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Waterfowl on weather radar: applying ground-truth to classify and quantify bird movements

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ABSTRACT. Local and migratory movements aloft have important implications for the ecology and conservation of birds, but are difficult to quantify. Weather surveillance radar (WSR) offers a unique tool for observing movements of birds, but until now has been used primarily to address broad taxonomic questions. Herein, we demonstrate how natural history information and ground-truthing can be used to answer quantitative and taxon-specific questions regarding bird movements on WSR. We found that super-resolution Level II data from the National Oceanic and Atmospheric Administration's mass storage system was the most effective format and source of WSR data, and that several software packages were needed for thorough analysis of WSR data. Using WSR, we identified potential movements of birds emigrating from a waterfowl stopover area in Illinois in fall (1 September–31 December) 2006 and 2007. We compared spatial and temporal patterns of these movements to the natural history of taxa occupying the source habitat and classified these radar targets as dabbling ducks (tribe Anatini). A portable X-band radar measured the cruising heights of ducks at 400–600 m. During fall 2008, we conducted ground-truthing with a thermal infrared camera to enumerate birds passing over our field site during nocturnal migration events. This estimate of bird density, paired with an associated sample of WSR echo strength, provided a mean radar cross section the same as dabbling ducks (112.5 cm^2) and supported our natural-history-based classification. Thermal infrared-estimated duck densities explained most of the variation ($R^2 = 0.91$) in WSR echo strength across seven migration events of varying intensities, suggesting that radar cross sections of dabbling ducks and WSR reflectivity can be used to estimate duck numbers in other comparable contexts. Our results suggest that careful investigation of the spatial and temporal patterns of movements on radar, along with field-based ground-truthing, can be used to study and quantify the movements of specific bird taxa.

RESUMEN. **Las aves acuáticas en el radar del tiempo: aplicando la verificación de campo para clasificar y cuantificar los movimientos de las aves**

Los movimientos locales y migratorias de aves en vuelo tienen importantes implicaciones para la ecología y conservación de las aves, pero son difíciles de cuantificar. El radar para monitorear el tiempo (RMT) ofrece una herramienta única para la observación de los movimientos de las aves, pero hasta ahora ha sido usado principalmente para responder a preguntas taxonomicamente amplias. Aquí demostramos como la información sobre la historia natural y la verificación de campo pueden ser usadas para responder a preguntas cuantitativas y taxonomicamente específicas en términos de los movimientos de las aves en el RMT. Encontramos que los datos con una súper resolución de Nivel II del sistema de almacenamiento masivo del National Oceanic and Atmospheric Administration fue el formato y origen mas efectivo de datos del RMT. Una variedad de paquetes de software fueron necesarios para un análisis completo de los datos del RMT. Usando el RMT, identificamos movimientos potenciales de aves emigrando de un sitio de paso de aves acuáticas en Illinois en el otoño (1 de Septiembre-31 de Diciembre) del 2006 y 2007. Comparamos patrones espaciales y temporales de estos movimientos a la historia natural de taxones que ocupan el hábitat del sitio de origen y clasificamos estos puntos en el radar como aves del tribu Anatini. Un radar portátil de banda X midió la altura de vuelo crucero de patos, cual fue de 400–600 m. Durante el otoño del 2008 realizamos la verificación de campo con una cámara térmica infrarroja para contar las aves que estaban pasando encima de nuestro sitio durante los eventos de migración nocturna. Esta estimación de la densidad de las aves en combinación con una muestra de la fuerza del eco del RMT proveo un promedio de la muestra similar a la del tribu Anatini (112.5 cm^2) y dio apoyo a nuestra clasificación basado en la historia natural. Las densidades de patos estimadas por la cámara térmica infrarroja explicaron la mayoría de la variación ($R^2 = 0.91$) en la fuerza del eco del RMT para siete eventos migratorios de intensidad variable, cual sugiere que las muestras del radar del tribu Anatini y la cantidad del reflejo del RMT pueden ser usadas para estimar los números de patos en otros contextos comparables. Nuestros resultados sugieren que una investigación cuidadosa de los patrones espaciales y temporales de los movimientos en el radar en combinación con la verificación de campo pueden ser usadas para el estudio y cuantificación de los movimientos de taxones específicos de aves.

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The aerial movements of birds can provide information important for better understanding behavior, habitat use, disease transmission, effects of climate change, and aviation conflicts (Kaminski and Gluesing 1987, Akesson and Hedenstrom 2000, Reed et al. 2003, Marra et al. 2005, Mehlman et al. 2005, Zakrajsek and Bissonette 2005). 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 a tool capable of overcoming these challenges and providing insight into bird movements (Bruderer 1997, Gauthreaux and Belser 2003, Larkin 2005). Weather surveillance radar (WSR) is especially well-suited for this task because it permits the study of bird movements over large areas. The U.S. government currently operates a network of 154 WSR units known as WSR-88D (Weather Surveillance Radar 1988 Doppler) or NEXRAD (NEXt Generation RADar). Over the last 50 yr, investigators have used data from WSR-88D and the systems that preceded it to investigate patterns of bird movements, such as those of migrating passerines (Gauthreaux 1970, Gauthreaux and Belser 1998, Koistinen 2000, Diehl et al. 2003, Felix et al. 2008). However, only two studies involving the use of WSR have focused on a single species (Purple Martins [*Progne subis*], Russell and Gauthreaux 1999; European Starlings [*Sturnus vulgaris*], Larkin 2006).

Clearly, the ability to identify and quantify specific avian species or taxa on WSR would be useful for investigating questions regarding bird movements. We examined the potential of using natural-history-related patterns and independent ground-truthing (*sensu,* Larkin 2005) as an integrative technique for classifying and quantifying a specific class of WSR targets. In the process, we evaluated contemporary methods of WSR data acquisition and processing. Our specific objectives were to (1) evaluate WSR data sources, formats, and software, (2) examine spatial and temporal patterns of movements captured on WSR and classify targets based on their natural history, (3) estimate heights of WSR targets using portable radar, (4) test natural-history-based classification using a thermal-infrared camera to enumerate targets and estimate radar cross-section values, and (5) investigate the potential for using estimated radar cross section to quantify bird numbers.

METHODS

WSR-88D data sources, format, and software. WSR generates three data fields: (1) reflectivity, a measure of the amount of energy returned to the radar by a target, (2) radial velocity, a measure of target motion toward or away from the radar, and (3) spectral width, a measure of the variation in radar velocity during the radar's sampling period. Radial velocity and spectral width may be useful when classifying targets captured by WSR, but only in limited contexts. We focused solely on reflectivity due to its more consistent application to biological targets. Herein, we define "targets" as both individual radar reflectors and objects captured on thermal infrared, and "echoes" as distinct areas of reflectivity. Reflectivity is presented in units of Z, but Z varies greatly depending on the size and number of targets and is often presented logarithmically as dBZ. Additional details regarding the specifications of WSR and its application to avian research have been well documented (Crum et al. 1993, Gauthreaux and Belser 2003, Diehl and Larkin 2004).

There are multiple sources that archive these data and each distributes WSR files in a unique way. 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 the 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).

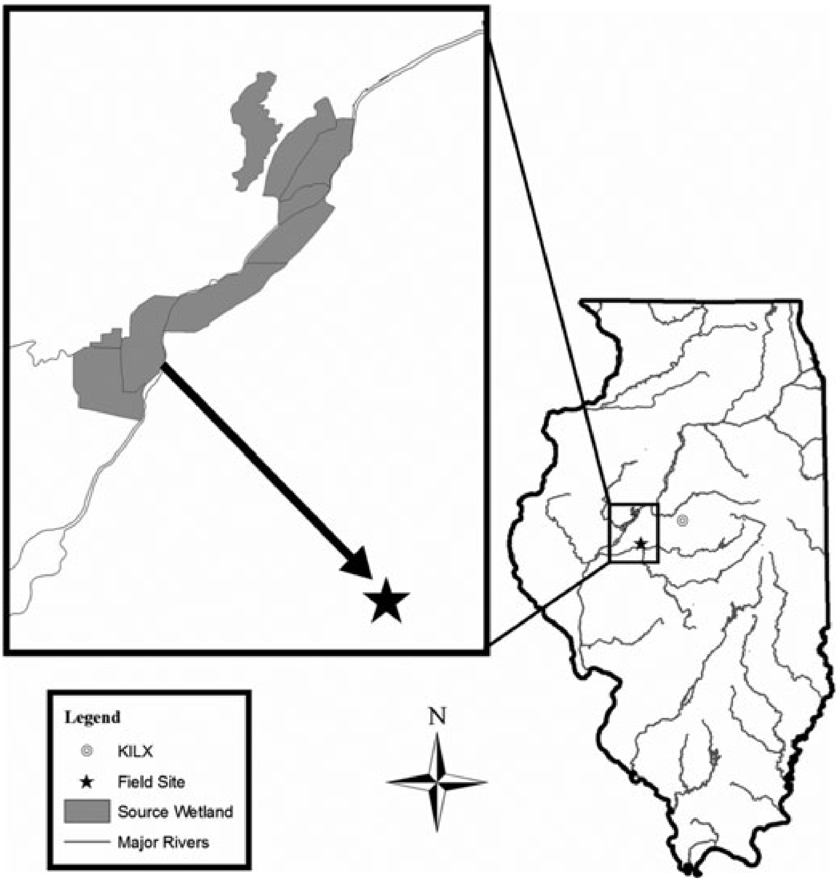

Fig. 1. Location of thermal infrared ground-truthing site in central Illinois, 2008. Dark-black arrow indicates mean track of emigrating ducks (155°) as indicated by WSR reflectivity data from 2006 and 2007.

In addition to variation among data sources, several data formats were available. Level III was the simplest (1-km cells in north/east [Cartesian] coordinates). Level II was more comprehensive and spatially accurate, recording data in spherical-coordinates and higher reflectivity resolution (0.5 dBZ increments). Beginning in 2008, many WSR-88Ds began to collect and archive a new super-resolution Level II data, with four times the former range resolution in reflectivity data and twice the former directional resolution for both reflectivity and velocity data (http://www.weather.gov/os/notification/tin07–95wsr-88d_level2.txt). Both Level II formats result in larger file sizes than Level III, which may have deterred biologists from using this format when storage requirements and processing power were more costly and restrictive. We compared the use of Level III, Level II, and super-resolution Level II reflectivity 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 archived reflectivity data collected at a WSR-88D site (KILX, Lincoln, Illinois) from 1 November–30 November 2006, we detected discrete patches of echo emerging from wetland areas in central Illinois (Fig. 1). We observed the strongest echoes originating from a 12,257-ha

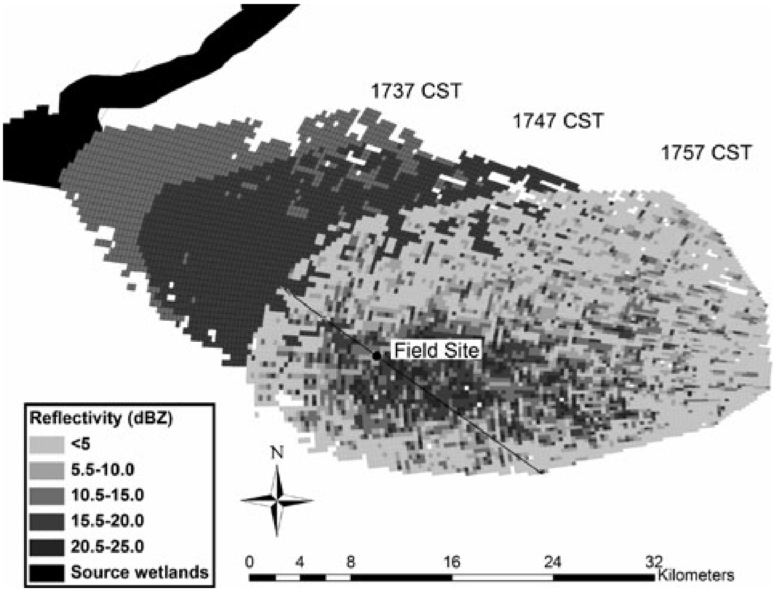

Fig. 2. Typical sequence of target progression in WSR reflectivity data, with final scan coded according to reflectivity value (dBZ). Black line indicates the portion of the overall target sampled by the thermal infrared camera at the indicated field site (see also Fig. 1).

wetland complex along the Illinois River that included The Emiquon Preserve, Chautauqua National Wildlife Refuge, Clear Lake, Rice Lake, Big Lake, Goose Lake, and Duck Creek Cooling Lake. This wetland complex contains several wetland types, including areas managed for the growth of moist-soil plants (Fredrickson and Taylor 1982), large areas of open water with submerged aquatic vegetation, floodplain forests, and shallow-water lakes (Havera 1999).

To determine the prevalence and consistency of the events we observed, we downloaded data that included and bracketed the fall seasons (1 September–31 December) of 2006 and 2007. WSR scans occur every 10 min when operating in the typical clear-air mode, often capturing airborne targets on multiple scans that may be viewed in sequence to create time-lapse depictions of movements useful for target classification (Koistinen 2000, Fig. 2). We used IDV 2.6 to display reflectivity data and focused on the scan at the lowest elevation (0.5°), extending from 159–940 m height above ground level (AGL) at the 45-km range of our ground-truthing field site. After examining all reflectivity scans over these two 4-mo periods and identifying all similar events, we found that echo movements originating from wetland areas were prevalent and unique, suggesting that they might be attributed to a common target type (Eastwood 1967). The magnitude of reflectivity and the distribution of reflectivity values within the discrete echo, along with the movement of the entire echo across space, indicated that these echoes were caused by biological targets rather than abiotic targets such as weather or ground clutter that also appear on WSR (Koistinen 2000, Larkin 2005).

We compiled a list of temporal and spatial patterns shared by echoes of interest and compared these characteristics with the natural histories of potential target organisms (Diehl and Larkin 2004). We paid particular attention to the morphology of aerofauna occupying the source wetland, the spatial distribution of aerofauna throughout the region and within our source wetland complex, the timing of movements at the daily and annual temporal scale, the distance of movements, the relative proportions of aerofauna using our source wetland within and among years, the environmental conditions associated with movements and nonmovements, and the unique social characteristics that can affect the distribution of aerofauna in flight (Diehl and Larkin 2004, Larkin 2005).

Ground-truthing (portable radar). Based on this natural-history-based classification, we hypothesized that the unique echoes emanating from the Illinois River were emigrating dabbling ducks (tribe Anatini). To test this hypothesis, we needed independent methods of observing and enumerating targets captured on WSR. First, we had to determine target heights to confirm that the KILX beam was capturing most of the birds when elevated at 0.5°, and that our ground-truthing techniques were capable of detecting nearly all of these targets. Literature estimates, range-finders, portable radars of many kinds, and even WSR itself can be used to estimate these heights when targets fly overhead. During fall 2007, we conducted field observations with a portable, stationary-beam radar at a field site along the anticipated path of ducks departing the Illinois River Valley (89°51′59″W 40°15′2″N). The radar was based on a Furuno Model 7252 transmitter/receiver operated at 9510 MHz, 25 kW, 0.07 microsecond pulse, pulse repetition frequency of 2087/s, horizontally polarized, 3-cm wavelength, 3° conical beam, and 7.5-m range resolution. The antenna was a 0.76-m-diameter paraboloid with a cylindrical cuff to reduce clutter (Larkin 2005). We operated the radar with the antenna stationary and elevated to 30° above the horizon, counting birds and measuring their ranges, radar cross sections, and amplitude modulation (Larkin 2005). We classified targets using an A-scope display showing time variation of echoes versus range, and a real-time display of wing-beat time series (Larkin 2005). We discarded signals from ground targets (e.g., trees and buildings) that showed slow (about 1/s or slower), irregular fluctuations in amplitude, and insects with amplitude fluctuations that were low and periodic frequencies, if any, that were fast (>30/s). We readily identified flap-coasting birds such as passerines because their signals showed characteristic "flapping and quiescent periods" (see Bruderer and Steidinger 1972 for illustrated example) or "fluctuations separated by pauses" (Larkin et al. 1979). We identified duck-like targets based on their steady, uninterrupted periodic components of about 4–5/s (see Bloch et al. 1981 for illustrated example). We also observed some targets of unknown identity that were difficult to classify. These unknown targets, likely including both ducks and passerines, resulted from a complicated mixture of two kinds of targets passing through the beam at the same range or a flying animal near close-range ground clutter. We excluded insects and ground targets from height analysis.

Ground-truthing (thermal infrared). During fall 2008, we conducted ground-truthing using a thermal-infrared camera. We selected a field site based on the dominant southeasterly track of echoes observed leaving our source wetland in 2006 and 2007, and the expected distribution of ducks within the source wetland in 2008 (Fig. 1). Along the average departure track (155°), we selected a site that was distant enough from the source habitat so that most targets would have climbed high enough to be within the WSR beam at 0.5°, but close enough to the source habitat that echoes would be distinct from echoes attributed to targets coming from other areas (Fig. 1). Within that eligible zone, we selected the point with the highest elevation (89°51′15″W, 40°10′37″N) to minimize the distance to flying targets.

We used a FLIR S-60 thermal infrared 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 had 320 × 240 resolution and a frame rate of 60/s. We tested the functional range of this camera on known duck targets in flight during daylight using a rangefinder, and determined that the camera could detect even small species of ducks at a range of 1 km. This allowed us to count targets throughout the altitudinal range sampled by WSR (159–940 m AGL). We collected thermal infrared data during the period from 30 to 70 min postsunset 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 × 8° high field-of-view (FOV). However, the lateral edges of the camera's FOV had reduced contrast, so we truncated FOV to 8° × 8°, or 70 m × 70 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 camera to a PC laptop where the video datastream was captured with ThermaCAM Researcher Pro 2.8 (FLIR Thermal Infrared Camera Systems 2004). We transferred the 40 min of thermal-infrared video data

(20 GB) to a portable hard drive nightly. We later screened the data visually on a desktop PC, noted all flying targets within the FOV, and summed the number of targets each night to determine the total number of targets that passed overhead in a given sample.

We examined KILX reflectivity data from nights we recorded thermal-infrared data and identified WSR targets based on the average amount of reflectivity generated by each bird. We chose one super-resolution KILX scan each night at the point immediately after most of the migrant group had flown over the site. To accurately match our thermal infrared 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 through the FOV of our thermal infrared camera each night (Fig. 2). The width of this swath was based on the mean width captured by the thermal infrared 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 targets on KILX. These dimensions provided an estimate of the volume of airspace sampled each night that we used to convert our thermal infrared-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 reflectivity cell (pulse volume), summed the total amount of reflectivity in the entire swath, and calculated the average reflectivity over the area of the swath (Z). By sampling a swath of the entire migration event each night rather than individual WSR pulse volumes, we avoided any potential pseudo-replication associated with spatial autocorrelation among adjacent pulse volumes.

In addition to morphology and range, the orientation of a bird with respect to the radar (aspect) may also affect reflectivity. We estimated aspect based on the heading of targets at the point of analysis. Heading was determined by subtracting the wind aloft vector from the ground vector. The velocity and track of targets was estimated using multiple KILX scans and the velocity and direction of the wind (600 m AGL) using radiosonde measurements collected at KILX ($\leq$ 30 km from target). The range of aspects across all nights was narrow (73°–104) and within the range of aspects defined by experimental studies as having comparable effects on radar cross section (i.e., broadside 20; Edwards and Houghton 1959). Therefore, we did not include aspect in our analysis.

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

$$\text{Average radar cross section per bird} = (Z.28)/\text{bird density},$$

where average radar cross section is cm^2/bird and density is birds/km^3. 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 radar cross section on comparable radars (Eastwood 1967, Houghton et al. 1975, Diehl et al. 2003).

Quantifying echo. We hypothesized that 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), in which case an average radar cross section could be used to convert reflectivity to a volumetric density of birds. To test this hypothesis, we regressed nightly mean reflectivity (Z) for 2008 KILX samples against the volumetric density of birds recorded on thermal infrared during the same nights in 2008. We calculated the coefficient of determination (R^2) to evaluate model fit. Values are presented as means $\pm$ 1 SD.

RESULTS

WSR-88D data sources, format, and software. Our evaluation revealed that our 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 the multiple iterations required to request and download multiple days took considerable time. 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 4 mo with a single command. Approximately 30 min 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 2007).

We found Level III data useful for quick overviews, but 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. GRLevel2 displayed Level II radar data quickly, but lacked the spatial mapping features necessary to study bird movements. GRLevel2 could also display super-resolution data, but required a free software patch (Gibson Ridge Software 2005). 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 allowed us to empirically estimate reflectivity associated with the particular swath of targets that passed over our thermal infrared field site by explicitly selecting portions of pulse volumes captured within the thermal infrared camera's FOV.

We used all of these programs in combination according to our objectives. We used GRLevel2 to perform the raw screening of all scans within season; then analyzed all movements flagged in GRLevel2 using IDV 2.6 to identify targets that were potential bird movements. Finally, we used the 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 movements from our focal wetland complex in the Illinois River Valley in 2006 and 2007, respectively. All movements shared the following characteristics: (1) echoes exceeded 10 dBZ in strength, (2) events ($N = 45$) occurred an average of 44 ± 6 min after sunset, (3) the only reflectivity observed in the region at this time of day was from these discrete echoes, (4) events occurred between late September and early December, (5) echoes originated only from wetland-habitat areas, (6) echoes covered geographic extents consistent with the entire source habitat (e.g., Illinois River Valley wetland complex = 150 km^2), (7) the southern portion of echoes showed greater intensity in 2007 than in 2006, (8) echoes moved > 60 km from the source wetland, (9) echoes generally appeared under similar weather conditions (decreasing temperatures over previous 24 h, clear skies, and northwesterly winds), (10) echoes were temporally and spatially discrete, and (11) the center of the echoes had higher reflectivity than the periphery.

We compared each of the just listed characteristics to the natural history of aerofauna potentially present at our source habitat and determined that (1) reflectivity values aligned with those expected theoretically for birds and exceeded those typical of insects (Diehl and Larkin 2004), (2) during the fall in central Illinois, appreciable insect emigrations typically occur at the warmest part of the day in the late afternoon, whereas avian emigrations generally occur after sunset (Bellrose 1980), (3) when insects emigrate they tend to originate from many habitats throughout the radar domain resulting in movements that encompass the entire region, whereas waterfowl emigrations in central Illinois originate from isolated patches of remnant habitat, (4) due to phenology and temperature limitations, most insect, bat, and passerine migration has ended by late October (Blokpoel and Burton 1975, Hoffmeister 1989, Koistinen 2000), whereas waterfowl emigration extends throughout the fall (October through December; Havera 1999), (5) passerines, including wetland-associated species (i.e., Red-winged Blackbirds [*Agelaius phoeniceus*]), roost in both wetland and nonwetland habitat, whereas waterfowl only roost in wetland habitats (aerial inventories indicated that dabbling ducks were the most common waterfowl present [81%], followed by geese [primarily Canada Geese, *Branta canadensis*, and Greater White-fronted Geese, *Anser albifrons*; 16%; Horath 2008] and diving ducks [tribe Aythyini; 3%]), (6) dabbling ducks were distributed throughout the wetland complex, whereas other species (i.e., Red-winged Blackbirds and geese) only occupied portions of the source complex, (7) between 2006 and 2007, dabbling duck abundance increased substantially in the southern portion of the wetland complex due to the addition of about 4000 ha of wetland habitat at The Emiquon Preserve, (8) movements > 60 km are likely migratory movements rather than local movements (Bellrose 1980), (9) dabbling ducks emigrate from Illinois under these weather conditions (Havera 1999), and (10 and 11) dabbling ducks are gregarious (Bellrose 1980).

Ground-truthing (portable radar). When our portable radar detected no duck-like targets, KILX also showed no echoes leaving the Illinois River Valley. Each evening, when KILX recorded patches of echo leaving the Illinois River Valley, the portable radar recorded a large cluster of duck-like targets passing overhead as the patch of KILX echo passed the field site. Heights of birds over the portable radar varied little from night to night when KILX recorded echoes emanating from the Illinois River Valley. The mean height of flap-coasting passerines ($\bar{x} = 490 \pm 163$ m, $N = 48$) was similar to that of ducks ($\bar{x} = 500 \pm 159$ m, $N = 110$), but passerines appeared an average of 20.2 min later (Richardson 1972).

The portable radar's maximum detectable range for ducks did not limit these height profiles because that radar routinely detected smaller targets flying higher than heights characteristic of ducks. A radar's maximum detectable range for a certain target occurs where the signal/noise ratio drops below 1.0. As expected, flap-coasting targets (mainly small passerines) were smaller (median radar cross section = 16.6 cm^2) than duck-like targets (median cross section = 40.8 cm^2) and generated smaller echoes, with a mean signal-noise value 74% that of duck-like targets. Nevertheless, these flap-coasting targets were detected at ranges at least as great as the duck-like targets. For example, the fourth quartile of the range of flap-coasters was 1207 m (604 m height AGL), whereas that of duck-like targets was 1148 m (547 m height AGL).

Ground-truthing (thermal infrared). The thermal infrared camera readily showed 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. Of the 395 targets we observed, 87% were flying with greater spacing than typically observed in diurnal flock formations (Bellrose 1980). In general, all targets had surface temperatures, sizes, speeds, and straight flight trajectories consistent with that expected of migrating ducks at 400–600 m range.

The volume of airspace sampled by the thermal infrared camera when the group of targets passed overhead ranged from 1.0–2.1 km^3, with a mean of 1.8 ± 0.4 km^3. Thermal infrared target density ranged from 0.0–83.6 targets/km^3 and averaged 30.8 ± 27.9 targets/km^3 (Table 1). Mean reflectivity (Z) of the sampled swaths of WSR targets over all seven nights ranged from 2–232 Z ($\bar{x} = 118 \pm 72$ Z; Table 1).

Nightly average estimates of radar cross section ranged from 66.5–150.9 cm^2 and averaged 112.5 ± 30.1 (Table 1). This was close to the expected value for an average-size dabbling duck based on the published estimate of 122.0 cm^2 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 thermal infrared) explained 91% of the variation in WSR reflectivity (Z; Fig. 3).

DISCUSSION

WSR has developed considerably since the recent publication of summaries of radar ornithology (Gauthreaux and Belser 2003, Diehl and Larkin 2004, Larkin 2005). For example, the introduction of super-resolution Level II data marks a substantial improvement in the spatial detail captured on long-range weather radar that has previously been defined by rather coarse spatial resolution. We are the first, to our knowledge, to use this super-resolution Level II WSR data for ornithological research. Although we did not quantity the effect of increased spatial resolution in reflectivity data, we are confident that it improved our ground-truthing by more accurately capturing the distribution of scattered bird targets. When enough computing capacity is available, this new data format increases the ability of biologists to address finer-scale questions with WSR and adds to the versatility of

Table 1. Thermal infrared target counts and densities, mean WSR reflectivities (Z), aspect of WSR target, volume of airspace sampled, and estimated nightly mean radar cross section for seven migration events in the Illinois River Valley during fall 2008.

Date	Thermal infrared targets	Target density (targets/km^3)	Z	Aspect (°)	Airspace (km^3)	Mean radar cross section (cm^2)
25 October	0	0.0	1.5	94	1.14	N/A
26 October	162	83.6	232.5	73	1.94	77.9
27 October	38	20.7	97.3	84	1.84	131.8
28 October	95	57.7	137.0	77	1.65	66.5
7 November	8	7.8	41.8	77	1.03	150.9
8 November	25	11.8	53.5	102	2.12	127.2
9 November	67	34.1	147.1	104	1.97	120.8
Mean	31	30.8	118.2	87	1.76	112.5
SD	28	27.9	72.3	13	0.39	30.1

WSR as a technique for the quantitative study of bird movements.

Ornithological radar research has also changed through advancements in data sources, formats, and software. After evaluating these developments, 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 (~$70 USD) software that display and animate radar data. Although WSR is rather technical and requires careful application, this technique can be readily applied to the study of bird movements.

The spatial and temporal patterns of movement revealed on WSR agreed closely with the natural history of ducks and contrasted that of other aerofauna at our source complex. Local knowledge of aerofauna abundance, distribution, and behavior enabled us to develop an informed hypothesis regarding the identity of our echoes, despite the presence of additional aerofauna taxa at some times of the year. Ground-truthing, often lacking in radar ornithology studies, allowed us to test and validate this

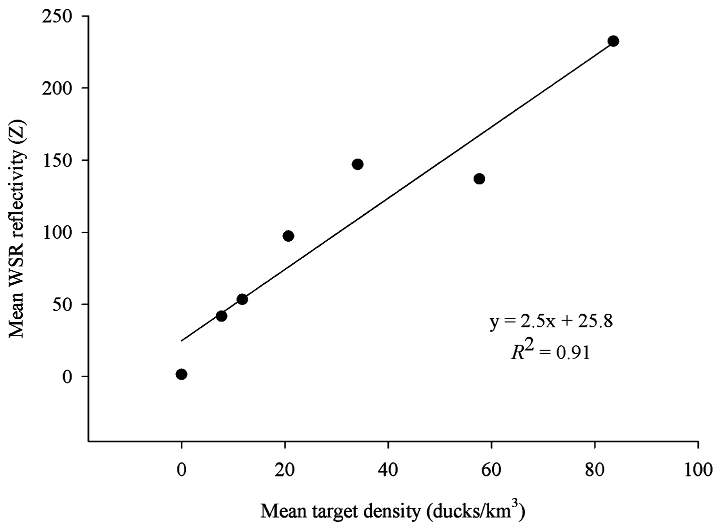

Fig. 3. Mean nightly WSR reflectivity (Z) versus mean target density (ducks/km^3) over seven fall evenings in 2008.

natural-history based classification (Eastwood 1967, Bruderer 1997, Larkin 2005).

To ground-truth the classification of WSR targets and the relationship between target density and WSR reflectivity, we first had to determine if the targets observed on WSR flew at a similar and consistent height above ground that was within both the height window captured by the 0.5° KILX beam and the functional range of the thermal-infrared camera. Portable radar definitively answered the question of target height (400–600 m) and also provided supplemental support for the classification of echoes by confirming the absence of duck-like targets on nights void of movements on KILX and confirming the presence of a discrete cluster of distinct duck-like targets on nights with movements on KILX.

To test the classification of our echoes and the relationship between echo strength and WSR reflectivity, we needed a technique capable of counting individual targets over great distances at night. The sensitivity and resolution of the FLIR S-60 thermal infrared camera met that need, allowing us to easily detect and enumerate targets at night flying at 30 m/s ground speed and 400–600 m range. We could even detect subtle wingbeats of large-bodied ducks at short range (i.e., 400 m). Based on these findings and those of others, thermal infrared cameras have great potential as a tool for learning about nocturnally migrating birds (Liechti et al. 1995, 2003Fortin et al. 1999, Zehnder et al. 2002, Desholm et al. 2006, Huppop et al. 2006, Gauthreaux and Livingston 2006).

Our estimate of the average radar cross section across all nights aligned closely with the expected value based on the published experimental estimate of radar cross section for Mallards and other morphologically-similar bird species (Eastwood 1967, Houghton et al. 1975). Our study provides the first published estimate of the radar cross section of dabbling ducks, an ecologically and economically important guild. However, our estimate of radar cross section was derived from ducks flying at certain aspects (73°–104°) and, therefore, should be applied cautiously to ducks at different aspects because aspect alone can substantially alter the relationship between duck density and WSR reflectivity (Vaughn 1985).

In addition to the mean estimate of radar cross section, the variation in radar cross-section across nights also reflected the natural history of our target guild. We detected lower average radar cross-sections on two nights early in our study period (late October) when smaller dabbling ducks (e.g., Green-winged Teal [*Anas crecca*] and Northern Pintail [*Anas acuta*]) were the predominant species emigrating from our source wetland complex. In contrast, the three average radar cross section values estimated later in November were consistent and appropriate for Mallards, the most common duck species present at that time. Overall, ground-truthing confirmed our natural-history-based classification and provided strong support for our 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. 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 radar cross section for dabbling ducks may be used to quantify duck movements under comparable conditions at other WSR units.

We suggest that researchers be mindful of four key criteria as they consider applying our estimate of radar cross section to the quantitative study of duck movements on WSR in other regions: (1) to avoid false classification, the species assemblage at the source habitat must be such that echoes can be taxonomically isolated according to natural history criteria, (2) the source habitat must be spatially isolated enough that targets from the source habitat can be distinguished from other targets originating from surrounding sources, (3) because the WSR beam increases in height radially, the source habitat must be sufficiently close to the radar that ducks will be within the heights sampled by the beam, and (4) the aspect of the flying birds should be approximately broadside at the point of analysis.

Our results also indicate that techniques such as thermal infrared can be used to estimate the radar cross section of other taxonomic groups of birds thereby broadening the application of WSR to quantitative study of other aerofauna (Ruth et al. 2005). For example, we suggest that WSR may be particularly well-suited for the study of waterbirds that often concentrate in spatially-isolated aquatic habitats. We encourage researchers to explore how WSR might be applied to the study of waterbird guilds that present important conservation challenges related to the way they move across the landscape to forage, breed, molt, and migrate. As we have demonstrated, WSR along with ground-truthing techniques can be a very effective tool for the quantitative study of bird movements.

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