

USING THE MOTUS SYSTEM TO TRACK POST-BREEDING DISPERSAL OF AMERICAN KESTRELS NESTING IN MINNESOTA, USA

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ABSTRACT.—Understanding breeding ground dispersal, migratory timing and routes, and winter distribution of birds that are facing population declines, such as the American Kestrel (*Falco sparverius*), can provide insight into their life history traits and potentially inform management decisions. We used Lotek NanoTags and CTT LifeTags to track American Kestrels breeding in three locations in Minnesota, USA, across the Motus network. We tagged nine juvenile American Kestrels in July and August 2020 and 24 more kestrels between April and August 2021 (21 adults and three juveniles). We subsequently detected 15 (45%) of the 33 birds tagged. Eleven birds (33%) were detected while still on their breeding grounds; detections on the breeding grounds after tag deployment lasted an average of 64.3 d (SD = 59.7 d) and 19.9 d (SD = 13.2 d) for adults and juveniles, respectively. Two of the three juvenile males left their natal area 44 d after fledging and the third left 68 d after fledging. However, the average date of departure did not differ by age or sex. Twelve of 33 tagged birds (39%) were detected at post-breeding ground locations during flybys (25 events) or stopovers (2 events), and they all followed a relatively consistent migratory pathway from Minnesota through Iowa and Missouri. However, a lack of Motus receiver stations south of Missouri limited our ability to determine wintering areas. The use of the Motus system to determine dispersal and migratory pathways of American Kestrels, while currently limited in the central part of North America by the availability of receiver stations, is a valuable tool in furthering our understanding of American Kestrel life cycles and possibly revealing causes of the species' population decline in North America.

KEY WORDS: *American Kestrel*; *Falco sparverius*; dispersal; migration; Motus.

USO DEL SISTEMA MOTUS PARA RASTREAR LA DISPERSIÓN POSNUPIAL DE INDIVIDUOS DE *FALCO SPARVERIUS* QUE ANIDAN EN MINNESOTA, EEUU

RESUMEN.—Comprender la dispersión en las zonas de reproducción, el momento y las rutas migratorias y la distribución invernal de las aves que se enfrentan a una disminución de la población, como *Falco sparverius*,

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puede proporcionar información sobre sus rasgos de historia de vida y potencialmente contribuir a las decisiones de gestión. Usamos Lotek NanoTags y CTT LifeTags para rastrear individuos de *F. sparverius* que se reproducen en tres lugares de Minnesota, EEUU, a través de la red Motus. Marcamos nueve juveniles de *F. sparverius* en julio y agosto de 2020 y 24 individuos más entre abril y agosto de 2021 (21 adultos y tres juveniles). Posteriormente detectamos 15 (45%) de las 33 aves marcadas. Once aves (33%) fueron detectadas mientras aún se encontraban en sus áreas de reproducción; las detecciones en las áreas reproductivas después de la colocación de las marcas alcanzaron un promedio de 64.3 d (DE = 59.7 d) y 19.9 d (DE = 13.2 d) para adultos y juveniles, respectivamente. Dos de los tres machos juveniles abandonaron su área natal 44 d después de emplumar y el tercero lo hizo 68 d después de emplumar. Sin embargo, la fecha promedio de partida no difirió por edad o sexo. Doce de las 33 aves marcadas (39%) fueron detectadas en lugares postreproductivos durante sobrevuelos (25 eventos) o escalas (dos eventos), y todas las aves siguieron una ruta migratoria relativamente constante desde Minnesota a través de Iowa y Missouri. Sin embargo, la falta de estaciones receptoras de Motus al sur de Missouri limitó nuestra capacidad para determinar las áreas de invernada. El uso del sistema Motus para determinar las rutas migratorias y de dispersión de *F. sparverius*, aunque actualmente está limitado en la parte central de América del Norte por la disponibilidad de estaciones receptoras, es una herramienta valiosa para mejorar nuestra comprensión de los ciclos de vida de *F. sparverius* y posiblemente para revelar las causas de la disminución de la población de la especie en América del Norte.

[Traducción del equipo editorial]

INTRODUCTION

Complex life histories and migratory patterns of many avian species make it difficult to ascertain their conservation status and the specific causes of their population decline (Faaborg et al. 2010, McClure et al. 2017). It is also difficult to determine how to manage lands to better support avian populations without a full understanding of habitat use and migratory patterns. An impediment to monitoring many birds during migration is that many small-bodied species are too light to carry a GPS transmitter (the standard is not to exceed more than 3% of a bird's weight; Kenward 1987, Lefevre and Smith 2020). Instead, researchers have primarily relied on breeding and wintering surveys, migration count sites, and banding to obtain clues on population dynamics and conservation threats. Innovative technologies are now able to provide the ability to monitor small-bodied avian migration in more thorough and cost-effective ways. The Motus Wildlife Tracking System (hereafter Motus) is a network of passive, automated radio telemetry receiver stations that can track wildlife that have been fitted with small, lightweight radio transmitters. Motus currently has 1004 receiver stations located in 31 countries on four continents, and tracks 25,298 animals of 235 different species, including birds, bats, and insects (Motus 2022).

The American Kestrel (*Falco sparverius*) is a widely distributed breeding species in Minnesota, USA (Pfannmuller et al. 2017) and is classified as a Species of Greatest Conservation Need in the state (Minne-

sota Department of Natural Resources 2015). State-wide, the population has declined 2.68% yr⁻¹ (credible interval -3.44% yr⁻¹, -1.94% yr⁻¹) from 1966 to 2015 and -3.91% yr⁻¹ (CI -6.72% yr⁻¹, -1.51% yr⁻¹) from 2005 to 2015 which exceeds the continental decline of 1.41% yr⁻¹ during that same time period (Sauer et al. 2020). Declines in American Kestrel populations in North America have been widely noted (Bird 2009) with documented declines in both breeding and migratory surveys (Farmer and Smith 2009, Smallwood et al 2009). A number of hypotheses have been explored to explain the causes of the decline. Smallwood et al. (2009) used Christmas Bird Count data to rule out West Nile virus, predation by Cooper's Hawks (*Accipiter cooperii*), and land use change as reasons for these notable population declines. Neonicotinoids remain an understudied risk factor for these small-bodied insectivores, and overall, the causes for the decline are at this time unknown (McClure et al. 2017).

Reversing declining populations requires a more holistic view of American Kestrel natural history, including a better understanding of their phenological patterns, nesting survival, and breeding behavior, including mate choice, habitat and nest selection, and departure pathways. To address the causes of American Kestrel population declines, McClure et al. (2017) presented a number of research recommendations, two of which seem particularly relevant to Minnesota: (1) improving our understanding of fledgling survival for the first full year of life, and (2) improving our understand-

ing of adult full lifecycle needs and survival by tracking adult American Kestrels from successful nest box programs. The objectives of our study were to determine dispersal patterns, migratory timing, and migratory pathways of American Kestrels breeding in Minnesota. We believe understanding these features will help determine which life phase is most vulnerable to mortality and why, and this will inform adaptive management strategies on breeding, migration, and wintering areas.

METHODS

In July of 2020 and from April to August of 2021 we trapped adult (after hatch year) and juvenile (birds in their hatch year) American Kestrels at three breeding sites in Minnesota: the Arden Hills Army Training Site (AHATS, 45.09°N, 92.17°W), Sax-Zim bog (Sax-Zim, 47.15°N, 92.73°W), and Carpenter St. Croix Valley Nature Center (CNC, 44.77°N, 92.81°W, Fig. 1). AHATS is located approximately 17 km northeast of downtown Minneapolis, Minnesota. As a military training area, it has limited public access and consists of a mix of open areas, woodlands, open water and wetlands. A portion of AHATS is part of an Audubon Important Bird Area (National Audubon Society 2021). There are 12 American Kestrel nest boxes (nest boxes) that have been monitored since 2016 located in a 102-ha area in the western section of AHATS. Sax-Zim is located approximately 61 km northwest of Duluth, Minnesota. Sax-Zim is a mix of spruce/tamarack (*Picea* spp./*Larix laricina*) bog, upland aspen/maple (*Populus* spp./*Acer* spp.) forest, floodplain forest, pasture and row crops with a mix of public, private, and conservation lands (Friends of Sax-Zim 2021). There were 23 nest boxes that each contained at least one kestrel egg at Sax-Zim in 2021. CNC is located along the St. Croix River and is approximately 3.5 km northeast of Hastings, Minnesota. CNC is a mix of restored prairie, woodland bluffs, and nature center facilities (CNC 2021) with 10 nest boxes, three of which have had nests with eggs at least once during the past 4 yr. The habitat in proximity to nest boxes where kestrels successfully fledged young at CNC also includes a wetland and an integrated pest management teaching apple orchard.

Trapping and Transmitter Attachment. Adult and juvenile American Kestrels were trapped using bal-chatri (eight juveniles) and modified box traps (four juveniles) baited with mice, or by hand in nest boxes (21 adults; Bloom et al. 2007, Supplemental Material Table S1). All trapped birds were aged and sexed

based on plumage (Klucsarits and Rusbuldt 2007), weighed, measured for length of wing chord and central rectrices, and banded with US Geological Survey aluminum bands. In June of 2021 we began using Darvic red, yellow, and blue color bands (Avinet Research Supplies, Portland, Maine, USA) to increase resighting opportunities within the breeding area.

We deployed two different transmitters; the Lotek NanoTag NTQB2-6-1 (NanoTag; Lotek Wireless Inc., Seattle, Washington, USA) and the Cellular Tracking Technologies (CTT) LifeTag (LifeTag; Cellular Tracking Technologies, Inc., Cape May, New Jersey, USA). Both weigh 2–3 g including glue and/or backpacks (see below), which was approximately 2% of the body mass of our study's American Kestrels (mean mass = 129.0 ± 18.7 g [SD]). The NanoTag transmits in the 166.38 MHz frequency (which is currently more widely detected within the Motus network), is battery powered, and programmed at a 13-sec burst rate with on/off capabilities. Duration of the NanoTag was estimated at 449 d for the size and burst rate we used. The LifeTag transmits in the 434 MHz frequency range, has a 2-sec burst rate, is solar powered (thus does not transmit when not in direct sunlight), and is expected to last for many years.

NanoTags were attached to fledged juveniles by gluing to a central rectrix using super glue (J. Kolodinsky pers. comm.). Juveniles were targeted for this approach because they will retain the central rectrix for a full year until undergoing their first prebasic molt (Smallwood and Bird 2020). LifeTags were attached to both fledged juveniles and adults using 3D printed harness backpacks developed in collaboration between CTT and Cornell University (Technology for Animal Biology and Environmental Research). Male American Kestrels were fitted with size 5 harness backpacks, females with size 6 harness backpacks.

Motus Network Build-Out. Because of delays in equipment availability and installation capacity (field work was limited because of the COVID pandemic) receiver station deployment at all three breeding sites (Fig. 1) was delayed until after we started deploying transmitters. The first receiver station at AHATS was erected on 27 September 2020 with east-west bearing antennas that could detect 434 and 166 MHz frequencies. North- and south-facing antennae (434 MHz detection frequencies) were added on 7 July 2021. CNC and Sax-Zim both had existing Motus receiver stations in place at the

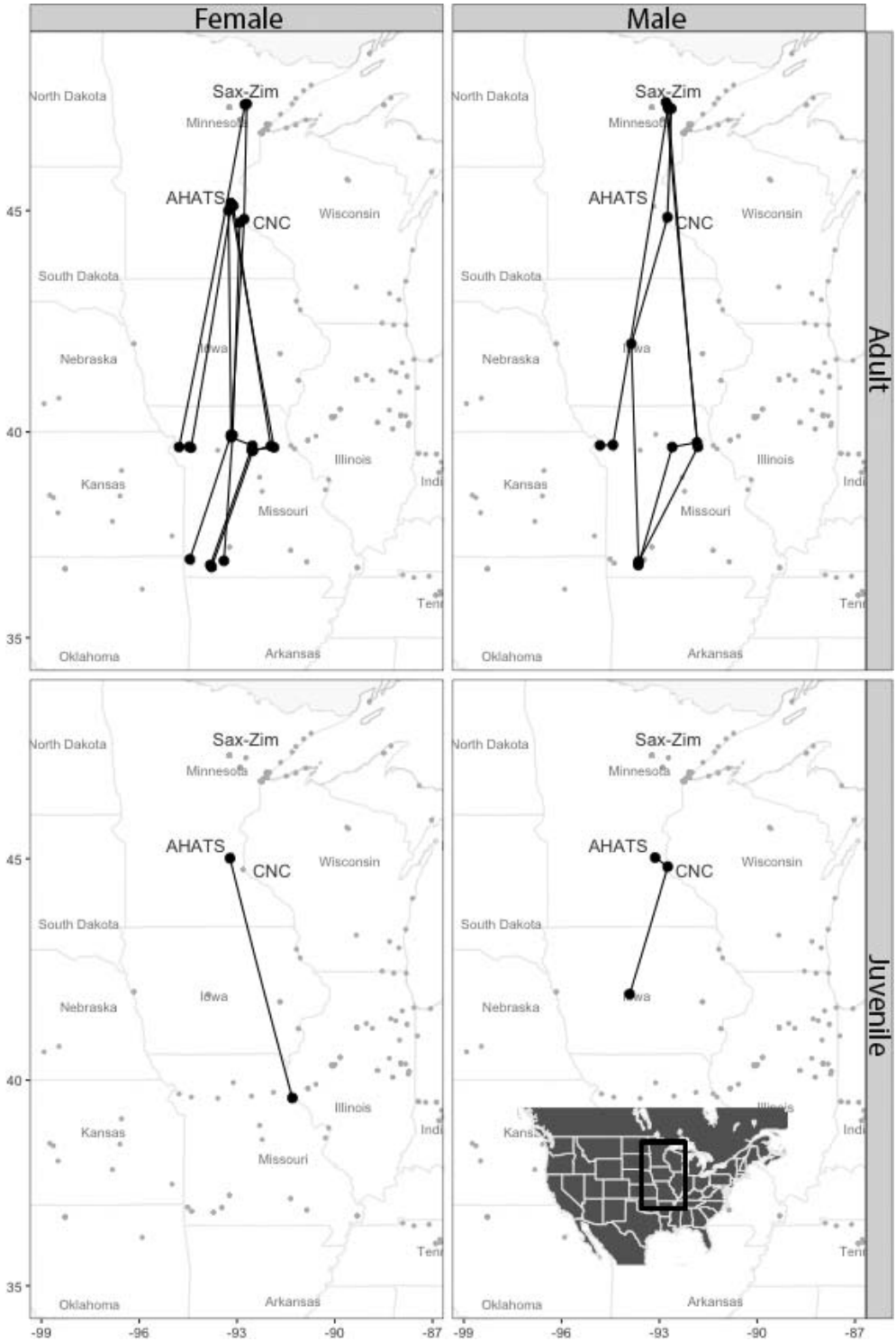


Figure 1. A map of the deployment locations and subsequent detections of American Kestrels by age (rows) and sex (columns). Seven adult females (top left panel), four adult males (top right panel), one juvenile female (bottom left panel), and one juvenile male (bottom right panel) are represented. The Motus receiver network is displayed with grey dots, with the three Minnesota project receiver locations (Arden Hills Army Training Site or AHATS, Carpenter Nature Center or CNC, and Sax-Zim Bog) labeled.

time of tag deployment, but they were not capable of detecting 434 MHz until they were retrofitted with new antennae (CNC on 7 September 2021 and Sax-Zim on 4 October 2021).

Telemetry Data Processing and Interpretation. All data processing and analysis, other than distance measurements, were conducted in R (version 4.1.2; R Core Team 2021) using the *motus* package (Birds Canada 2022). We report here on data last downloaded from the Motus network on 27 January 2022. We used the *motus* package's default filtering function to eliminate detections with run lengths less than three hits per run. The number of hits per run or "run length" is the number of continuous detections of a unique tag on a given receiver station (Birds Canada 2022). Detections with less than three hits per run are considered likely to be false detections from spurious background noise. Next, we eliminated any detections that occurred prior to deployment (e.g., detections of the tag en route to the deployment site or detections of the tag at our research sites prior to deployment). Then, we visually inspected detections for each bird and antennae versus time to verify that the detections were valid following the *motus* package user documentation (Birds Canada 2022). We removed three invalid detections that were either aliased signals (i.e., two separate tags that combined in a way that mimicked one of our tag IDs; two such detections) or for a nonexistent receiver station with no metadata (one detection). We calculated distances between breeding sites and receiver stations where birds were detected post-breeding as a straight-line distances using Google Earth Pro (Version 7.3.4) from the centroids of the relatively smaller sites (AHATS and CNC) or from specific nest box locations at Sax-Zim, which is a larger area.

We interpreted the type of flight as breeding ground flight, flyby, or stopover behavior by calculating the total duration of the detections at each receiver station and by plotting the signal strength versus time by antennae. One example bird's detection history is illustrated in Fig. S1. Detections of birds at their deployment locations were designated as breeding ground flights. We were able to determine departure flights from the breeding grounds as the last detection at the breeding grounds in a direction consistent with migration (based on the antenna bearings) following Mills et al. (2011; Fig. S1). We used *t*-tests to compare departure dates (as Julian dates) by age (juveniles vs. adults) and sex. Following Smetzer et

al. (2017), we interpreted any flight duration at a receiver station that was <100 min as a flyby, unless already designated as a breeding ground flight. Finally, we designated any of the remaining flights that were longer than 100 min and were not at a breeding/deployment site as stopover flights.

RESULTS

We deployed transmitters on 33 American Kestrels during the 2020 and 2021 breeding seasons in Minnesota (Table 1, S1). In 2020 we attached transmitters to nine American Kestrels at AHATS: four juveniles with tail-mounted NanoTags (three male, one female) and five juveniles with backpack-mounted LifeTags (four female, one male; Table 1). All birds tagged at AHATS in 2020 were released before the AHATS receiver station was online. In 2021 we exclusively used LifeTags, attaching transmitters to eight adults (five females, three males) and three juvenile males at AHATS, one adult female at CNC, and four adult males and eight adult females at Sax-Zim (Table 1). All birds tagged at CNC and Sax-Zim in 2021 were released with CTT LifeTags before those receiver stations were retrofitted with 434 KHz receivers.

We captured the 21 adults from 19 nest boxes, and 18 (85%) of those adults successfully raised at least one young to banding age from 16 boxes (84%). This included all the adults at AHATS and CNC, and nine of the 12 adults tagged at Sax-Zim.

Of the 21 adult American Kestrels (14 females, seven males) tagged on their breeding grounds in Minnesota, we detected five females (35.7%) and three males (42.8%) at the breeding grounds post-deployment (Table 1). None of the birds from Sax-Zim or CNC, which were tagged before their receiver stations were online in the 434 KHz range, were detected at their breeding grounds (although some were detected post-breeding, see below and Table 1). All of the adults tagged at AHATS in 2021 were subsequently detected on the breeding ground. The duration of individual adult detections at AHATS (i.e., first detection to last detection) ranged from 10.5 min to 188.9 d (mean = 64.3 ± 59.7 [SD] d; Table 1). The earliest verified departure flight from AHATS was by an adult female bird on 15 July 2021 at 1646 H; this bird flew in a southerly direction. The latest departure flight was an adult male on 12 November 2021 at 2021 H; this bird also flew toward the south (Table 1). Departure dates did not differ by sex ($t = 0.567$, $df = 5$, $P = 0.60$): the average departure date for female adults was 6 August 2021

Table 1. Deployment and detection history for 33 American Kestrels trapped during 2020–2021 in Minnesota (MN) by year, transmitter (tag) type, sex, age, transmitter deployment location and date, breeding ground detections, breeding ground departure dates (times, direction), and post-breeding ground detections.

MOTUS TAG ID	TAG TYPE ^a	SEX	AGE ^b	DEPLOY DATE	DEPLOY LOCATION ^d	MN BREEDING GROUND DETECTIONS ^c	BREEDING GROUND DEPARTURES ^f (TIME, DIRECTION)	POST-BREEDING DETECTIONS ^h (STATE, NUMBER AND TYPE)
52365	LifeTag	F	Adult	26 May 2021	AHATS	<1 (<1)	unknown ^g	–
52361	LifeTag	F	Adult	28 May 2021	AHATS	48 (45)	15 July (1646 H, S)	MO 2 flyby, 1 stopover
52381	LifeTag	F	Adult	28 May 2021	AHATS	109 (28)	27 Sept (1640 H, SW)	MO 2 flyby
52359	LifeTag	F	Adult	2 Jun 2021 ^c	Sax-Zim	–	–	MN 1 flyby, MO 2 flyby
52063	LifeTag	F	Adult	2 Jun 2021 ^c	Sax-Zim	–	–	–
51909	LifeTag	F	Adult	2 Jun 2021 ^c	Sax-Zim	–	–	–
51348	LifeTag	F	Adult	3 Jun 2021	AHATS	49 (35)	24 July (1437 H, S)	MO 3 flyby
52358	LifeTag	F	Adult	5 Jun 2021	AHATS	19 (4)	24 July (1917 H, SE)	MO 1 flyby
51885	LifeTag	F	Adult	7 Jun 2021 ^c	CNC	–	–	MO 1 flyby, 1 stopover
52362	LifeTag	F	Adult	9 Jun 2021 ^c	Sax-Zim	–	–	MO 1 flyby ⁱ
51344	LifeTag	F	Adult	9 Jun 2021 ^c	Sax-Zim	–	–	–
52056	LifeTag	F	Adult	9 Jun 2021 ^c	Sax-Zim	–	–	–
52058	LifeTag	F	Adult	9 Jun 2021 ^c	Sax-Zim	–	–	–
52351	LifeTag	F	Adult	9 Jun 2021 ^c	Sax-Zim	–	–	–
46219	NanoTag	F	Juv	17 Jul 2020 ^c	AHATS	–	–	–
47220	LifeTag	F	Juv	30 Jul 2020 ^c	AHATS	–	–	MO 1 flyby
47219	LifeTag	F	Juv	3 Aug 2020 ^c	AHATS	–	–	–
47226	LifeTag	F	Juv	3 Aug 2020 ^c	AHATS	–	–	–
47227	LifeTag	F	Juv	3 Aug 2020 ^c	AHATS	–	–	–
52360	LifeTag	M	Adult	30 Apr 2021	AHATS	188 (137)	12 Nov (2021 H, S)	–
47652	LifeTag	M	Adult	13 May 2021	AHATS	60 (42)	19 July (1532 H, S)	–
52364	LifeTag	M	Adult	2 Jun 2021 ^c	Sax-Zim	–	–	MN 1 flyby, IA 1 flyby, MO 1 flyby
52363	LifeTag	M	Adult	2 Jun 2021 ^c	Sax-Zim	–	–	MO 3 flyby
52380	LifeTag	M	Adult	5 Jun 2021	AHATS	40 (18)	24 July (1740 H, W)	–
46193	LifeTag	M	Adult	9 Jun 2021 ^c	Sax-Zim	–	–	MO 2 flyby
51903	LifeTag	M	Adult	9 Jun 2021 ^c	Sax-Zim	–	–	MO 1 flyby ⁱ
46218	NanoTag	M	Juv	2 Jul 2020 ^c	AHATS	–	–	–
46220	NanoTag	M	Juv	8 Jul 2020 ^c	AHATS	–	–	–
46221	NanoTag	M	Juv	10 Jul 2020 ^c	AHATS	–	–	–
45905	LifeTag	M	Juv	29 Jul 2020 ^c	AHATS	–	–	–
52377	LifeTag	M	Juv	3 Aug 2021	AHATS	12 (12)	14 Aug (2111 H, SW)	MN 1 flyby, IA 1 flyby
47540	LifeTag	M	Juv	3 Aug 2021	AHATS	12 (12)	14 Aug (1920 H, W)	–
48096	LifeTag	M	Juv	4 Aug 2021	AHATS	35 (35)	8 Sept (1545 H, S)	–

^a LifeTag = Cellular Tracking Technology (CTT) LifeTags, solar-powered, indefinite lifespan; NanoTag = Lotek Wireless Inc, battery-powered, 636-d lifespan.

^b Juv = hatch year; Adult = after hatch year.

^c These deployments occurred before the deployment location receiver stations were online.

^d AHATS = Arden Hills Army Training Site; CNC = Carpenter Nature Center; Sax-Zim = Sax-Zim Bog.

^e Breeding ground detections are provided in total duration in days followed by the total number of individual detection days in parentheses.

^f Departure flights were verified by plotting signal strength versus time by antenna direction; i.e., when the final flight from breeding grounds was in a direction consistent with migration (Mills et al. 2011).

^g This bird was only detected for approximately 10 min the day after deployment and was recaptured in May 2022 without a backpack. We surmise that this bird's backpack transmitter fell off shortly after deployment in May 2021; thus breeding ground departure date is unknown.

^h flyby flights = detection durations < 100 min; stopover flights = detection durations > 100 min; IA = Iowa; MO = Missouri.

ⁱ Indicates birds that were detected on two adjacent receivers simultaneously; although these birds were technically detected twice (at the same time on two receiver stations), we considered this to be one flyby event.

(SE = 24.6 d) and for male adults was 27 August 2021 (SE = 28.4 d).

Two pairs of breeding adult birds were trapped at AHATS, fitted with transmitters, and released. The female from the first pair (#52381, Table 1) was tagged on 28 May 2021, while the male (#52380 Table 1) was tagged on 5 June 2021. Both were detected at AHATS after release (Fig. S3) and they left AHATS 65 d apart, the male on 24 July 2021 and the female on 27 September 2021. The female was later detected in Missouri on 4 October 2021 (Table S2), but the male has not been detected since 24 July 2021. The male from the second nesting pair was tagged on 13 May 2021 and the female on 3 June 2021. The male was last detected at AHATS on 19 July 2021 and the female was detected at AHATS through 24 July 2021 and later at three receiver stations in Missouri in early October 2021 (Fig. S1). The patterns of the detections at AHATS indicate synchronized activity by both breeding pairs on several days (Fig. S3). Specifically, of the 31 d with detections at AHATS after both birds' transmitters were deployed, the first breeding pair was detected at the same antennas at the same time on 11 d (35.5%). The second breeding pair had 47 d with detections at AHATS, during which the birds were detected at the same antennas on 29 d (61.7%).

None of the nine juvenile birds that were tagged at AHATS in 2020, which was before the receiver station was installed, were subsequently detected at the breeding/deployment grounds, or on migration. The three juvenile males tagged at AHATS in 2021 with backpack-mounted LifeTags were all detected on the breeding grounds for 12.2–35.1 d (mean = 19.9 ± 13.2 [SD] d) after deployment. Two departed the breeding grounds on 14 August 2021, 44 d after fledging, and the third departed on 8 September 2021, 68 d after fledging. One of those birds was detected on 7 September 2021 at CNC and again near Boone, Iowa, on 11 September 2021. Overall, departure date of adults and juveniles did not differ by age ($t = 0.22$, $df = 8$, $P = 0.831$).

Of the 33 American Kestrels that we trapped and tagged with transmitters, 13 (36%; seven adult females [50%], four adult males [57%], one juvenile female [20%], and one juvenile male [14%]) were detected at receiver stations south of their breeding grounds (Table 1, S2; Fig. 1, S2). These detections indicated a common migratory pathway south from Minnesota and through central Iowa into north-central or northwestern Missouri and then toward the southwestern portion of Missouri (Fig. 1, S2).

Specifically, these post-breeding detection locations included three flybys in Minnesota, two flybys in Iowa, and 20 flybys and two stopovers in Missouri (Table 1, Fig. 1, Fig. S2). The durations of flyby flights were significantly shorter for adults than juveniles ($t = 2.55$, $df = 25$, $P = 0.017$). Adult flyby durations ranged from 6.2 to 85.6 min (mean = 28.5 ± 18.3 [SD] min) and juvenile flybys ranged from 27.1 to 98.5 min (mean = 60.2 ± 36.0 min). The stopover flights were both by adult females. The first stopover flight detected was in Missouri on 1 September 2021, and it lasted 2.74 hr (1211–1456 H) before that same individual was detected at another nearby Missouri receiver station from 1458–1509 H on the same day and in southern Missouri on 5 September 2021. The other stopover flight occurred in Missouri and lasted 33.1 d, from 29 October through 1 December 2021, with seven different specific days of detections during that duration.

DISCUSSION

We placed Lotek NanoTags and CTT LifeTags on 33 American Kestrels at their Minnesota breeding grounds. Using the Motus wildlife tracking system, we were able to successfully obtain detections on 15 individuals (45%), 11 on the breeding grounds and 12 at post-breeding locations in Minnesota, Iowa, and Missouri. We determined that both juvenile and adult American Kestrels departed their breeding grounds on average in early to late August, although the departure period extended from July to November (Table 1). The number of days between juvenile fledging and departure from the breeding area was 2–3 times that recorded by Varland et al. (1993). We documented synchronized breeding ground activity by two breeding pairs. Our data illustrated a fall migratory pathway through Minnesota to Iowa and into Missouri, although the relatively lower densities of Motus receiver stations in southern North America limited our ability to detect birds in overwintering grounds. Male American Kestrels migrate shorter distances than females (Heath et al. 2012), but there was no determinable sex-difference in migration path or distance shown with our data, possibly due to the lack of detections south of Missouri. It is possible that our filtering process removed some detections that were true detections and that we retained some possible false positives. This may have affected our analyses, including an under- or overestimation of departure dates or missed detections along the migration route.

Our results demonstrate that Motus technology can successfully be used on American Kestrels. Based on a literature review of all studies published from the Motus network (i.e., 133 citations listed on the Motus Zotero library, Zotero 2022), this is the first study to report tracking of American Kestrels using Motus. Previously, American Kestrels have been tracked using VHF radios (Varland et al. 1993, Stupik et al. 2015) and GPS data loggers (e.g., geolocators; Crandall and Craighead 2019). Geolocators, which can determine location estimates based on time and light period, have been widely used in tracking lighter mass birds. Limitations to using geolocators are that tags must be retrieved to recover data and analysis is prone to relatively large latitudinal errors (McKinnon et al. 2018). Kestrels do not exhibit high site fidelity to individual nest boxes, mainly due to nest-box switching (Steenhof and Peterson 2009), which would hinder data retrieval of geolocators.

The battery-only NanoTag transmitters were deployed in 2020 with a tail-mount attachment. Both the short battery lifespan and attachment type are limiting factors to their use as the tail-mount application results in the unit being dropped when the feather is molted. This restricts the ability to gain multiple seasons of data from them. NanoTags can be attached with a backpack harness if configured for that application in the manufacturing phase, which negates the problem with tail-mounts, and Lotek now offers a solar-powered NanoTag, which was not available at the time of our study. None of the NanoTags deployed in 2020 were detected after deployment. The solar-powered LifeTags that were attached with a 3D-printed backpack proved to be successful for tracking both adult and juvenile American Kestrels both on the breeding area and in subsequent fall migration. The 3D material appears to be durable enough for use on a small raptor and sizing allowed for crop expansion without restriction. The 3D harnesses were easy to apply, with most of the sizing conducted prior to having the bird in hand, which was an advantage over other backpack harnesses such as Teflon ribbon (Kenward 1987). It remains to be seen how long the 3D harnesses will last. A potential limitation in longevity of the attachment is the glue points where the harness and radio meet. We do believe, however, that the backpack style attachment of the LifeTag transmitters increases the probability the transmitters remain on the bird for at least one full year or longer, which helps provide more detections and the

possibility to monitor a full migratory cycle. We recommend attaching similar transmitters with a backpack harness, when possible, rather than a tail mount, and postulate that solar-powered transmitters may provide longer detection lifespans (although with the potential downside of a loss of monitoring during crepuscular hours).

Although we found a remarkable difference in detection rates between the juvenile and adult birds, this may have been due to the timing of deployment and availability of Motus receiving stations. Detection rates were also higher for adults in a Motus study of six shorebird species, which the authors equated with survival (Anderson et al. 2019). Both Stupik et al. (2015) and Varland et al. (1993) found relatively high rates of mortality in recently fledged American Kestrels, which if true in our study area would reduce the detection rate of juveniles. We also found that juveniles had significantly longer flyby flight durations, but we did not find a statistically significant effect of age on departure dates. Other raptors such as Ospreys (*Pandion haliaetus*; Martell et al. 2001) and Lesser Kestrels (*F. naumanni*; Mihoub et al. 2010) have different adult and juvenile migration patterns.

To minimize potential interference with nesting success for the adults, we waited until the full clutch was laid and incubation was well established before we attempted to hand-capture adults at the nest box. This method proved quite successful and enabled us to capture both males and females during incubation. We were also able to visually verify that the backpacks did not interfere with birds returning to or entering the nest boxes. We did not observe any changes in nest success after deployment, and our results suggest attaching LifeTags on backpack harnesses to nesting adult American Kestrels during the incubation period had no effect on nest success.

Our ability to detect birds on the breeding grounds in the first two years of this study seemed to be most limited by the fact that many birds were trapped and tagged before their respective breeding ground receiver stations were activated or retrofitted. Similarly, the Motus network in surrounding states was growing at the same time we began deploying transmitters. As of January 2022, LifeTag capable receiver stations (for the 434 MHz frequency) were sparsely located south of Missouri with only one in Mississippi and 10 along the Gulf Coast of Texas (Motus 2022; Fig. 1). Efforts to build out the Motus network in Iowa, Indiana, Minnesota, Mis-

souri, Ohio, and Wisconsin are ongoing, and include funding through a federally awarded, competitive State Wildlife Action Grant in collaboration with the Midwest Migration Network to install up to 48 dual frequency (166 and 434 MHz) receiver stations in these states and 11 additional receivers in Columbia, Costa Rica, and Mexico. Unfortunately, supply chain issues and the COVID-19 pandemic delayed the original deployment schedule of these receiver stations, so our 2021 season of LifeTag transmitter deployments was restricted by the current limitations of the Motus network. We are also continuing to deploy more transmitters on birds from the Minnesota breeding grounds, and we hope that these efforts will improve our ability to detect American Kestrel movement behavior and phenology in future years.

In conclusion, we demonstrated relatively consistent departure dates and migration pathways for American Kestrels nesting in Minnesota, regardless of age or sex. Our results demonstrate the potential of using Motus to track migratory American Kestrels, and we point out several best practices to improve detections (e.g., receiver station activation timing, transmitter types and attachment methods, trapping timing and methods) and that these small transmitters are equally viable for both male and female birds. Although we were unable to capture detections in the southern extent of the migration route or on the overwintering ground locations because of limitations with transmitter deployment methods and receiver station distributions, further Motus receiver station installation and activation along the entire migratory corridor and the continued deployment of transmitters on more birds will enhance this research in the future.

SUPPLEMENTAL MATERIAL (available online). Figure S1: A map of the receiver locations at which we detected a female adult American Kestrel since we deployed her LifeTag tag on 3 June 2021 (center panel) plus her flight activity by location, antenna bearing, and time (left and right panels). Figure S2: Maps of the receiver locations and dates of American Kestrels that were detected at post-breeding ground locations (panels). Figure S3. Daily flight patterns for two different breeding pairs of American Kestrels by signal strength and antenna bearing at AHATS. Table S1: American Kestrels trapped and deployed with transmitters in 2020 and 2021 by study area. Table S2: American Kestrel detections at post-breeding location receivers.

ACKNOWLEDGMENTS

The authors thank Alison Cariveau, Clinton Dexter-Nienhaus, Margaret Edwards, Matt Hall, Jennifer Vieth, and Xcel Energy for assistance in the field. The Midwest Migration Network, Sarah Kendrick, Cellular Tracking Technologies, and Bird Studies Canada provided assistance in understanding the deployment and use of LifeTags, NanoTags, and the Motus Network. We also thank three anonymous reviewers and the editors of *The Journal of Raptor Research* for their helpful feedback and comments. Funding for this project was provided in part by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR) and The State Wildlife Grant Program funds administered by the Wildlife and Sport Fish Restoration Program. Banding and radio attachment was done under USGS banding permit #23797.

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Received 9 February 2022; accepted 8 June 2022