological models, which were analyzed using an information theoretic approach (Burnham and Anderson 1998). These include the temporal covariates of date and days since last movement along with discrete combinations of the weather variables described above. We quantified migration based on a binary response variable representing whether or not an emigration event occurred. Logistic regression will be used to model variation in daily emigration probability (Cox and Afton 2000). Competing models will be ranked according to their complexity and parsimony based on Akaike's Information Criteria (AIC, Burnham and Anderson 1998).

Results

Our initial analysis of radar-derived departure data revealed a high level of synchrony in the timing of departure among dabbling ducks from independent stopover sites in the Illinois River valley. Furthermore, the weather radar data revealed departures occurring in temporal

clusters of two to three days, which corresponds with the temporal cycles of regional weather in the Midwest. These two observations provide local, empirical evidence of a relationship between proximate environmental conditions and emigration in dabbling ducks. We will complete this modeling effort by the end of FY 2010.

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Table 1. Avian targets detected by portable radar and mean height (standard deviation).

target type	N	mean (SD) height AGL (m)
duck-like	110	500 (159)
unknown	185	490 (194)
flap-coasting	48	490 (163)

Table 2. Thermal Infrared (TIR) target counts and densities (targets/km³), mean WSR reflectivities (Z), volume of airspace sampled (km³), and estimated nightly mean RCS (cm²) for seven fall-migration events in 2008.

Date	TIR Targets	Target Density	Z	Airspace	Mean RCS
25 October 2008	0	0.0	1.5	1.14	N/A
26 October 2008	162	83.6	232.5	1.94	77.9
27 October 2008	38	20.7	97.3	1.84	131.8
28 October 2008	95	57.7	137.0	1.65	66.5
7 November 2008	8	7.8	41.8	1.03	150.9
8 November 2008	25	11.8	53.5	2.12	127.2
9 November 2008	67	34.1	147.1	1.97	120.8
Mean	31	30.8	118.2	1.76	112.5
SD	28	27.9	72.3	0.39	30.1

Table 3. Aerial inventory-derived estimates of dabbling duck use-days, WSR-derived estimates of fall emigrants from Illinois River valley complex, average annual stopover duration for dabbling ducks (days), and index of annual foraging habitat quality.

Year	Use-Days	Emigrants	Stopover Duration	Habitat
1996	3,401,475	486,763	7.0	0.0
1997	7,323,358	648,093	11.3	3.5
1998	5,954,070	427,969	13.9	3.0
2003	3,477,913	299,993	11.6	3.0
2005	3,655,468	314,812	11.9	5.0
2006	3,574,975	429,591	8.3	2.5
2007	2,094,240	348,460	6.0	1.5
2008	2,658,003	353,001	7.5	1.5

Fig. 1. Primary source of weather surveillance radar echoes and field location for 2008 thermal infrared ground-truthing in central Illinois. Dark black arrow indicates mean track of emigrating ducks (155°) as indicated by WSR reflectivity data from 2006 and 2007.

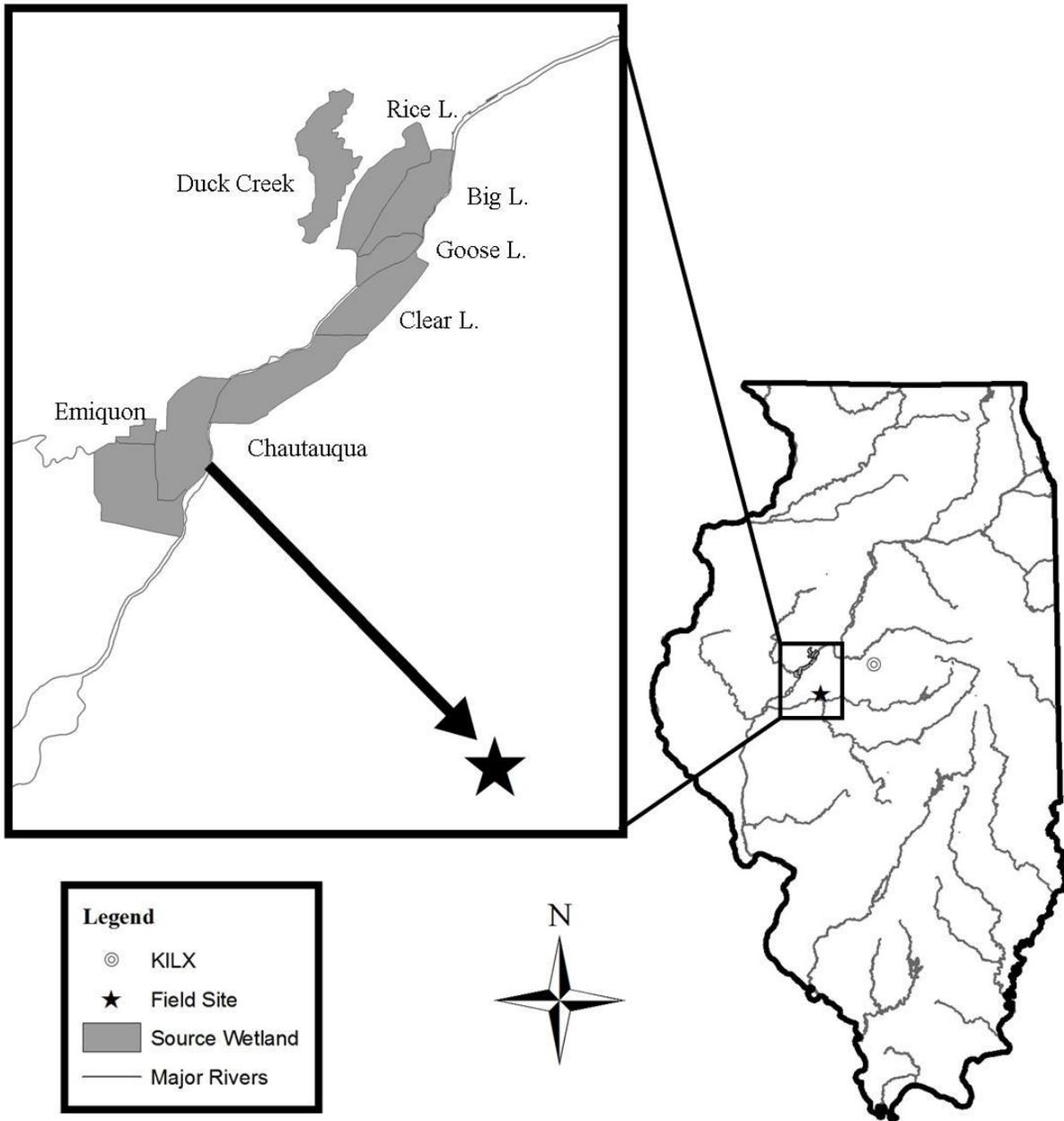


Fig. 2. Typical sequence of target progression on WSR, with final scan coded according to reflectivity value (dBZ) for each pulse volume. Black line indicates the portion of the overall target sampled by the thermal infrared camera at the indicated field site (see also Fig. 1).

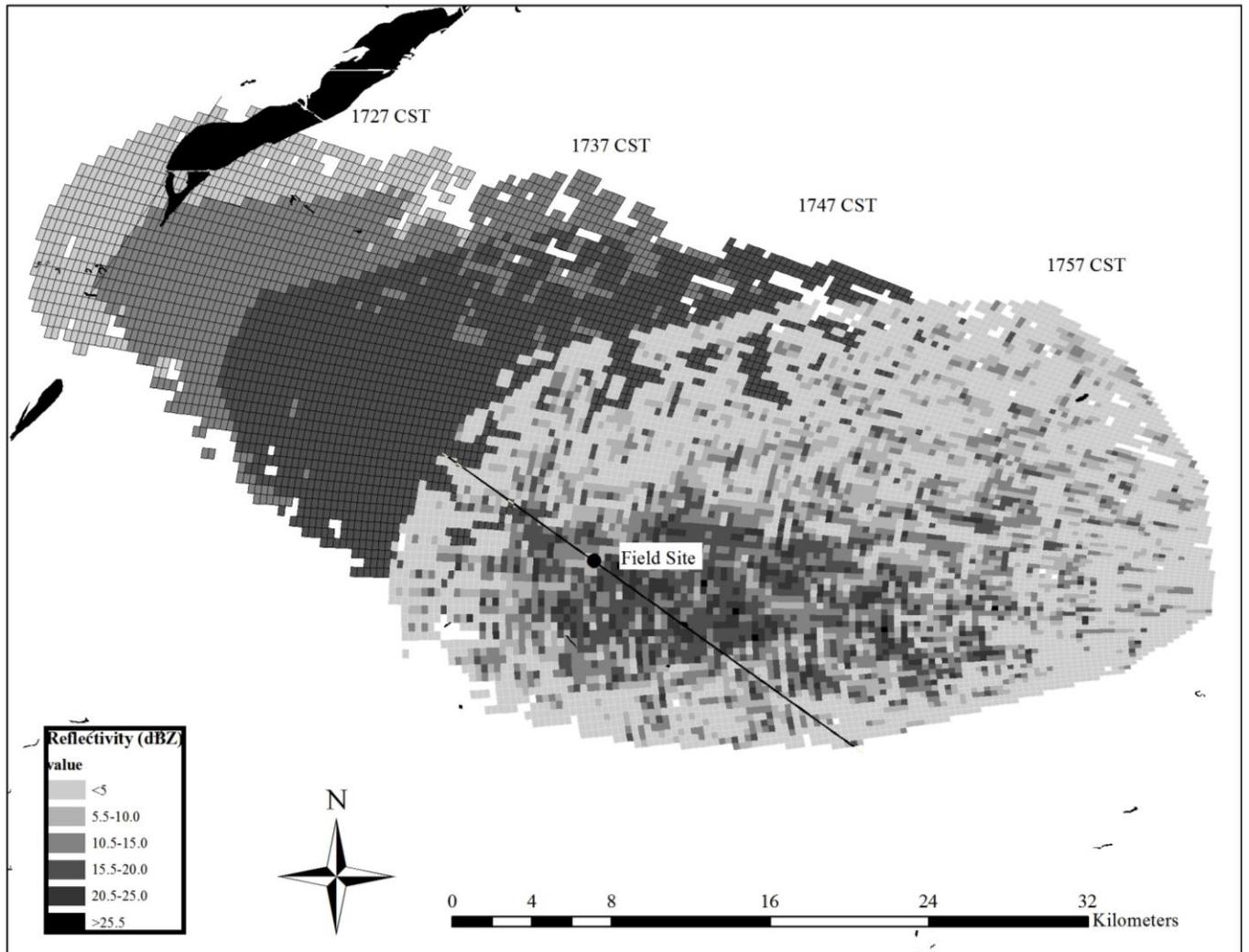


Fig. 3. Mean nightly WSR reflectivity (Z) versus mean target density (ducks/km³) over seven fall evenings in 2008.

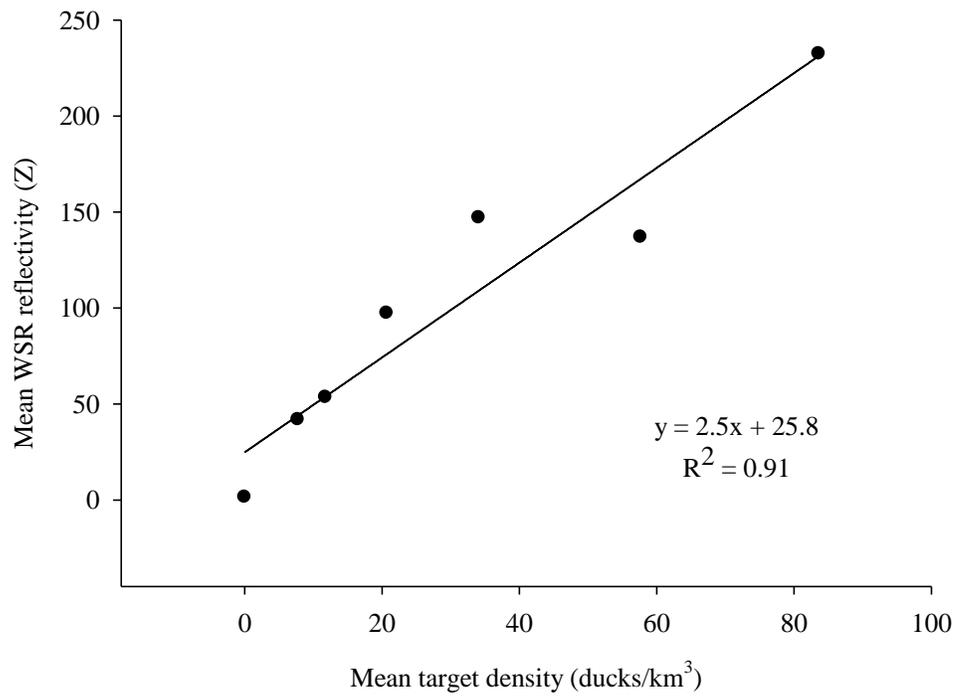
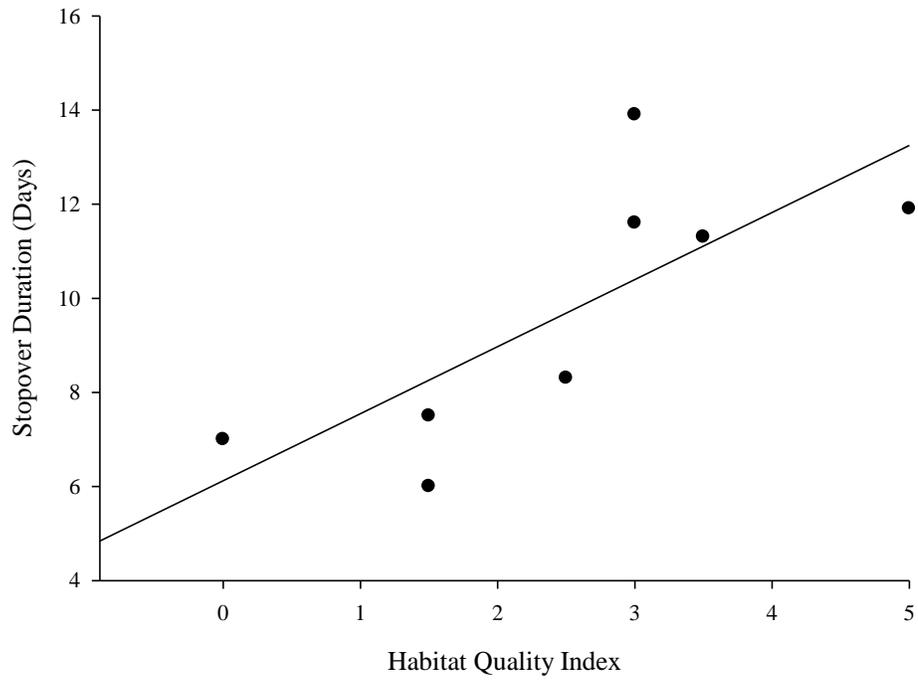


Fig. 4. Average annual stopover duration for fall migrating dabbling ducks versus index of habitat quality at local stopover (1-5 scale).



Submitted by:

Joshua D. Stafford, Ph.D.
Field Station Director and Waterfowl Ecologist
Illinois Natural History Survey

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