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NRRI TECHNICAL REPORT

MAPPING AVIAN MOVEMENT IN MINNESOTA

Submitted by:

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Date: September 2021

Report Number: NRRI/TR-2021/23

Funding:

Funding for this project was provided by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR).

The Trust Fund is a permanent fund constitutionally established by the citizens of Minnesota to assist in the protection, conservation, preservation, and enhancement of the state's air, water, land, fish, wildlife, and other natural resources.

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

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Recommended Citation
Grinde, A., Bracey, A., and Kolbe, S. 2021. Mapping avian movement in Minnesota. Natural Resources Research Institute, University of Minnesota Duluth, Technical Report NRRI/TR-2019/23, 25 p. + Appendices.

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INTRODUCTION

Breeding bird populations across North America have experienced population declines estimated at a net loss approaching 3 billion individuals, or 29% of birds since 1970 (Rosenberg et al. 2019). It is well known that for bird conservation efforts to be effective they must take into account full annual cycle habitat needs; until recently, studying migration movements and stopover behavior was limited by the ability to track individuals across the landscape. Over the past two decades there have been several key advances in tracking technologies that are small and light enough to be applied to many smaller landbirds including the miniaturization of geolocators (Stutchbury et al. 2009), platform transmitter terminals (PTTs), which transmit data regularly via communication with Argos satellites (e.g., PinPoint tag; www.Lotek.com; Hewson et al. 2016), and archival Global Positioning System tags (GPS; e.g., PinPoint-10 archival GPS tags, www.Lotek.com; Fraser et al. 2017). However, each of these technologies still has limitations associated with the size, cost, and logistics of the tags. For example, satellite transmitters are expensive and still too heavy for small songbirds. Geolocators and archival GPS tags require that birds be recaptured to recover their movement data. Similarly, traditional banding is inefficient; less than 1% of songbirds banded are ever relocated. Lastly, traditional radio telemetry is labor intensive because birds must be followed by human technicians on the ground and cannot be easily tracked over large spatial scales.

Automated radio telemetry systems are a rapidly emerging tool used for tracking movements of small landbirds. This technology consists of an array of radio receivers dispersed over an area of interest and digitally coded radio transmitters that are attached to organisms of interest. These transmitters allow for many tagged individuals to be detected on the same radio frequency, and as a result, movements of many individual birds can be simultaneously tracked over a large area, such as a major migratory stopover region. One of the biggest projects involving this technology is the Canada-based Motus Wildlife Tracking System (www.motus-wts.org), which has over 1250 receiving stations across the globe, with the highest density of stations currently in the Eastern Great Lakes region of the United States and Canada (Taylor et al. 2017).

Documenting migration pathways and studying stopover ecology appears to be one of the best applications of automated telemetry systems and has led to key insights into how small landbirds use stopover areas during migration (Mills et al. 2011, Gómez et al. 2017, McKinnon and Love 2018). For example, Motus stations were used to document broadscale movements of Gray-cheeked Thrush (*Catharus minimus*) that were tagged at a stopover site in Colombia: tagged birds were recorded at subsequent stopovers in North America, allowing inferences about fat accumulation at the stopover site and migration strategies (Gómez et al. 2017). Research conducted by Wright et al. (2018) used this technology to study Rusty Blackbird (*Euphagus carolinus*) stopover biology in northern Ohio, USA, and documented a pattern of extended stays during both spring and fall migration as well as correlations between stopover duration, molt, and body condition.

The western Great Lakes region is home to one of the most diverse breeding bird communities in North America (Niemi et al. 2016) and is a key migration pathway for a wide array of species, including neotropical migrants and birds that breed in boreal ecosystems (Diehl et al. 2003, Bonter et al. 2009). To better understand and document how birds move in this region, we focused on two applications of automated radio telemetry technology: 1) large- and small-scale (local) movements of birds during the non-breeding season (i.e., migration and winter), and 2) local movements of breeding Common Terns and dispersal behavior of both adult and juvenile birds.

Our goal was to assess the utility of using Motus automated telemetry technology at various spatial scales and on a variety of species to study different ecological questions. First, to study timing and behavior of fall migration along the shores of Lake Superior (Fig. 1), we focused on two species: Blue Jay (*Cyanocitta cristata*) and Northern Saw-whet Owl (*Aegolius acadicus*). These species are common in the area, yet there is a dearth of knowledge related to their migratory movements and habitat use. Second, we focused on Rusty Blackbirds in the St. Louis River Estuary (SLRE; Fig. 1) to document the temporal and geographic use during their fall migratory stopover. Rusty Blackbirds are among the most rapidly declining bird species in North America, but the reasons driving these declines are unknown (Greenberg et al. 2011); a lack of suitable habitat during the migratory and non-breeding seasons is likely a contributing factor. Thousands of Rusty Blackbirds use the north shore of Lake Superior and the SLRE as a migration corridor each spring and fall, yet habitat use and duration of stopover is poorly understood. For this reason, we used automated radio tracking technology to document stopover duration of individual birds in relation to minimum daily temperature and to assess potential differences between sex and age. Third, we focused on documenting winter movement patterns of Black-capped Chickadees (*Poecile atricapillus*) in an urban-forested landscape: Hartley Park, Duluth MN, USA (Fig. 1), to assess how detection rates related to minimum daily temperature and food availability at feeding stations. Black-capped Chickadees are an abundant resident species in our study area and have broad public appeal but are relatively understudied in the winter, particularly in urban settings. Finally, we assessed the utility of automated radio telemetry to study breeding behavior of Common Terns (*Sterna hirundo*). Common Tern are identified as one of the most vulnerable species at both a federal and state level in the region and as a high priority species for conservation in the state (Bracey et al. 2018, USFWS 2021). Interstate Island, located in the SLRE (Fig. 1), is one of only two breeding colonies of Common Terns in Lake Superior. Movement of juvenile birds is also a critical piece of the life-history of Common Terns that is not well understood due to previously existing limitations of tracking this age class. The ability to track individuals using the Motus network, which does not require re-encountering the individual to retrieve data, is a huge advancement in tracking of juvenile birds. Documenting breeding behavior and dispersal of adult and juvenile terns will help inform population dynamics, which is particularly important for at-risk and declining populations.

Hypotheses

Blue Jay and Northern Saw-whet Owl. Documenting the migration movements of Blue Jay and Northern Saw-whet Owl was exploratory and observational, but we expected to detect birds on sequential stations and as they migrated down the shore and predicted the time between station detections would differ between the two species.

Rusty Blackbird. The Rusty Blackbird telemetry was largely exploratory, but based on research conducted in other portions of the Great Lakes, we predicted that:

1. Rusty Blackbirds would remain in the SLRE for a relatively long migratory stopover (> 1 week).
2. Rusty Blackbirds would show high site fidelity in the SLRE for the duration of the migratory stopover.

Black-capped Chickadee. Two hypotheses were tested for Black-capped Chickadee winter movements in Hartley Park:

1. Black-capped Chickadee activity (as determined by number of transmitter detections) would be higher following the addition of food near the telemetry station.
2. Black-capped Chickadee activity near feeding stations would be higher during periods of colder temperatures.

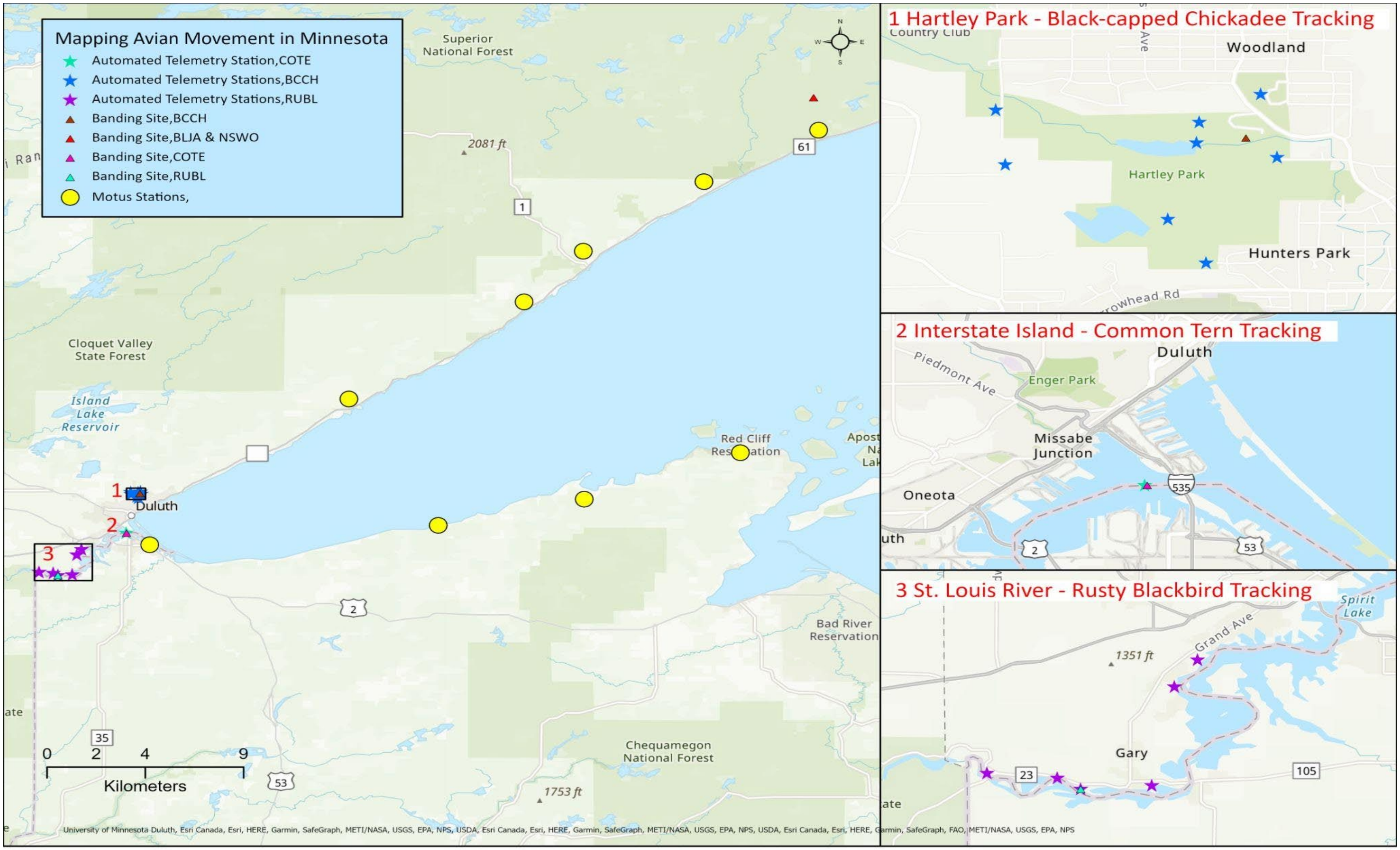

Figure 1. Location of the Motus Stations (large-scale tracking), Automated Telemetry Stations (local-scale tracking), and Banding Sites associated with the Mapping Avian Movements in Minnesota Project.

Common Tern. The three hypotheses we tested using automated radio telemetry for breeding Common Tern were as follows:

1. Detection rates for females would be higher than for males during the incubation phase of the nesting season (late May through peak nest count: June 24) and detection rates would be lower for females during the chick-rearing period (post June 24), when males do more of the post-fledging care.
2. Colony attendance should be complimentary for nesting pairs (e.g., when one mate is foraging the other will be incubating, etc.).
3. Nesting pairs that successfully hatch young should be detected at a higher frequency after eggs hatch and until young fledge relative to pairs that do not successfully rear young. For individuals in the second case, detections should be more sporadic post-nest failure, and if no secondary nesting attempt occurs, both partners should leave the island earlier than successful pairs.

Our hypotheses for migratory movement patterns were based on observations from solar geolocators placed on adults breeding at the Lake Superior colonies (Bracey et al. 2018). We expected that non-breeding distributions for both adult and juvenile Common Terns would mirror those from band re-encounters and other tracking studies for Great Lakes breeding terns, with birds staging in the lower Great Lakes, and migrating along both inland and coastal southern states.

METHODS

Deployment of Motus Stations

To document large-scale movements of bird migration along the north and south shores of Lake Superior, we installed nine Motus stations in the fall of 2018. These stations effectively covered an area that stretched from Duluth, MN to Grand Marais, MN on the north shore and Superior, WI to Bayfield, WI on the south shore (Fig. 1). The stations are hosted by a variety of partners including Lutsen Mountains Ski and Summer Resort, Minnesota Power, Wolf Ridge Environmental Learning Center, City of Beaver Bay, Two Harbors High School, National Estuarine Research Reserve, and two private landowners. All site installations were secured with a three-year agreement; these agreements have been renewed through 2024.

Each Motus station consisted of two major components: an antenna array and a receiver (Fig. 2B and C). Stations were equipped with three nine-element, highly directional Yagi antennas each with a theoretical range of over 15 kilometers (Fig. 2A). Two antennas were pointed parallel to the shore at each location, which effectively created a “fence” of antennas through which any bird migrating perpendicular or parallel to the shore would eventually cross and be detected (Fig. 2A). Each station had a receiver into which all antenna detections fed; receivers were built using a Raspberry Pi single-board computer with a FUNcube Dongle (FCD) for each antenna, GPS, and a power source converter (Fig. 2B). The FCDs are software-defined radios that detect signals from the tags placed on birds and translate them from analog to digital signals. The Raspberry Pi collects and stores the data from each antenna, including time of detection and signal strength along with relevant metadata about the receiver.

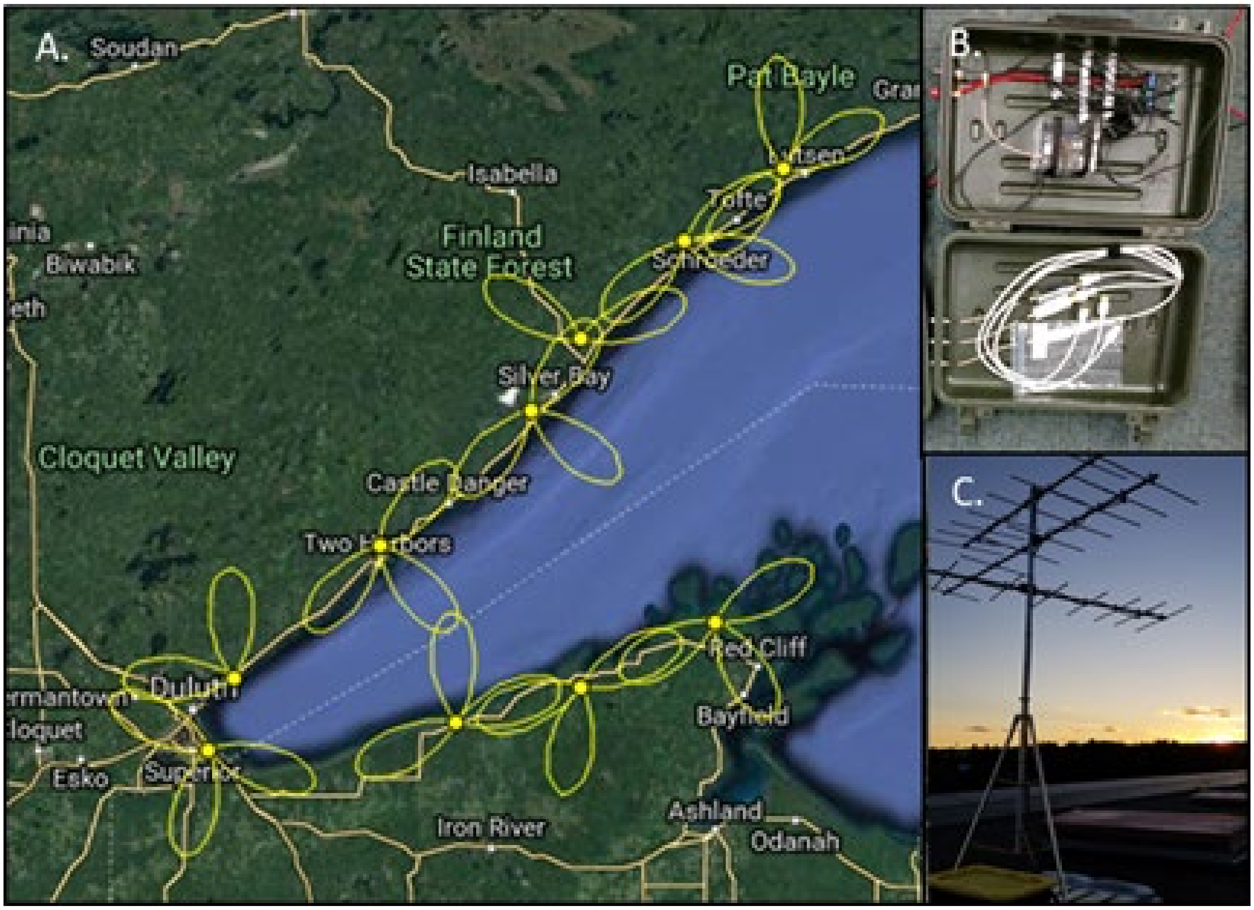

Figure 2. Motus stations and components. A.) Map of Motus station locations; yellow ovals indicate theoretical detection radii (~15 km) for the antennae associated with each Motus station,
B.) Sensorgnome components including a Raspberry Pi, three FUNcube Dongles, and power converter, and C.) Motus station mounted on the roof of Two Harbors High School, Two Harbors, MN.

Deployment of Automated Telemetry Stations

To document local-scale movements of birds, we installed automated telemetry stations in three different studies around the Duluth area. These were non-permanent stations that consisted of a single omnidirectional whip antenna connected to the same receiver setup and described above for the Motus stations (Fig. 3). The omnidirectional antenna monitored the airspace for detections within a ~1 km radius around the station. Because these stations drew much less power (as a result of one FCD instead of three) and were deployed remotely, they were powered by deep-cycle marine batteries. Routine maintenance and battery changes were conducted every seven to ten days.

- Nine automated telemetry stations were deployed in Hartley Park from late January through mid April 2021 to monitor the winter movements and activities of Black-capped Chickadees (Fig. 1, inset 1). All nine of the stations were placed directly adjacent to a wooden feeding platform upon which 20 oz. of sunflower seeds were placed every three to four days (Fig. 3).

Figure 3. Automated telemetry stations located on Interstate Island (left) and in Hartley Park (right). Stations consisted of a Raspberry Pi, one FUNcube Dongle , power converter, and marine deep-cycle battery (all located in plastic bin), and an omnidirectional antenna attached to a PVC mast.

- One automated telemetry station was placed on Interstate Island and activated during the breeding season and the start of autumn migration each year (2019 – 2021; Fig. 1, inset 2). In 2019, the receiving station was deployed on May 30 and deactivated on September 16. In 2020, the station was deployed on May 4 and deactivated on October 13. In 2021, the station was deployed on May 4 and deactivated on September 1.
- Six automated telemetry stations were deployed in the St. Louis River Estuary from early October through late November 2020 to monitor the fall stopover ecology of Rusty Blackbirds (Fig. 1, inset 3).

Transmitter Specifications and Capture Techniques

We obtained a Federal Bird Banding Permit (Permittee: Annie Bracey; Permit Number: 24165) required for capturing, banding, and attaching radio-transmitters on focal species. We also obtained approval from the Institutional Animal Care and Use Committee (IACUC) of the University of Minnesota for our protocol for the project (PI: Alexis Grinde; Protocol ID: 1806-36074A). All birds in this study were fitted with USGS issued leg bands and radio transmitters (nanotags) manufactured by Lotek (http://www.lotek.com/nanotag.htm; Fig. 4). We used a rump-mounted harness technique for securing the transmitters to the birds using different harness materials based on species size and longevity of

Figure 4. Pictures of deployment of radio transmitters (nanotags) on target species. A.) Black-capped Chickadee, B.) Blue Jay, C.) Rusty Blackbird, D.) Adult Common Tern, E.) Juvenile Common Tern, and F.) Northern Saw-whet Owl.

tags (Streby et al. 2015, Bracey et al. 2020). Each tag emitted a unique signal allowing individual birds to be tracked. Duration between signals varied, depending on tag type and species, ranging from every 5 seconds up to 30 seconds; tag life also varied and ranged from theoretical life span of 3 weeks to 2 years, depending on model and signal rates. Nanotags deployed on birds ranged from 0.6 g to 2.8 g, and the combined weight of the tag and harness materials was always under the 3% body weight standard. All tags were registered with Bird Studies Canada Motus Network (https://motus.org/) and could be detected at any radio receiving station that was active when tags were active and functioning. A total of 139 nanotags were deployed on five species over the course of this project. Deployment and general detection information associated with each species are provided in Appendices A, B, and C.

Northern Saw-whet Owl. Northern Saw-whet Owls (n = 7) were captured near the north shore of Lake Superior (Fig. 1) in October 2020. We used an audio lure playing owl calls surrounded by a triangle of mist nets to attract and capture migrating Northern Saw-whet Owls.

Rusty Blackbird. Rusty Blackbirds (*n* = 35) were captured at one location in the SLRE (Fig. 1) over the course of three capture periods using an array of mist nets and an audio lure playing the calls of a Rusty Blackbird flock.

Black-capped Chickadee. A wire box trap with a manual door-pull mounted on a feeder platform was used to capture Black-capped Chickadees (*n* = 23) at Hartley Park (Fig. 1). Chickadees were also given three color bands: one was placed on the leg above the federal bird band and two were placed on the other leg.

Common Tern. Adult Common Terns (*n* = 16) were captured on a nest during incubation using a box trap, which facilitated ease of trapping. Juvenile Common Terns (*n* = 44) were captured by hand just prior to fledging (~18 + days post-hatch).

Data Filtering

All detection data associated with this study were filtered based on probability of detection, which was determined following filtering recommendations provided by Bird Studies Canada (https://motus.org/MotusRBook/). Basic filtering thresholds were based on run length of detections, station noise, etc., with run lengths ≥ 3 considered true detections and detections ≤ 3 run lengths considered to be false detections. After initial filtering of data, all detections likely to be false were reviewed to ensure detections were indeed likely false (e.g., dates or distance from previous detection, or high station noise, etc.). All data were filtered in program R (R Core Team 2019). All detections that were determined to have a high probability of being true were summarized for each bird by hour and day.

Data Summarization

Blue Jay and Northern Saw-whet Owl. The detections associated with Blue Jay and Northern Saw-whet Owl were observational, thus no formal analyses were conducted on these species. Basic measurements of migration speed and distance were calculated for every individual that was detected outside of the trapping location.

Rusty Blackbird. We summarized Rusty Blackbird detections in two ways. We determined length of stopover (in days) for each individual by noting the first and last instances each bird was detected at any of the automated telemetry stations. We also described the apparent site fidelity of Rusty Blackbirds by determining how many other automated telemetry stations detected each individual bird. Temperature data were taken by the Duluth National Weather Service, which is located 9.4 km west of Hartley Park and downloaded from the National Centers for Environmental Information (https://www.ncdc.noaa.gov/).

Black-capped Chickadee. We assumed that the number of times a Black-capped Chickadee was detected by an automated telemetry station near a feeding platform was an adequate proxy for the activity level of each bird near that feeding station. Thus, birds with increased visits to the feeding stations would show an increase in the number of detections at the telemetry stations; the number of detections was summarized by day. We assessed the relationship between chickadee activity level and minimum daily temperature and the addition of food at the feeding stations. Temperature data were obtained in the same manner as described above for Rusty Blackbirds.

Common Terns. To document large-scale migratory movements of both adult and juvenile Common Terns (2019 – 2021), we summarized daily detections at all Motus receiving stations where detections occurred. Only the last detection date was included for each bird at Interstate Island to estimate autumn departure from the colony. Access to the island required travel by boat; therefore, the battery was replaced ~ every 2 – 3 weeks. There were periods of time during each deployment year when the station was not active (e.g., battery was dead or the cable connecting the station to the computer component was not working), even when birds may have been using the island. Therefore, although we do provide median departure dates for each group (adults and juveniles), estimates of departure date for each bird likely do not reflect true departure dates and should be interpreted as crude estimates. Last detection date post-breeding season is a more accurate reflection of when birds were no longer using the island.

We used generalized linear regression models (GLMs) to assess the association between the number of detections at the Interstate Island receiving station and four predictor variables: sex, nest fate (successful or failed), breeding phase (incubation period or post-hatch), and time of day (daylight vs. nighttime hours). To address hypothesis 1, four glm models were compared for daily detections and included: 1) null model, 2) sex only model, 3) sex + breeding phase model, and 4) breeding phase only model. To address hypothesis 2, four glm models were compared for hourly detections and included: 1) null model, 2) sex only model, 3) sex + time of day model, and 4) time of day only model. To address hypothesis 3, four glm models were compared for daily detections and included: 1) null model, 2) nest fate only model, 3) nest fate + breeding phase model, and 4) nest fate + sex + breeding phase model. Top models were selected based on AICc using package ‘AICcmodavg’ (Mazerolle 2020), and all data were analyzed in R (R Core Team 2019).

Citizen science and community outreach

Black-capped Chickadee. Since Hartley Park is a highly-visited public space within the city of Duluth, we incorporated a citizen science component into the Black-capped Chickadee study. We placed informational fliers at park entry points and at each automated telemetry station to inform the public about the study and to recruit them to look for color-banded chickadees while visiting the park (Figure 3; Appendix E). Persons who encountered a color-banded Black-capped Chickadee were instructed to send an email to a gmail account set up specifically for this project.

RESULTS

Motus Stations

Blue Jay. A total of 14 Blue Jays were trapped and tagged over the course of the study (10 in 2018, 3 in 2019, 1 in 2020). Overall, only 3 of these 14 Blue Jay tags were documented by the Motus network. A Blue Jay tagged near Lutsen on 24 September 2018 was detected at the Schroeder station the next day on 25 September (26.9 km/day) and at the Beaver Bay station a few days later on 28 September (12.7 km/day). The overall speed of this bird from Lutsen to Beaver Bay was 16.8 km/day. A second Blue Jay banded in Grand Marais on 18 September 2019 was detected at the Beaver Bay station on 26 September 2019 (14.4 km/day). Finally, a Blue Jay banded on 19 September 2019 in Grand Marais was detected at the Two Harbors High School Motus station on 22 October 2019 (3.84 km/day). All birds flew in a southwesterly direction “down” the shore after banding. No Blue Jays were detected by Motus stations outside of the local Lake Superior array.

Northern Saw-whet Owl. Seven Northern Saw-whet Owls were trapped and fitted for nanotags in fall of 2020.

Foreign detections. Four individuals of three species tagged by unaffiliated migration projects were documented on our Motus stations. A Sora (*Porzana carolina*) that was tagged near the Patuxent River in eastern Maryland on 5 May 2021 was detected at the Bark Point Motus station on the south shore of Lake Superior on the night of 23 May 2021 (Fig. 5). A second Sora also tagged at the same site in Maryland on 30 April 2021 was detected at the National Estuarine Research Reserve Motus station in the early morning hours of 24 May 2021 (Fig. 5). A Swainson's Thrush (*Catharus ustulatus*) tagged in British Columbia, Canada on 29 August 2019 was detected at the Beaver Bay Motus station just before sunrise on 22 September 2019 (Fig. 5). A Short-billed Dowitcher (*Limnodromus griseus*) that was tagged near Churchill, Manitoba on 19 June 2021 was detected at the Bark Point Motus station in the late afternoon of 17 July 2021 (Fig. 5).

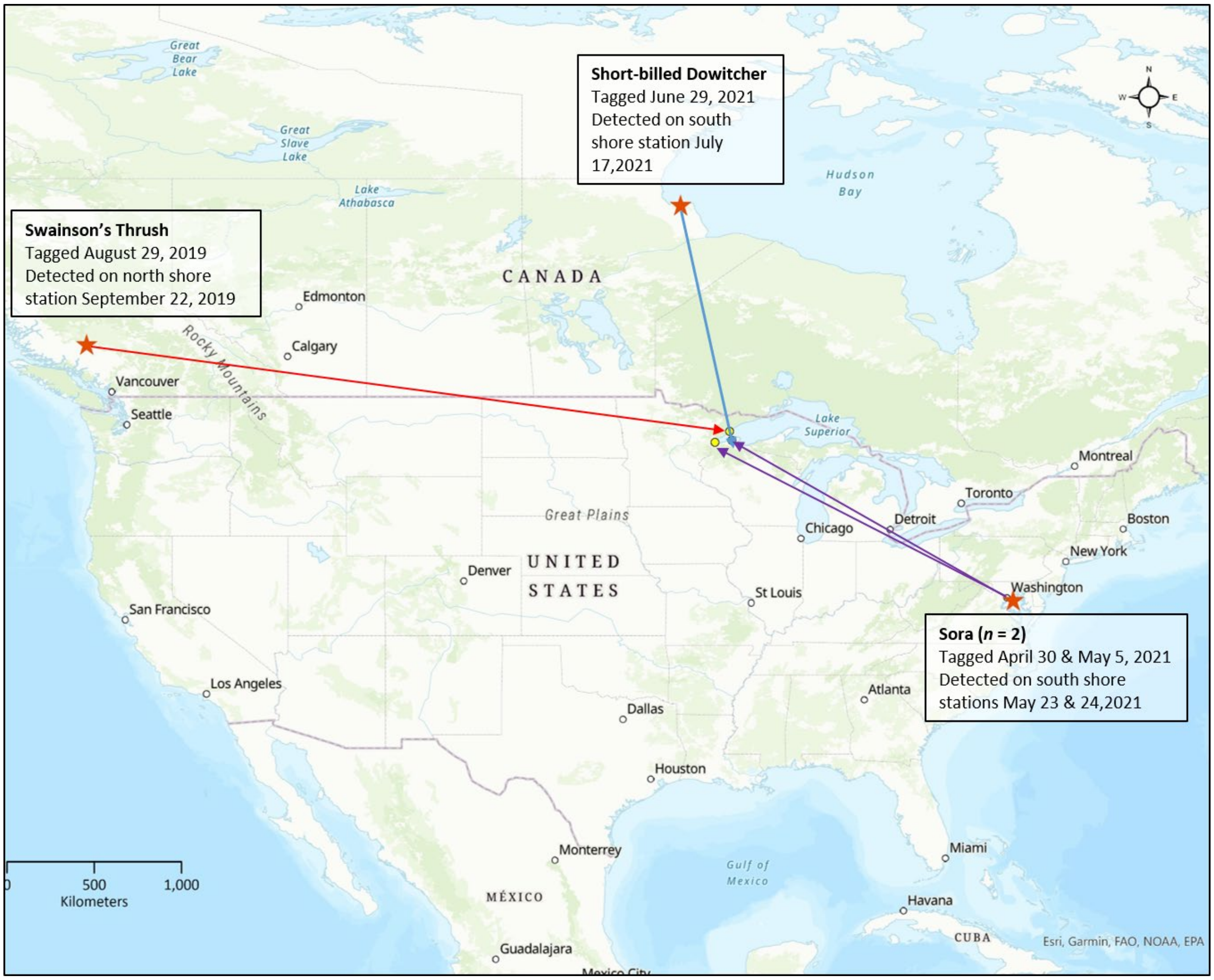

Figure 5. Deployment and detection information for three bird species tagged by unaffiliated migration projects and detected at the Motus stations deployed along Lake Superior.

Automated Telemetry Stations

detected 1.2 km away at Perch Lake, and 2 (5.7%) were detected 1.8 km away at Radio Tower Bay. The average stopover duration in the SLRE was 9.4±1.4 days and ranged from 1 to 24 days (Fig. 6). Juvenile (hatch year) birds tended to have a longer stopover duration than adult (after hatch year) birds, but this difference was not significant (Fig. 6). Likewise, female Rusty Blackbirds had marginally longer stopover durations than males, but this was also not significant (Fig. 7). Rusty Blackbirds tended to remain on migratory stopover in the SLRE, when daily minimum temperatures were relatively stable, and typically departed one to three days after a drop in daily minimum temperatures (Fig. 8).

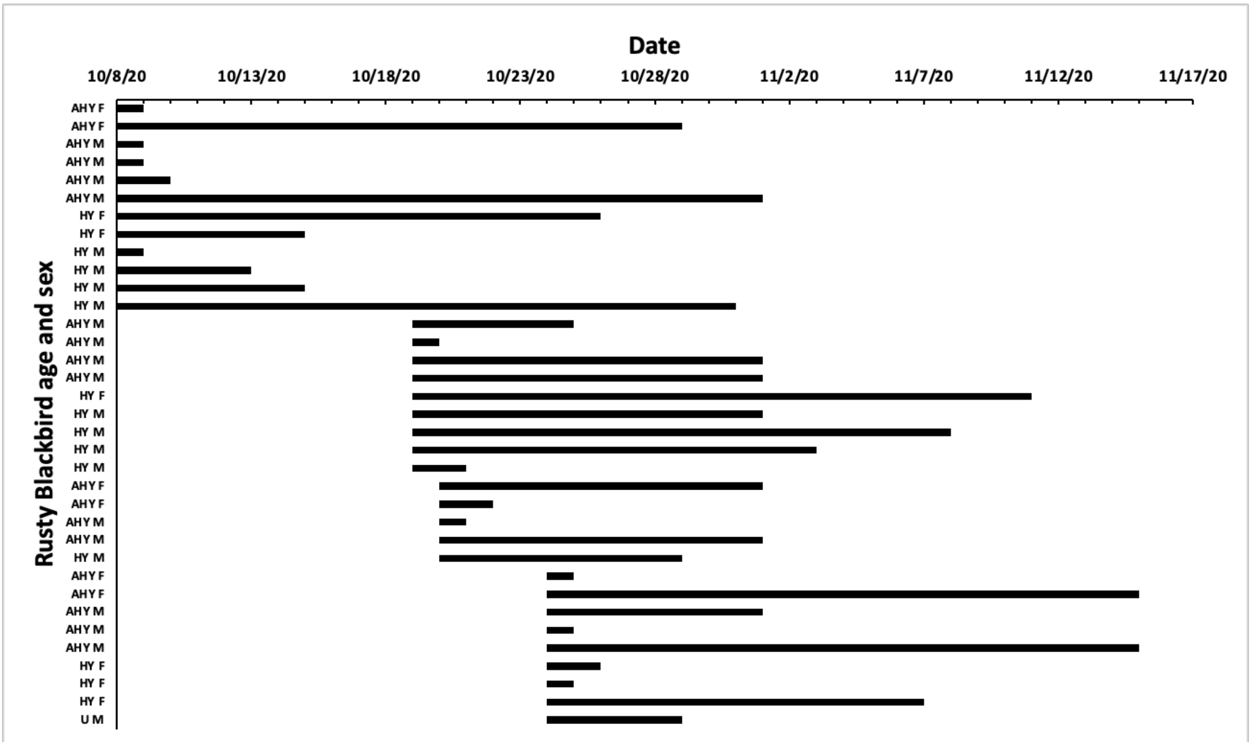

Figure 6. Stopover duration of 35 Rusty Blackbirds in the St. Louis River Estuary in late fall 2020. 12 birds were tagged on 8 October, 9 on 19 October, 5 on 20 October, and 9 on 24 October.

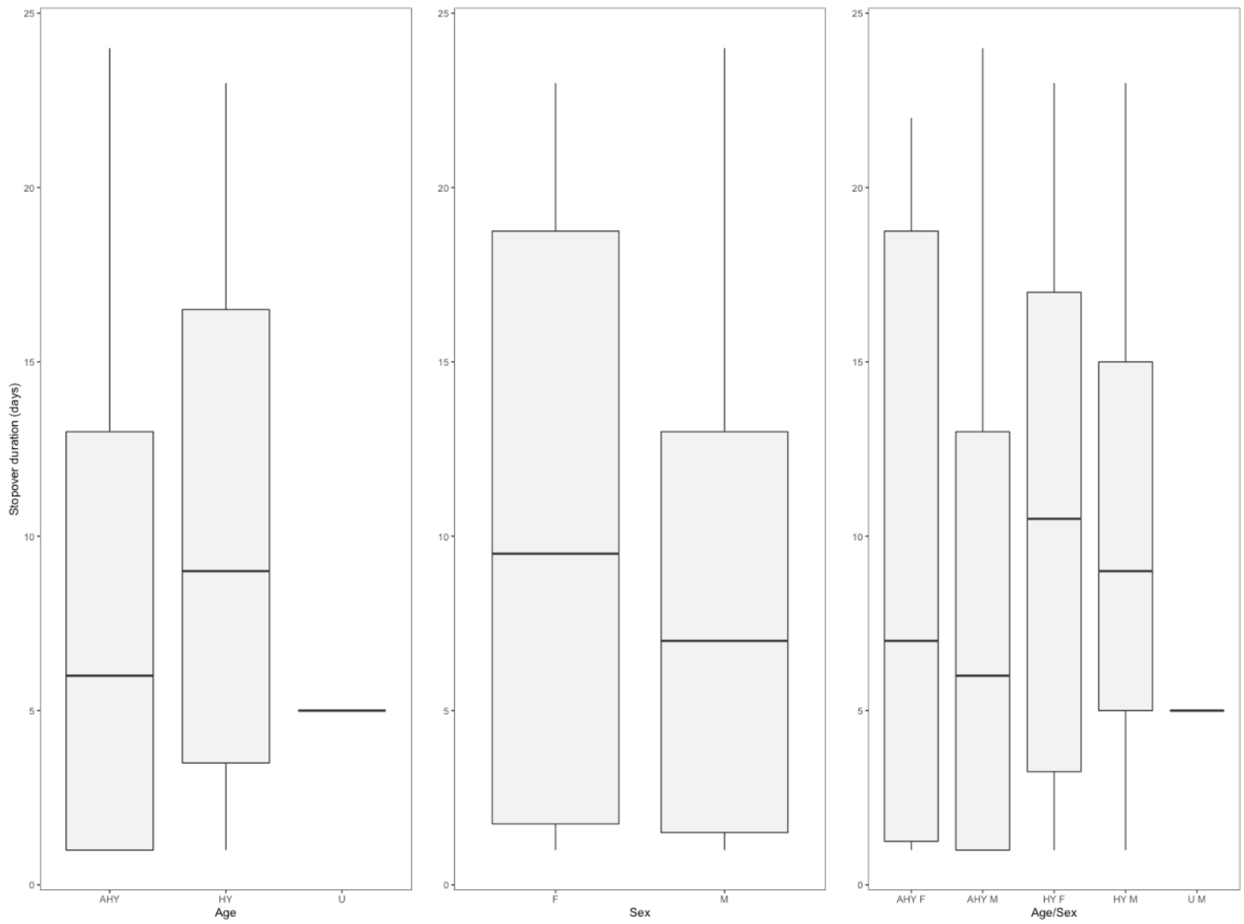

Figure 7. Length of migratory stopover in the St. Louis River Estuary of Rusty Blackbirds by age (HY = hatch year, AHY = after hatch year, U = unknown) and sex (F = female, M = male). Midline values represent the median number of detections. The upper and lower limits of the boxes represent the 75th and 25th percentiles, respectively, with whiskers representing up to 1.5x the interquartile.

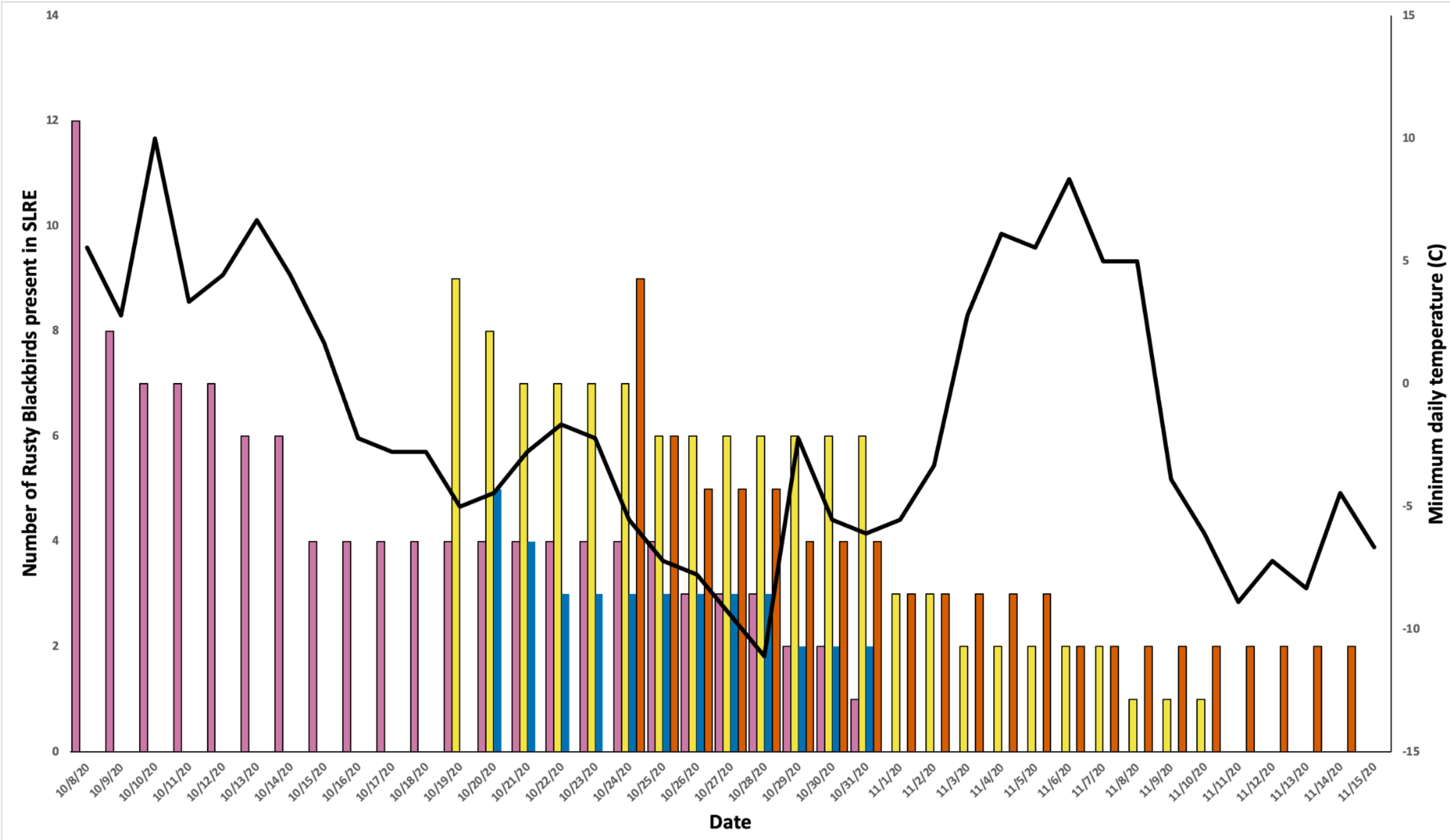

Figure 8. Number of Rusty Blackbirds present in the St. Louis River Estuary and minimum daily temperature from 8 October to 15 November 2020. The black line represents minimum daily temperature, while each color represents Rusty Blackbirds banded on each of four banding dates throughout October (8, 19, 20, and 24 October).

Black-capped Chickadees. We deployed 23 tags on Black-capped Chickadees in the winter of 2021 in Hartley Park. The nine automated telemetry stations placed in Hartley Park to track Black-capped Chickadee winter movements and activities accumulated over 1,368,000 detections of all 23 birds between late January and late February. We were able to detect activity level changes at the feeding stations in relation to days when the feeding stations were stocked. Typically, chickadee activity increased one or two days after feeding (Fig. 9). There was no relationship between Black-capped Chickadee activity levels detected at the telemetry stations and temperature (Fig. 10).

We received multiple reports of color-banded Black-capped Chickadees from Duluth citizen scientists. Color-banded chickadees were reported visiting bird feeders at two different private residences near Hartley Park. One citizen scientist who was hiking in Hartley obtained a cell phone image of a color-banded chickadee and sent it in an email to the project account. Additionally, color-banded chickadees were observed six times by researchers when they were placing seed on the feeding platforms.

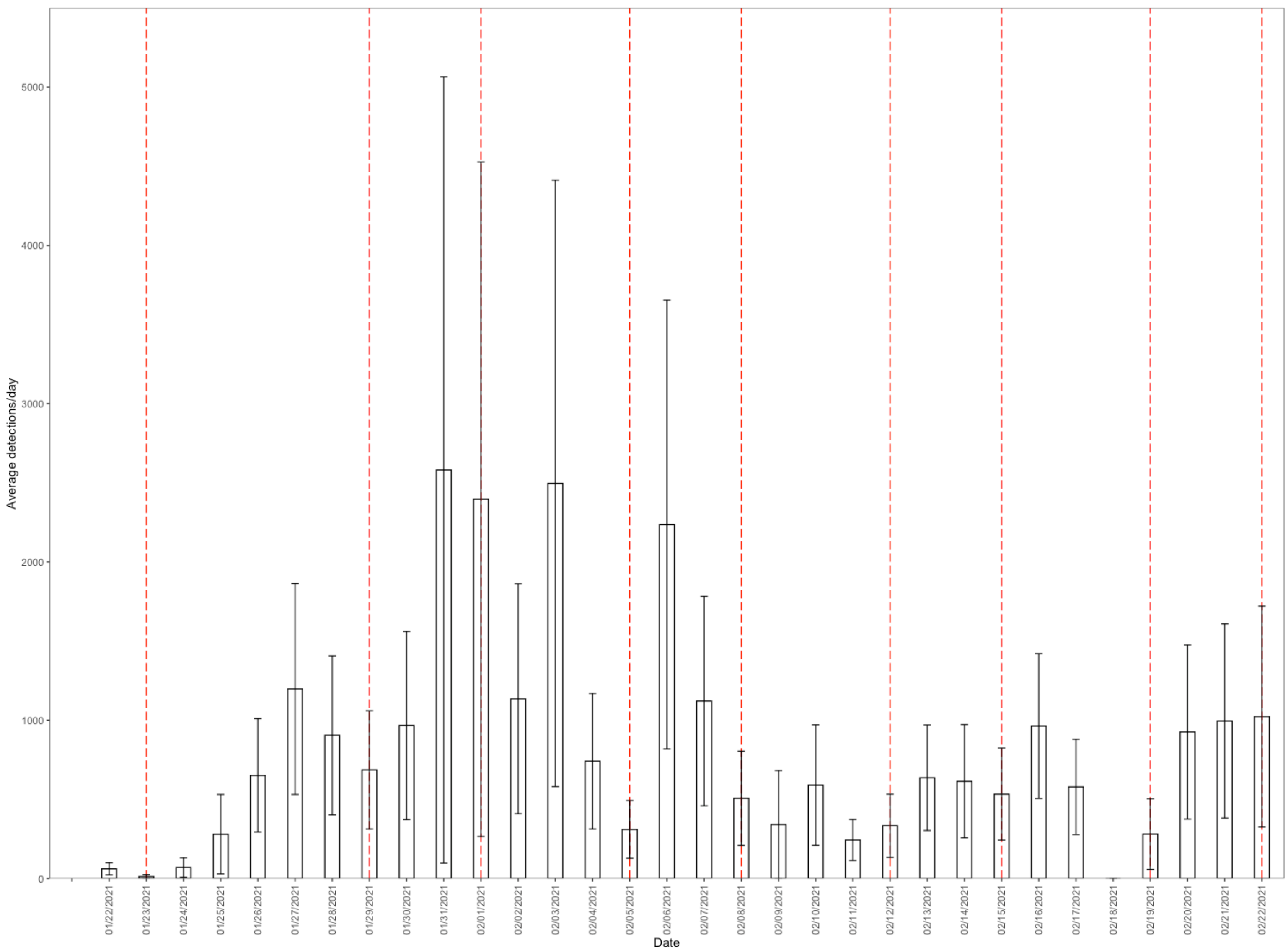

Figure 9. Average number of detections per day of Black-capped Chickadees in Hartley Park from 22 January to 22 February 2021. Red dashes indicate when feeding stations were stocked with sunflower seeds. Error bars are ± 1 standard error.

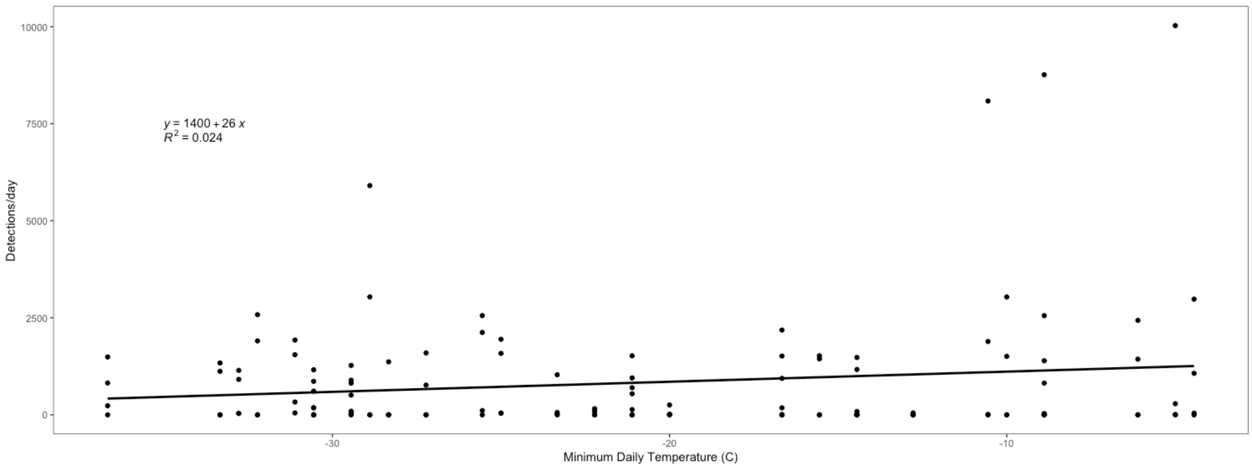

Figure 10. Relationship between minimum daily temperature and number of detections per day for four Black-capped Chickadees at one automated telemetry station where they were initially tagged.

Common Tern. Adult Breeding Season Movements. In 2019, 16 adult Common Terns were fitted with radio transmitters at Interstate Island. Juvenile Common Terns were fitted with transmitters at Interstate Island in 2019 (*n = 14*) and 2020 (*n = 30*). The number of receiving stations where Common Terns were detected ranged from one (Interstate Island) to 10, with birds being detected on an average of four stations across the Motus network. The longest tracking duration was for an adult that was detected up to 79 days post-deployment. The median number of days detected was 55, with a range of 20 – 79 d. In 2020, we recaptured and removed radio transmitters from eight adult birds. Two of the birds recaptured were mated in 2019 (M7); all others were mated with new partners, and their mates from 2019 were not observed during the breeding season. Only two of eight transmitters still had antenna attached, and none of the tags were still functioning (i.e., none of the birds that returned to nest in 2020 were detected on the Interstate Island station or any other stations). In 2021, two additional adult birds that were tagged in 2019 were recaptured and transmitters were removed; one was captured at Interstate Island and one was captured at Ashland Island in Wisconsin. A third bird fitted with a transmitter was observed late in the nesting season at Interstate Island and never attempted to nest, so we were unable to recapture it. Of the 10 transmitters removed, none were still functioning.

A total of 1,046,005 detections were recorded for adult Common Terns in 2019 at Interstate Island during the breeding season. The top model associated with hypothesis 1 was a model that included both sex and breeding phase (Fig. 11; Appendix D). The number of daily detections (mean ± SD) were higher for females during both the incubation phase of the breeding cycle (May 31 – June 24; females = 1851 ± 594; males = 1563 ± 488) and post-hatch/fledging period (June 25 –- Sept 4; females = 1159 ± 762; males = 870 ± 659). The top model associated with hypothesis 2 was a model that included both sex and time of day (Fig. 11; Appendix D). The number of hourly detections were higher for females than males and similar for both day and nighttime hours (females = 81 ± 36 (day) and 83 ± 37 (night) and for males was = 70 ± 40 (day) and 65 ± 41 (night)). The top model associated with hypothesis 3 was a model that included nest fate, sex, and breeding phase (Fig. 12; Appendix D). The number of daily detections was higher for females during both breeding phases regardless of nest success (Fig. 12). Detection rates were lower and more variable for both sexes during the later part of the breeding cycle (June 25 – Sept 4; Fig. 12).

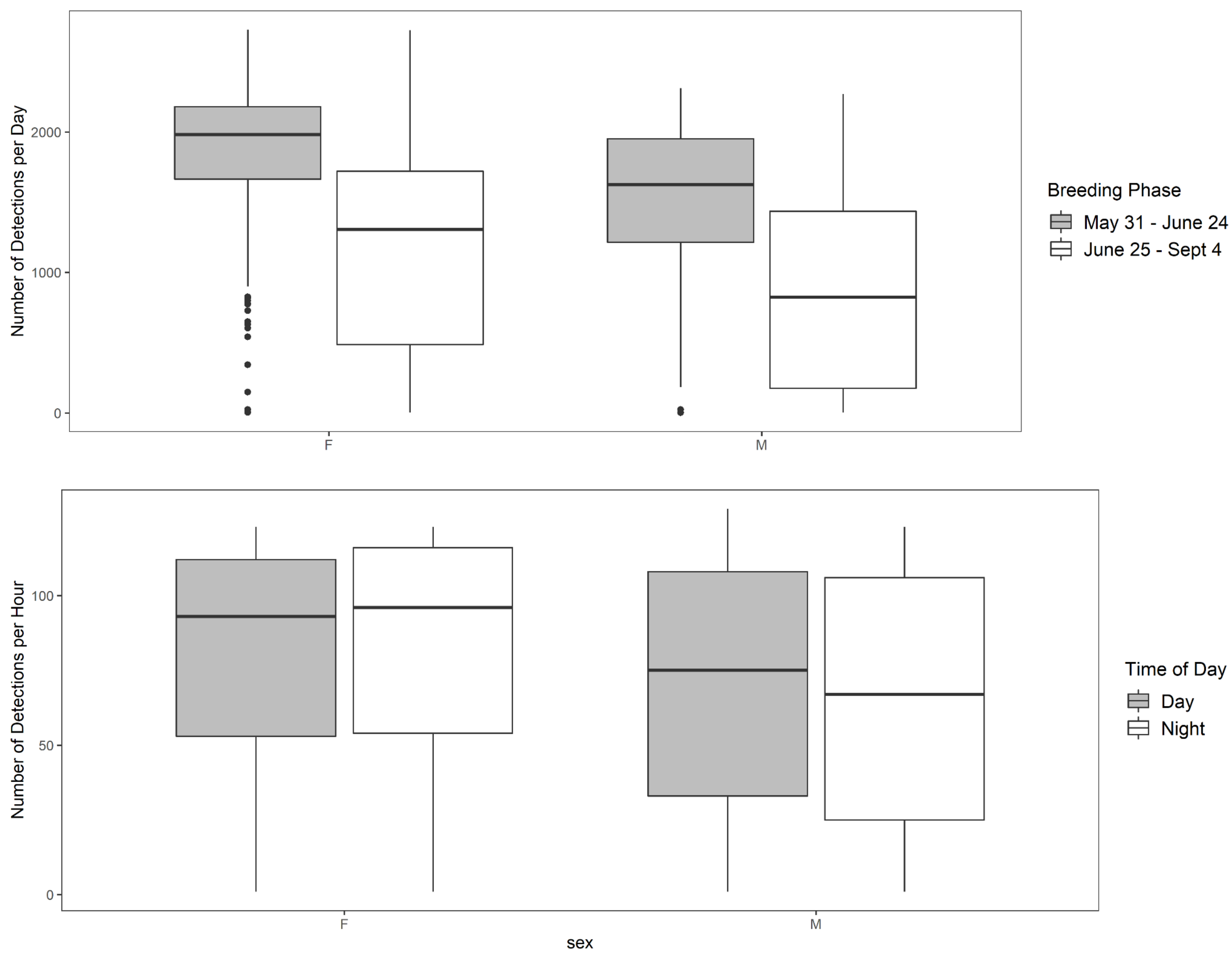

Figure 11. Above plot of number of detections per day by sex (F = female; M = male) during two breeding phases. Lower plot of number of detections per hour by sex during daylight (05:00 – 21:00) and nighttime (22:00 – 04:55) hours. Midline values represent the median number of detections. The upper and lower limits of the boxes represent the 75th and 25th quartiles, respectively, with whiskers representing up to 1.5 x the interquartile.

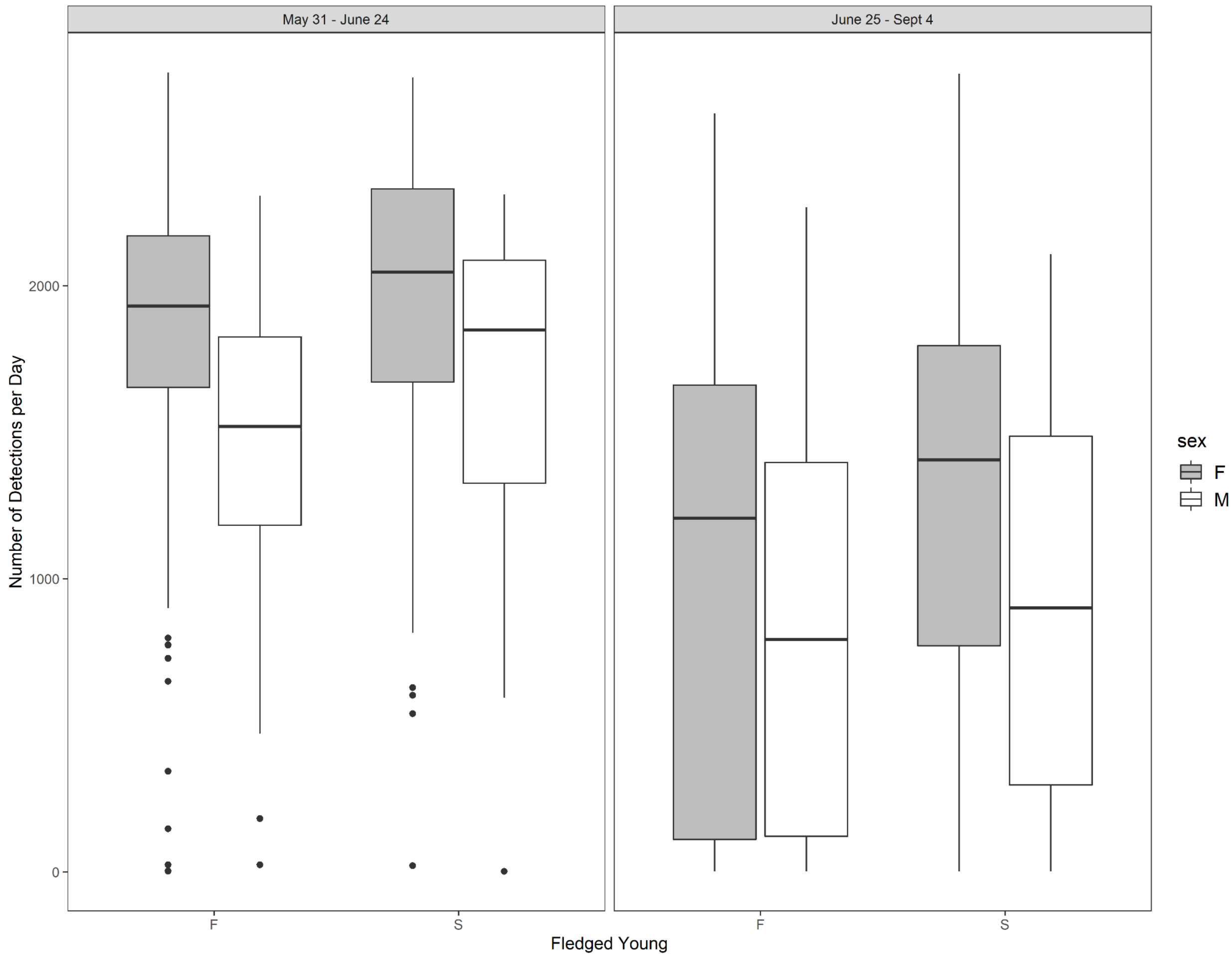

Figure 12. Number of detections per day by sex and nest fate (F = failed; S = successful) during two breeding phases (May 31 – June 24; June 25 – Sept 4). Midline values represent the median number of detections. The upper and lower limits of the boxes represent the 75th and 25th quartiles, respectively, with whiskers representing up to 1.5 x the interquartile.

Adult Migratory Movements. All 16 adult birds fitted with nanotags in 2019 were detected at at least one station outside of the breeding colony. The median departure date for adult birds in 2019 was August 3; departures ranged from June 12 to August 24, with the caveat that the receiving station battery was down between August 25 and August 30, 2019. Therefore, birds listed as last detected on August 24 (n =2) may have departed anywhere between August 24 through August 30. When only including the last detection day at Interstate Island for each bird, a total of 140 detections were recorded, 124 of which occurred at stations outside of Interstate Island (Fig. 13). Of those 124 detections, 73% occurred at stations in Lake Erie (*n* = 9 birds), with the remaining detections occurring at stations along the south shore of Lake Superior (20 detections (*n* = 6 birds) and the remaining 11 detections (*n* = 6 birds) occurring along the coasts of South Carolina, Georgia, Florida, and Texas (*n* = 8 birds; Fig. 13).

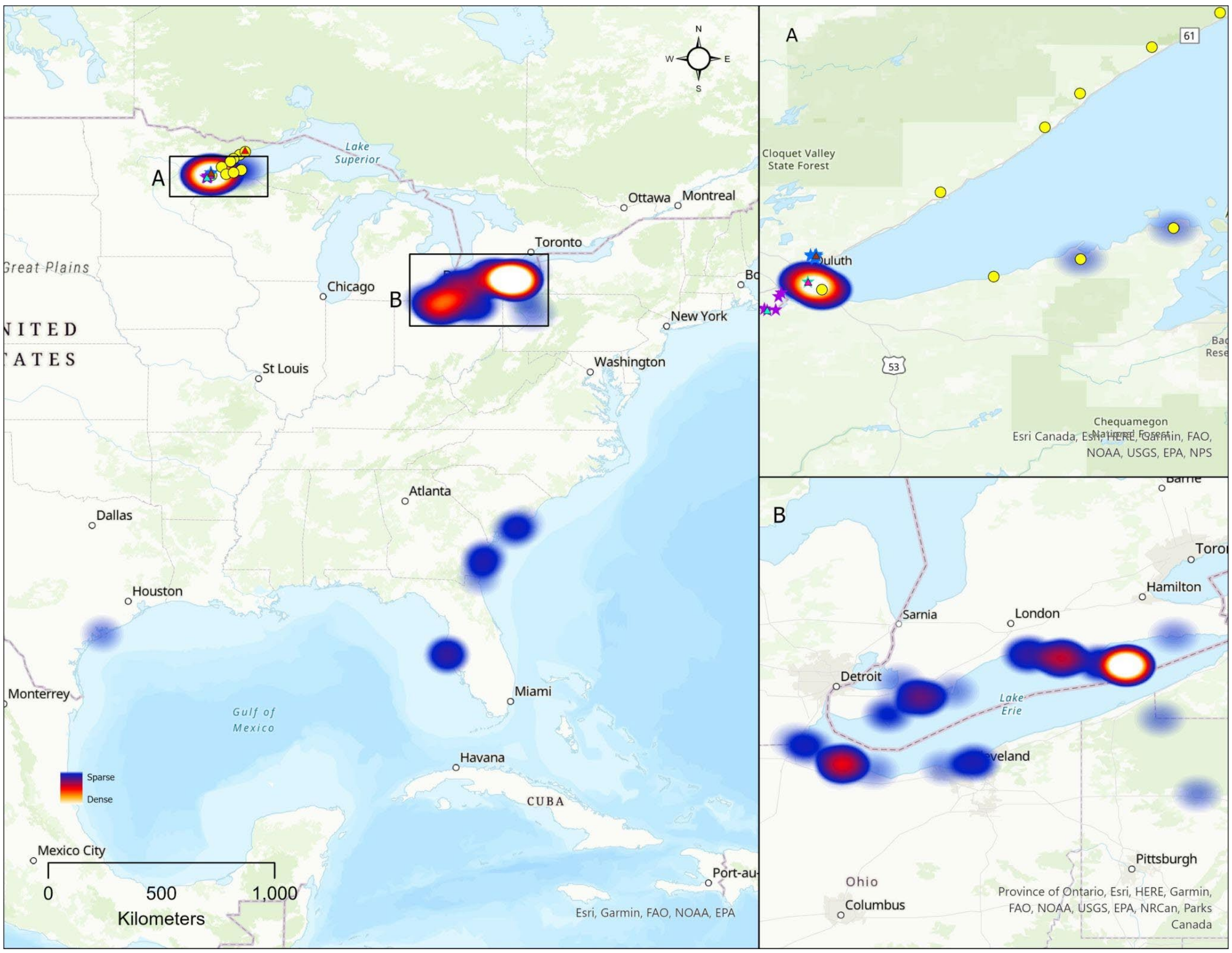

Figure 13. Locations of detections of adult Common Terns fitted with nanotags in 2019. A.) Shows detections at stations placed along the south shore of Lake Superior. B.) Shows detections occurring at stations located primarily along the shores of Lake Erie.

Many adult Common Terns were detected at more than one Motus station and nine were detected at the Long Point Tip Motus station in northern Lake Erie between August 5 and August 20. Two of the birds were mates that were detected at that location within 4 days of each other and with one of the two individuals detected twice 11 days apart. Adult Common Terns were detected at 17 Motus stations along the shores of Lake Erie from July 26 to October 13, 2019. These detections are evidence that use of radio transmitters is effective in obtaining more fine-scale information than that of geolocation data, especially during migration.

Juvenile Migratory Movements. A total of 1,310,609 detections were recorded for juvenile Common Terns in 2019 – 2020. The majority of these detections occurred on Interstate Island and are not summarized in the same manner as the adult data due to the fact that the juvenile birds were not moving to and from the island, as they were still being fed by parents. As with the adult data, we only retained the last detection date for each juvenile bird to summarize estimated movement rates for each individual, which is included below.

A total of 23 juvenile birds fitted with nanotags in 2019 – 2020 were detected at at least one Motus station outside of the breeding colony. The number of receiving stations where individuals were observed ranged from 2 to 10, with an average of 3. The longest detection period was 62 days, with the latest detection occurring on February 27, 2021. The median number of days detected was 22, with a range of 5 – 62 d. Because juveniles do not recruit as breeders for at least three years, we did not anticipate observing or recapturing any birds fitted with transmitters as juveniles. As such, no birds were detected at Interstate Island in 2020 or 2021. The median departure data for juvenile birds in 2019 and 2020 was August 21 (2019) and August 8 (2020), with departures ranging from July 13 (2019) and July 21 (2020) to September 16 (2019) and September 2 (2020), with the caveat that the receiving station battery was down between July 13 and July 15, 2019. Therefore, the bird listed as last detected on July 13 may have departed anywhere between July 13 and July 15. In 2020, the receiving station was down between July 24 and August 4 and between August 8 and August 18; therefore, birds last detected on July 24 ($n = 8$) may have departed anywhere between July 24 and August 4, and birds last detected on August 8 ($n = 10$) may have departed anywhere between August 8 and August 18. In 2019, the receiver was active until September 16, with last detection occurring on September 16 ($n = 1$); therefore, the majority of individuals had departed the island by September 16, with only one bird remaining. In 2020, the receiver was active until October 13, with last detection on September 2, which likely reflects the true last departure date.

When only including the last detection at Interstate Island for each bird, a total of 261 detections were recorded in 2019 – 2020, 216 of which occurred at stations outside of Interstate Island (Fig. 14). Of those 216 detections, 81% occurred at stations in Lake Erie (n = 13 birds), with the remaining detections occurring at stations along the south shore of Lake Superior 7 detections (n = 7 birds) and the remaining 35 detections (n = 6 birds) occurring along the Atlantic and Gulf coasts from Connecticut to Florida and Texas (n = 14 birds; Fig. 14). Juvenile Common Terns were detected at 20 Motus stations along the shores of Lake Erie from August 1 to November 3.

MapMap showing

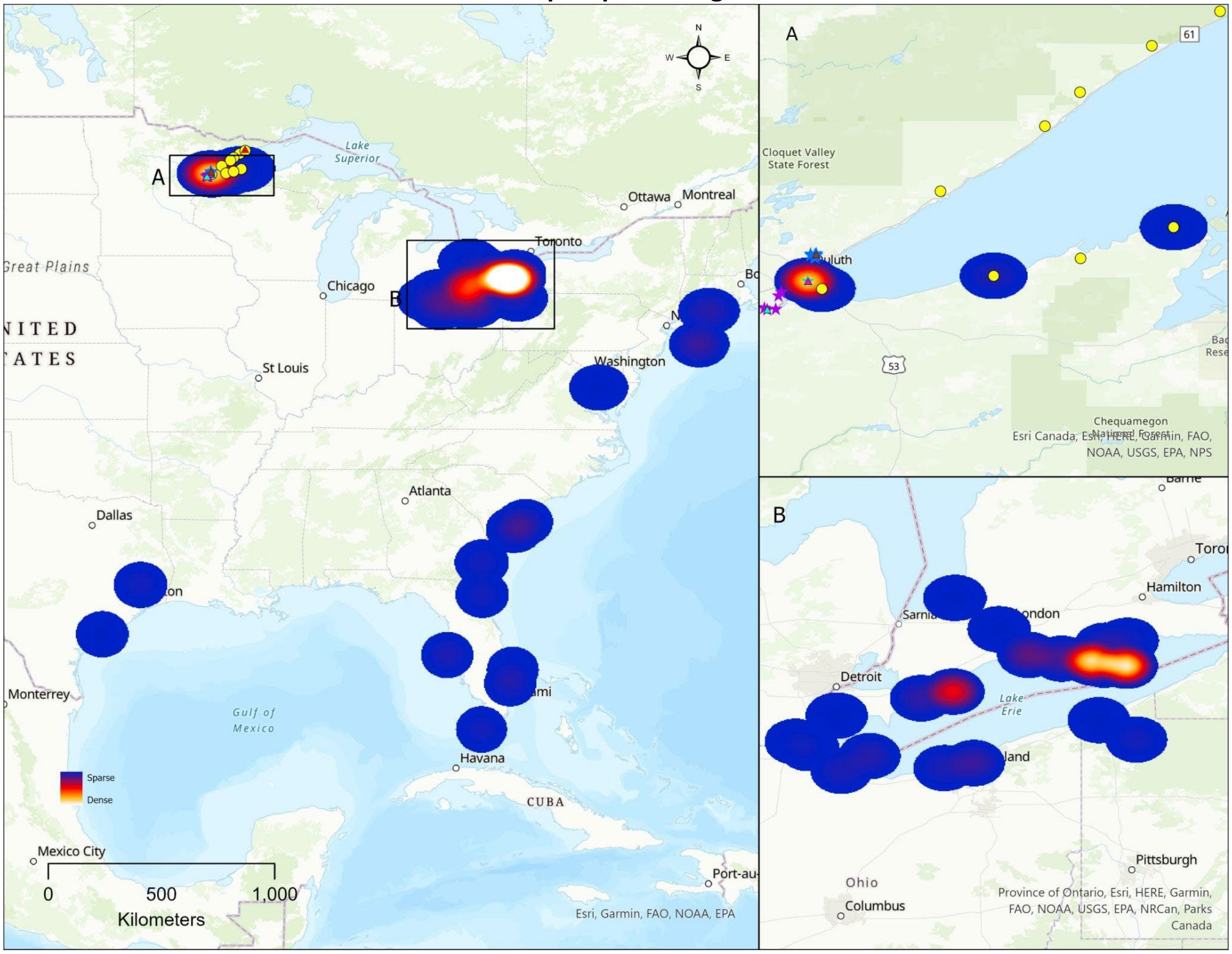

Figure 14. Locations of detections of juvenile Common Terns fitted with nanotags in 2019. A.) Shows detections at stations placed along the south shore of Lake Superior. B.) Shows detections occurring at stations located primarily along the shores of Lake Erie.

DISCUSSION

Over the course of the project, we were able to develop a deep understanding of the benefits of Motus technology as well as learn some of its limitations. We explored the use of Motus for tracking large-scale movements along the north shore of Lake Superior with Blue Jays and Northern Saw-whet Owls, colonial waterbird behavior on Interstate Island with Common Terns, local-scale migratory stopover in the St. Louis River Estuary with Rusty Blackbirds, and winter activity levels and movements in Hartley Park with Black-capped Chickadees. Each of these studies provided us with a greater understanding of the flexibility and adaptability of Motus technology to answer a range of questions in different situations and seasons.

Blue Jay and Northern Saw-whet Owl. As predicted, Blue Jays were detected migrating in a southwesterly direction down the north shore of Lake Superior in fall after tagging. Despite our limited sample size, this study is the first to document travel speed and migration timing in this species.

Anecdotal evidence suggests that some of the Blue Jays that were tagged for this study, particularly in 2018, may have been residents and thus not available to be detected by Motus stations farther south down the shore. Despite the fact that tens of thousands of Blue Jays migrate along the north shore of Lake Superior each fall, a small proportion of individuals remain in northern Minnesota for the winter.

At this point in time, we find limited utility in using the Motus network for tracking large-scale migration in the region. The reason for our low detection rate of foreign detections was likely due to the small number of research groups deploying tags in this geographic region. The utility of our current Motus station array will increase as more researchers deploy tags and additional Motus stations come online. Further, a new tag model produced by United States-based Cellular Tracking Technologies is available and has a longer battery life than the nanotags, increasing the chance of detections of small birds across large scales. Another consideration is the ongoing maintenance of these sites: consistent, long-term funding is necessary for the continued operation, data collection, and associated personnel costs for maintaining each station.

Rusty Blackbird. Rusty Blackbirds exhibited high levels of stopover site fidelity and remained within the SLRE for up to 24 days (Fig. 6), far longer than a typical migratory bird stopover. Also, while some of the birds detected at North Bay used the location as an overnight roosting site, most were only detected during daylight hours, which suggests that many of the birds are likely using other locations within the SLRE to roost at night, including some of the small wet forested island habitats in the upper estuary. Our research highlights the critical importance of forested wetlands in the SLRE to declining Rusty Blackbird populations and emphasizes the need to protect and conserve this habitat. It also highlights the need for additional research in the estuary that can elucidate the fine-scale habitat needs of Rusty Blackbirds during this important phase of their annual cycle.

The use of Motus technology to study Rusty Blackbirds was very successful. Using six automated telemetry stations to track 35 birds, we were able to record an astonishing 145,000 detections in less than two months. As stated above, these data are and will continue to be extremely valuable for describing the importance of the area for the species, but the success of the concept will be equally valuable in providing a template for researchers to study local-scale movements, stopover, and site fidelity during migration. We strongly recommend using automated telemetry stations like those constructed for this project for these types of studies.

Black-capped Chickadee. Black-capped Chickadees proved to be a highly suitable study species for exploring the potential of Motus technology to study local-scale bird movements in winter conditions. Because chickadees are extremely hardy and are readily trapped at bird feeding stations, we were able to quickly and easily deploy a large number of transmitters and collect an extremely large number of detections in a short amount of time. In support of our first hypothesis, activity levels increased one to two days after feeding stations were restocked. The apparent lag between feeding and activity levels was interesting because anecdotal observations suggested that Black-capped Chickadees immediately started visiting feeders (often within < 1 minute). More study is needed, but perhaps individuals that find re-stocked feeding stations do not immediately (or ever) share this information with other naive members of the flock. Our hypothesis that chickadee activity would increase near the feeding stations in cold weather was not supported. Black-capped Chickadees are well-suited for winter conditions and apparently maintain similar levels of foraging and movement regardless of temperature.

Based on our success tracking Rusty Blackbirds, we were confident that tracking Black-capped Chickadees would produce similar results and provide large numbers of detections for analysis.

However, we also were interested in how this tracking technology would perform in the cold Minnesota winter. The automated telemetry stations worked well despite bitterly cold conditions (e.g., daily minimum temperatures sometimes reaching -25 C), and the only limiting factor appeared to be the life of the deep-cycle marine batteries, which depleted more rapidly under cold conditions. There was no indication that the stations performed differently during cold conditions, and most of the nanotags placed on Black-capped Chickadees met their expected lifespan.

Common Tern. Summarizing detections by adults at Interstate Island allowed us to identify patterns in attendance throughout the breeding season for nesting adults. Based on detections, hypothesis 1 was not supported, as attendance by females was generally greater during both breeding phases. However, due to high rates of nest failure and predation in 2019, behavior may have been atypical. It is also possible that the majority of post-fledging care by males would not be detected using this technology, since it would occur primarily after adults and their young leave the island to begin autumn migration. Hypothesis 2 was also not supported, as detection rates by sex did not vary by time of day. Females show higher attendance rates than males regardless of time of the day. It is interesting to note how detection rates varied throughout the course of the day, with pre-dawn and morning hours (3:00 am – 9:00 am) showing the highest and least variable detection/attendance rates by both sexes regardless of nest success (Appendix F: Fig. 1 and Fig. 2). Although the number of detections varied by sex, nest fate, and season, nesting pairs that successfully hatch young were not detected at a higher frequencies after eggs hatch relative to pairs that did not successfully rear young. However, detection rates of non-successful nesting pairs generally showed a more sporadic attendance pattern post-nest failure with evidence of some renesting attempts and some early departures of non-successful pairs (Appendix F: Fig. 3 and Fig. 4).

By using automated radio transmitters, we were able to track the movement of juvenile Common Terns hatched in the Great Lakes region for the first time. This study helped us identify large-scale movement patterns of juvenile Common Terns and reinforced the importance of Lake Erie as a stopover location for both adult and juvenile birds. We were able to document, in greater detail than previously possible, post-breeding dispersal, distances traveled, direction of movement from the breeding site, duration of stay within stopover locations, and to document movement during winter months. We were able to document differences in colony attendance based on sex, nest fate, and time of the breeding phase as well as estimate post-breeding departure from the breeding colony. The benefit of obtaining data without needing to recapture individuals is of exceptional value.

This study documented three unique applications of automated radio telemetry systems for tracking movements of small landbirds. Overall, we found the use of this technology to document small-scale movements of Rusty Blackbirds, Black-capped Chickadees, and Common Tern to be the most valuable and suggest it as a relatively low-cost way to study local movements while potentially enhancing migration studies simultaneously. For example, using an automated telemetry station at Interstate Island allowed us to obtain additional behavioral information on breeding Common Terns before the birds left and interacted with any foreign Motus towers. We suggest researchers that are deploying nanotags for the purposes of long-range migratory studies strongly consider deploying automated telemetry stations like those we developed for this project in strategic locations nearby tagging sites. In this way, researchers will be able to obtain potentially large amounts of local-scale data that can then be used to inform and enhance any large-scale detections after a bird migrates from the trapping site. Bird tracking research has broad public appeal, and stories of bird migrations provide an effective way to engage non-scientists and even non-birders in understanding the many threats small migratory landbirds face. Overall, bird migration connects distant locations in a way that few other phenomena can (Fig. 5), and automated radio telemetry systems are a useful tool for not only studying migration but also can facilitate public engagement and be used for education to increase the awareness and impact for conservation efforts.

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Appendix A. Deployment information for Black-capped Chickadee (*n* = 23), Blue Jay (*n* = 14) , Northern Saw-whet Owl (*n* = 7) , and Rusty Blackbird (*n* = 35). For each individual, the deployment date, total number of receiving stations where detections occurred (nRecv), and total number of days the bird was tracked (totDay) are listed by the unique identification number associated with each tag (motusTagID and DeploymentID). Species English and Scientific name are provided along with each species' 4-letter alpha codes, which are often referred to in text and figures.

motusTagID	DeploymentID	Deployment Date	English Name	Scientific Name	Alpha Code	totDay	nRecv
46084	ID# 31777	2021-01-21	Black-capped Chickadee	*Poecile atricapillus*	BCCH	48	5
46086	ID# 31778	2021-01-21	Black-capped Chickadee	*Poecile atricapillus*	BCCH	50	3
46089	ID# 31779	2021-01-21	Black-capped Chickadee	*Poecile atricapillus*	BCCH	58	5
46092	ID# 31776	2021-01-21	Black-capped Chickadee	*Poecile atricapillus*	BCCH	5	4
46095	ID# 31774	2021-01-21	Black-capped Chickadee	*Poecile atricapillus*	BCCH	17	3
46099	ID# 31773	2021-01-21	Black-capped Chickadee	*Poecile atricapillus*	BCCH	55	6
46112	ID# 31775	2021-01-21	Black-capped Chickadee	*Poecile atricapillus*	BCCH	39	6
46094	ID# 31782	2021-01-25	Black-capped Chickadee	*Poecile atricapillus*	BCCH	26	2
46098	ID# 31781	2021-01-25	Black-capped Chickadee	*Poecile atricapillus*	BCCH	27	1
46110	ID# 31780	2021-01-25	Black-capped Chickadee	*Poecile atricapillus*	BCCH	23	2
45690	ID# 28436	2021-03-03	Black-capped Chickadee	*Poecile atricapillus*	BCCH	34	1
45692	ID# 28438	2021-03-03	Black-capped Chickadee	*Poecile atricapillus*	BCCH	32	2
45695	ID# 28441	2021-03-03	Black-capped Chickadee	*Poecile atricapillus*	BCCH	34	1
45696	ID# 28442	2021-03-03	Black-capped Chickadee	*Poecile atricapillus*	BCCH	34	1
45698	ID# 28444	2021-03-03	Black-capped Chickadee	*Poecile atricapillus*	BCCH	34	1
46076	ID# 31830	2021-03-03	Black-capped Chickadee	*Poecile atricapillus*	BCCH	5	1
46077	ID# 31831	2021-03-03	Black-capped Chickadee	*Poecile atricapillus*	BCCH	7	2
46101	ID# 31832	2021-03-03	Black-capped Chickadee	*Poecile atricapillus*	BCCH	34	1
46113	ID# 31833	2021-03-03	Black-capped Chickadee	*Poecile atricapillus*	BCCH	34	1

motusTagID	DeploymentID	Deployment Date	English Name	Scientific Name	Alpha Code	totDay	nRecv
46115	ID# 29334	2021-03-03	Black-capped Chickadee	*Poecile atricapillus*	BCCH	24	1
35318	ID# 31859	2021-03-12	Black-capped Chickadee	*Poecile atricapillus*	BCCH	24	1
45682	ID# 28428	2021-03-12	Black-capped Chickadee	*Poecile atricapillus*	BCCH	25	1
45699	ID# 28445	2021-03-12	Black-capped Chickadee	*Poecile atricapillus*	BCCH	24	1
31473	ID# 18731	2018-09-24	Blue Jay	*Cyanocitta cristata*	BLJA	0	0
31474	ID# 18732	2018-09-24	Blue Jay	*Cyanocitta cristata*	BLJA	0	0
31475	ID# 18733	2018-09-24	Blue Jay	*Cyanocitta cristata*	BLJA	2	2
31468	ID# 18726	2018-09-26	Blue Jay	*Cyanocitta cristata*	BLJA	0	0
31469	ID# 18727	2018-09-26	Blue Jay	*Cyanocitta cristata*	BLJA	0	0
31470	ID# 18728	2018-09-26	Blue Jay	*Cyanocitta cristata*	BLJA	0	0
31471	ID# 18729	2018-09-26	Blue Jay	*Cyanocitta cristata*	BLJA	0	0
31472	ID# 18730	2018-09-26	Blue Jay	*Cyanocitta cristata*	BLJA	0	0
31476	ID# 18734	2018-09-26	Blue Jay	*Cyanocitta cristata*	BLJA	0	0
31477	ID# 18735	2018-09-26	Blue Jay	*Cyanocitta cristata*	BLJA	0	0
38794	ID# 26168	2019-09-19	Blue Jay	*Cyanocitta cristata*	BLJA	15	4
38795	ID# 26169	2019-09-19	Blue Jay	*Cyanocitta cristata*	BLJA	21	4
38801	ID# 26175	2019-09-23	Blue Jay	*Cyanocitta cristata*	BLJA	12	4
38798	ID# 26172	2020-09-04	Blue Jay	*Cyanocitta cristata*	BLJA	1	1
38809	ID# 26183	2020-10-24	Northern Saw-whet Owl	*Aegolius acadicus*	NSWO	1	1
38800	ID# 26174	2020-10-25	Northern Saw-whet Owl	*Aegolius acadicus*	NSWO	0	0
38810	ID# 26184	2020-10-25	Northern Saw-whet Owl	*Aegolius acadicus*	NSWO	0	0
38811	ID# 26185	2020-10-25	Northern Saw-whet Owl	*Aegolius acadicus*	NSWO	2	1
38812	ID# 26186	2020-10-25	Northern Saw-whet Owl	*Aegolius acadicus*	NSWO	0	0

motusTagID	DeploymentID	Deployment Date	English Name	Scientific Name	Alpha Code	totDay	nRecv
38815	ID# 26189	2020-10-25	Northern Saw-whet Owl	*Aegolius acadicus*	NSWO	0	0
38816	ID# 26190	2020-10-25	Northern Saw-whet Owl	*Aegolius acadicus*	NSWO	0	0
36186	ID# 24050	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	1	1
45210	ID# 27987	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	21	2
45212	ID# 27989	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	30	8
45214	ID# 27991	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	5	2
45225	ID# 28002	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	7	2
45703	ID# 28449	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	1	1
45713	ID# 28459	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	1	1
45714	ID# 28460	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	1	1
45715	ID# 28461	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	18	1
45716	ID# 28462	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	1	1
45717	ID# 28463	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	4	1
45718	ID# 28464	2020-10-08	Rusty Blackbird	*Euphagus carolinus*	RUBL	2	2
45701	ID# 28447	2020-10-19	Rusty Blackbird	*Euphagus carolinus*	RUBL	13	1
45704	ID# 28450	2020-10-19	Rusty Blackbird	*Euphagus carolinus*	RUBL	17	2
45705	ID# 28451	2020-10-19	Rusty Blackbird	*Euphagus carolinus*	RUBL	14	2
45708	ID# 28454	2020-10-19	Rusty Blackbird	*Euphagus carolinus*	RUBL	15	2
45711	ID# 28457	2020-10-19	Rusty Blackbird	*Euphagus carolinus*	RUBL	2	1
45712	ID# 28458	2020-10-19	Rusty Blackbird	*Euphagus carolinus*	RUBL	6	2
45719	ID# 28465	2020-10-19	Rusty Blackbird	*Euphagus carolinus*	RUBL	2	2
45720	ID# 28466	2020-10-19	Rusty Blackbird	*Euphagus carolinus*	RUBL	8	2
46057	ID# 30638	2020-10-19	Rusty Blackbird	*Euphagus carolinus*	RUBL	23	11

motusTagID	DeploymentID	Deployment Date	English Name	Scientific Name	Alpha Code	totDay	nRecv
36182	ID# 24046	2020-10-20	Rusty Blackbird	*Euphagus carolinus*	RUBL	5	2
45702	ID# 28448	2020-10-20	Rusty Blackbird	*Euphagus carolinus*	RUBL	9	2
45706	ID# 28452	2020-10-20	Rusty Blackbird	*Euphagus carolinus*	RUBL	1	1
45709	ID# 28455	2020-10-20	Rusty Blackbird	*Euphagus carolinus*	RUBL	2	2
45710	ID# 28456	2020-10-20	Rusty Blackbird	*Euphagus carolinus*	RUBL	12	2
36184	ID# 30668	2020-10-24	Rusty Blackbird	*Euphagus carolinus*	RUBL	4	3
36187	ID# 24051	2020-10-24	Rusty Blackbird	*Euphagus carolinus*	RUBL	1	1
36188	ID# 24052	2020-10-24	Rusty Blackbird	*Euphagus carolinus*	RUBL	1	1
36190	ID# 30666	2020-10-24	Rusty Blackbird	*Euphagus carolinus*	RUBL	2	2
36191	ID# 24055	2020-10-24	Rusty Blackbird	*Euphagus carolinus*	RUBL	3	1
45707	ID# 28453	2020-10-24	Rusty Blackbird	*Euphagus carolinus*	RUBL	2	2
46055	ID# 30667	2020-10-24	Rusty Blackbird	*Euphagus carolinus*	RUBL	13	3
46058	ID# 30664	2020-10-24	Rusty Blackbird	*Euphagus carolinus*	RUBL	13	1
46065	ID# 30665	2020-10-24	Rusty Blackbird	*Euphagus carolinus*	RUBL	21	1

Appendix B. Total number of detections for all adult Common Terns fitted with radio transmitters in 2019 (n = 16) on Interstate Island, Duluth, MN. For each individual, the total number of detections (nDet), total number of receiving stations where detections occurred (nRecv), and total number of days the bird was tracked (totDay) are listed by the unique identification number associated with each tag (motusTagID). The start and end dates/times indicate when transmitters were deployed (tsMin) and when the last detection occurred (tsMax). The last detection date at Interstate Island (depart_II) indicates when birds likely departed the island and moved to another staging area or began autumn migration. Nesting pairs are recorded by code (M1 - M8) and information regarding sex (male = M; female = F), age, and nest fate (successfully fledged young = S; nest failed (i.e. eggs predated) = F). Species English and Scientific name are provided along with each species' 4-letter alpha codes, which are often referred to in text and figures.

English Name	Scientific Name	Alpha Code	Nesting Pairs	motusTagID	sex	age	Nest Fate	nDet	nRecv	tsMin	depart_II	tsMax	totDay
Common Tern	*Sterna hirundo*	COTE	M1	34694	F	11	S	104497	7	5/31/2019 18:02	8/15/2019	7/23/2020 16:52	79
Common Tern	*Sterna hirundo*	COTE	M1	34697	M	11	S	80477	3	6/1/2019 2:42	8/14/2019	9/22/2019 3:54	72
Common Tern	*Sterna hirundo*	COTE	M2	34699	F	Unk	F	51340	5	5/31/2019 18:01	07/21/2019 08/25/2019	7/30/2020 13:48	49
Common Tern	*Sterna hirundo*	COTE	M2	34702	M	14	F	40235	6	6/1/2019 0:17	7/25/2019	7/28/2020 3:20	47
Common Tern	*Sterna hirundo*	COTE	M3	34700	M	9	F	62385	1	5/31/2019 18:02	8/24/2019	8/24/2019 8:47	60
Common Tern	*Sterna hirundo*	COTE	M3	34701	F	9	F	84635	2	5/31/2019 18:02	8/23/2019	7/29/2020 0:36	55
Common Tern	*Sterna hirundo*	COTE	M4	34706	M	10	F	49371	6	6/6/2019 17:18	8/22/2019	7/30/2020 11:59	68
Common Tern	*Sterna hirundo*	COTE	M4	34712	F	14	F	85717	3	6/6/2019 23:42	8/4/2019	9/15/2019 1:35	64
Common Tern	*Sterna hirundo*	COTE	M5	34703	M	Unk	F	74643	5	6/6/2019 15:11	8/2/2019	7/26/2020 13:22	57
Common Tern	*Sterna hirundo*	COTE	M5	34708	F	Unk	F	6989	2	6/6/2019 15:24	6/12/2019	7/28/2020 21:20	20
Common Tern	*Sterna hirundo*	COTE	M6	34704	M	Unk	S	56529	10	6/6/2019 15:08	7/26/2019	10/28/2019 20:08	55
Common Tern	*Sterna hirundo*	COTE	M6	34710	F	18	S	82212	2	6/6/2019 18:19	7/21/2019	8/2/2020 17:33	43

English Name	Scientific Name	Alpha Code	Nesting Pairs	motusTagID	sex	age	Nest Fate	nDet	nRecv	tsMin	depart_II	tsMax	totDay
Common Tern	*Sterna hirundo*	COTE	M7	34705	M	Unk	F	65640	4	6/6/2019 16:16	8/24/2019	10/16/2019 0:09	55
Common Tern	*Sterna hirundo*	COTE	M7	34709	F	15	F	69175	1	6/6/2019 16:21	7/26/2019	7/26/2019 8:19	47
Common Tern	*Sterna hirundo*	COTE	M8	34707	M	10	S	58298	2	6/6/2019 14:24	7/26/2019	7/26/2019 17:35	48
Common Tern	*Sterna hirundo*	COTE	M8	34711	F	19	S	73986	7	6/6/2019 14:35	08/01/2019 ; 08/25/2021	7/19/2020 6:10	62

Appendix C. Total number of detections for all juvenile Common Terns fitted with radio transmitters in 2019 and 2020 (*n = 45*) on Interstate Island, Duluth, MN. For each individual, the total number of detections (nDet), total number of receiving stations where detections occurred (nRecv), and total number of days the bird was tracked (totDay) are listed by the unique identification number associated with each tag (motusTagID). The start and end dates/times indicate when transmitters were deployed (tsMin) and when the last detection occurred (tsMax). The last detection date at Interstate Island (depart_II) indicates when birds likely departed the island to move to another staging area or began fall migration. Species English and Scientific name are provided along with each species' 4-letter alpha codes, which are often referred to in text and figures.

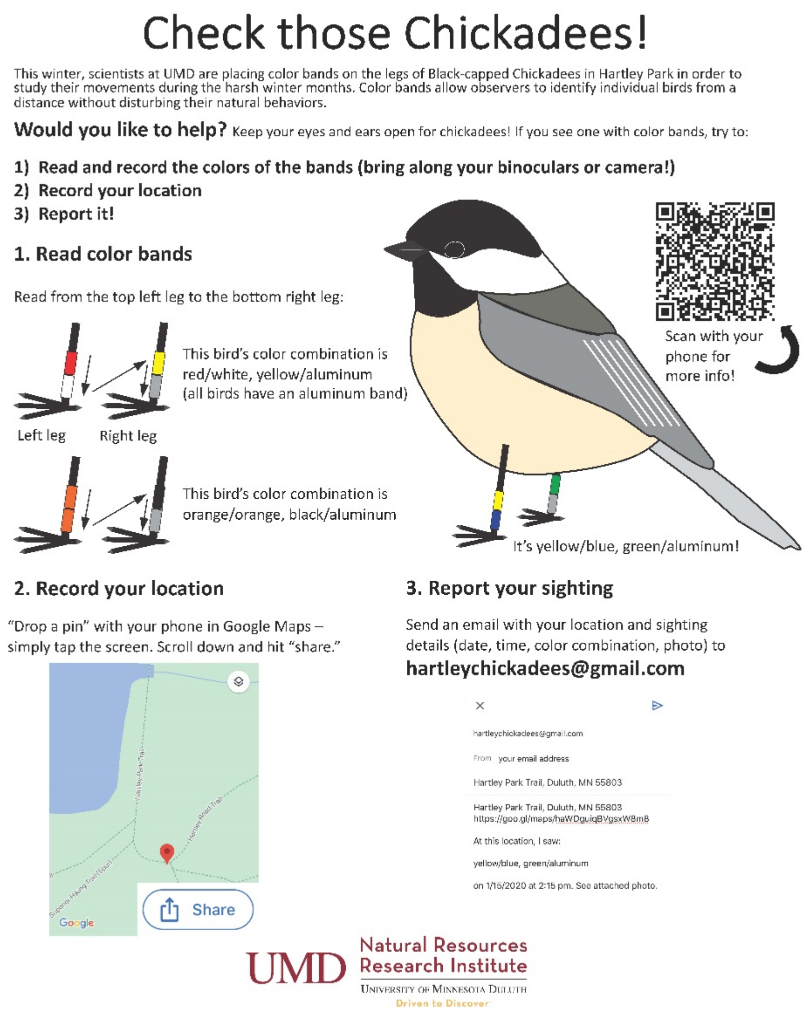
English Name	Scientific Name	Alpha Code	motusTagID	nDet	nRecv	tsMin	depart_II	tsMax	totDay
Common Tern	*Sterna hirundo*	COTE	34693	55748	3	7/26/2019 15:17	9/16/2019	8/1/2020 11:07	50
Common Tern	*Sterna hirundo*	COTE	34695	45918	2	7/26/2019 15:20	9/16/2019	7/21/2020 0:56	37
Common Tern	*Sterna hirundo*	COTE	34696	25085	2	7/26/2019 15:27	8/14/2019	7/26/2020 12:09	21
Common Tern	*Sterna hirundo*	COTE	34698	17788	2	7/26/2019 15:42	8/8/2019	7/29/2020 10:38	15
Common Tern	*Sterna hirundo*	COTE	34713	25440	2	7/26/2019 15:08	9/15/2019	7/28/2020 0:47	29
Common Tern	*Sterna hirundo*	COTE	34714	103411	3	7/22/2019 18:36	9/16/2019	7/26/2020 15:14	56
Common Tern	*Sterna hirundo*	COTE	34715	134290	2	7/12/2019 15:19	9/16/2019	7/26/2020 3:23	62
Common Tern	*Sterna hirundo*	COTE	34716	42330	5	7/12/2019 14:54	8/21/2019	7/26/2020 22:08	34
Common Tern	*Sterna hirundo*	COTE	34717	17130	2	7/26/2019 15:05	8/14/2019	7/27/2020 1:45	17
Common Tern	*Sterna hirundo*	COTE	34718	71636	2	7/22/2019 19:35	8/21/2019	7/28/2020 2:25	33
Common Tern	*Sterna hirundo*	COTE	34719	11997	10	8/2/2019 14:57	8/15/2019	7/25/2020 5:33	31
Common Tern	*Sterna hirundo*	COTE	34720	16154	6	7/29/2019 14:07	8/11/2019	2/27/2021 0:05	30
Common Tern	*Sterna hirundo*	COTE	34721	24018	2	7/29/2019 14:07	9/16/2019	7/26/2020 8:57	35
Common Tern	*Sterna hirundo*	COTE	34722	11536	3	8/2/2019 15:19	7/13/2019	1/19/2021 17:59	35
Common Tern	*Sterna hirundo*	COTE	46315	17562	2	7/10/2020 13:37	8/10/2020	8/10/2020 15:38	16
Common Tern	*Sterna hirundo*	COTE	46316	19599	2	7/15/2020 13:40	8/8/2020	8/8/2020 2:37	15
Common Tern	*Sterna hirundo*	COTE	46317	34160	6	7/10/2020 10:04	8/8/2020	11/7/2020 18:59	38
Common Tern	*Sterna hirundo*	COTE	46318	23256	2	7/10/2020 1:27	8/8/2020	8/8/2020 2:17	23
Common Tern	*Sterna hirundo*	COTE	46319	17258	2	7/10/2020 13:26	8/10/2020	8/10/2020 15:37	25
Common Tern	*Sterna hirundo*	COTE	46320	21636	2	7/7/2020 4:10	7/24/2020	7/26/2020 17:46	20

English Name	Scientific Name	Alpha Code	motusTagID	nDet	nRecv	tsMin	depart_II	tsMax	totDay
Common Tern	*Sterna hirundo*	COTE	46321	33951	7	7/7/2020 2:29	8/8/2020	10/16/2020 10:28	34
Common Tern	*Sterna hirundo*	COTE	46322	25668	10	7/10/2020 13:26	7/24/2020	1/19/2021 17:57	31
Common Tern	*Sterna hirundo*	COTE	46323	20756	2	7/10/2020 13:24	8/8/2020	8/8/2020 2:32	21
Common Tern	*Sterna hirundo*	COTE	46324	39476	2	7/10/2020 13:25	No Detections	8/10/2020 15:37	23
Common Tern	*Sterna hirundo*	COTE	46325	21615	5	7/7/2020 13:26	7/24/2020	10/27/2020 7:32	24
Common Tern	*Sterna hirundo*	COTE	46373	17590	2	7/10/2020 13:27	7/24/2020	7/25/2020 19:08	16
Common Tern	*Sterna hirundo*	COTE	46374	29330	2	7/10/2020 9:36	8/8/2020	8/8/2020 2:40	18
Common Tern	*Sterna hirundo*	COTE	46375	22823	5	7/10/2020 13:43	8/8/2020	9/14/2020 17:15	27
Common Tern	*Sterna hirundo*	COTE	46376	34104	2	7/10/2020 17:20	8/8/2020	8/8/2020 2:17	22
Common Tern	*Sterna hirundo*	COTE	46377	34168	9	7/10/2020 13:26	8/5/2020	11/17/2020 9:27	31
Common Tern	*Sterna hirundo*	COTE	46378	12530	2	7/10/2020 13:25	7/24/2020	7/26/2020 19:04	16
Common Tern	*Sterna hirundo*	COTE	46379	54552	2	7/10/2020 13:24	9/2/2020	9/2/2020 12:41	37
Common Tern	*Sterna hirundo*	COTE	46380	34550	2	7/10/2020 13:25	8/7/2020	8/7/2020 2:14	20
Common Tern	*Sterna hirundo*	COTE	46381	14986	2	7/10/2020 13:25	7/21/2020	7/26/2020 9:21	13
Common Tern	*Sterna hirundo*	COTE	46382	19874	2	7/10/2020 13:24	8/6/2020	8/6/2020 10:05	20
Common Tern	*Sterna hirundo*	COTE	46383	21741	2	7/10/2020 13:26	8/5/2020	8/5/2020 3:13	18
Common Tern	*Sterna hirundo*	COTE	46384	35806	2	7/10/2020 13:25	8/10/2020	8/10/2020 15:37	24
Common Tern	*Sterna hirundo*	COTE	46531	18284	3	7/15/2020 13:40	8/8/2020	7/8/2021 4:38	16
Common Tern	*Sterna hirundo*	COTE	46532	9842	2	7/15/2020 13:41	7/24/2020	7/24/2020 20:06	10
Common Tern	*Sterna hirundo*	COTE	46533	1630	2	7/15/2020 14:50	7/22/2020	7/22/2020 3:08	5
Common Tern	*Sterna hirundo*	COTE	46534	18078	2	7/15/2020 13:35	7/24/2020	7/26/2020 6:52	12
Common Tern	*Sterna hirundo*	COTE	46535	17123	2	7/15/2020 13:35	8/8/2020	8/8/2020 2:52	18
Common Tern	*Sterna hirundo*	COTE	46536	20267	2	7/15/2020 13:40	8/18/2020	8/18/2020 22:35	18
Common Tern	*Sterna hirundo*	COTE	46537	15913	4	7/15/2020 13:40	7/24/2020	9/8/2020 21:15	13

Appendix D. Generalized linear models (glms) used to assess the association between then number of detections (daily and hourly) relative to sex, breeding phase, time of day, and nest fate. The model selection results are provided for each set of candidate models (Model) associated with each of the hypotheses for adult detections at Interstate Island. Models were compared using Akaike's information criterion corrected for small sample size (AIC_c). Each fitted model provides a difference between AIC_c compared to the top model (ΔAIC_c), model weight (AIC_cWt), and the number of estimated parameters (K).

Hypothesis	Model	K	AIC_c	ΔAIC_c	AIC_cWt
1	**Sex + Breeding Phase**	3	398540.1	0.00	1
	Breeding Phase	2	411940.7	13400.54	0
	Sex	2	472551.8	74011.67	0
	Null	1	488676.9	90136.75	0
2	**Sex + Time of Day**	3	447458.5	0.00	1
	Sex	2	447528.5	69.95	0
	Time of Day	2	455877.9	8419.40	0
	Null	1	455925.4	8466.83	0
3	**Nest Fate + Sex + Breeding Phase**	4	395158.7	0.00	1
	Nest Fate + Breeding Phase	3	408127.5	12968.71	0
	Nest Fate	2	486266.7	91107.98	0
	Null	1	488676.9	93518.12	0

Appendix E. Informational flier posted at Hartley Park, Duluth, MN to inform the public about the study and to recruit them to look for color-banded chickadees while visiting the park.



Appendix F. Figures F1–F4 summarizing adult Common Tern detections at Interstate Island.

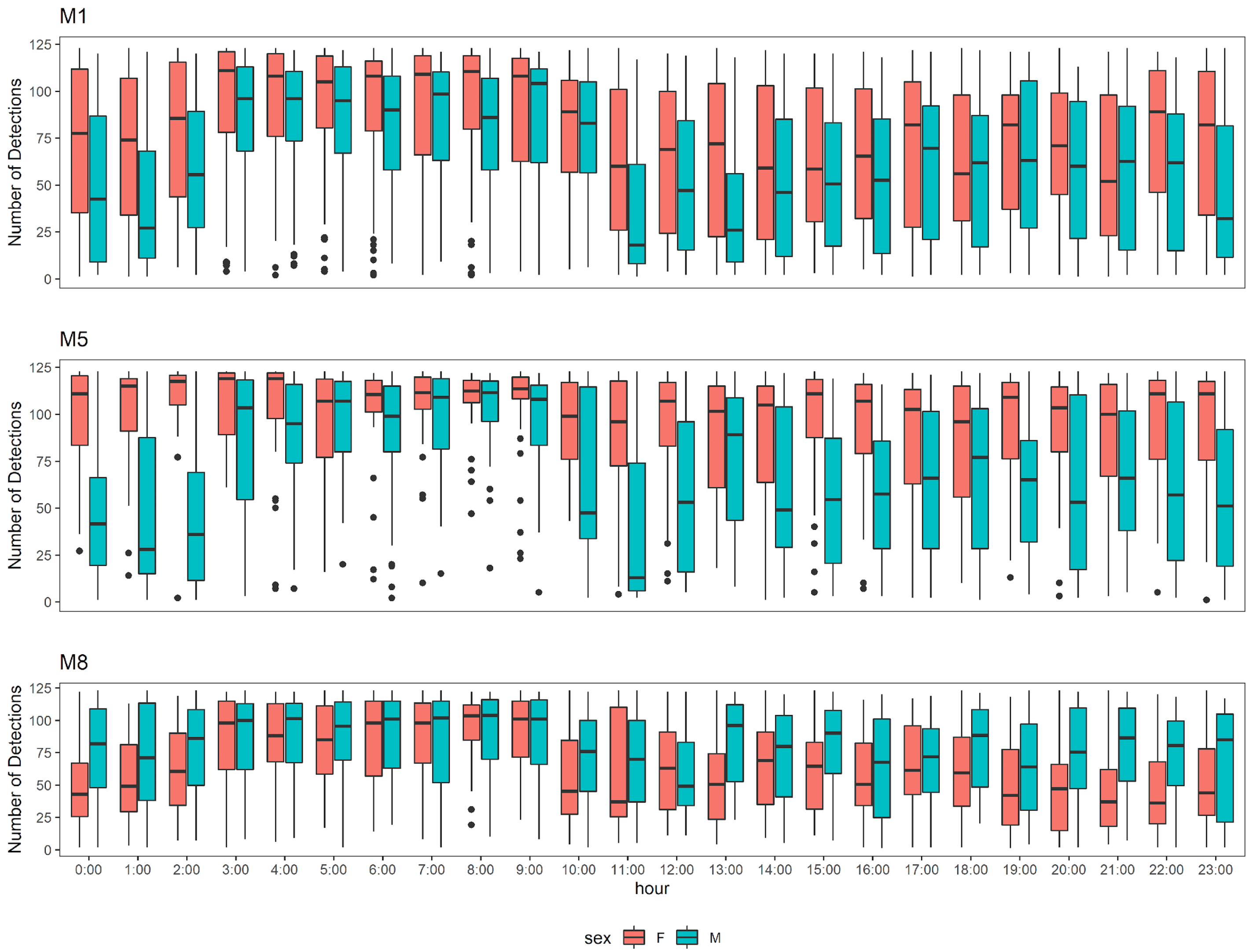


Figure F1. Number of detections of adult Common Terns per hour for nesting pairs that successfully fledged young at Interstate Island in 2019 (M1, M5, and M8).

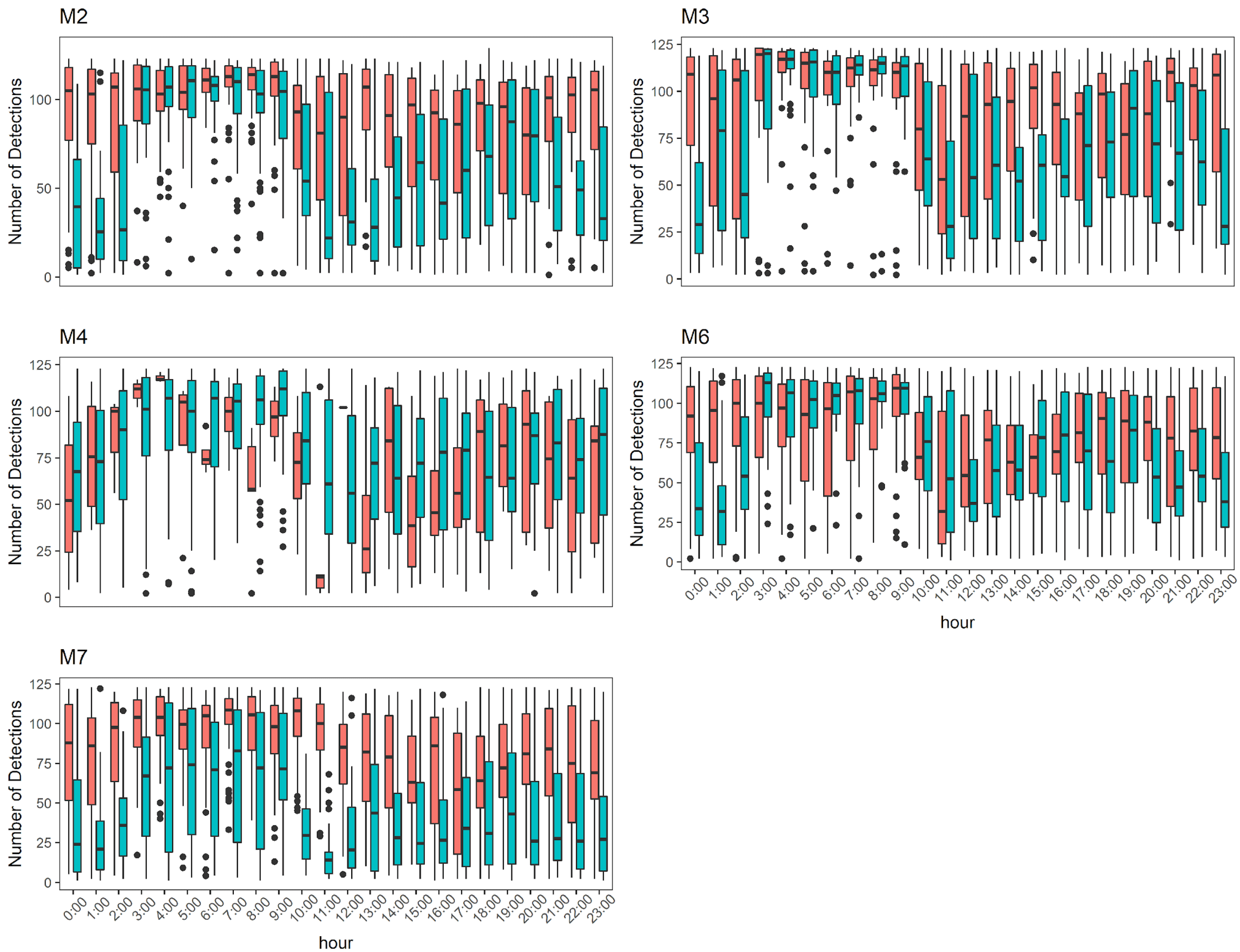


Figure F2. Number of detections of adult Common Terns per hour for nesting pairs that did not successfully fledged young at Interstate Island in 2019 (M2, M3, M4, M6, and M7).

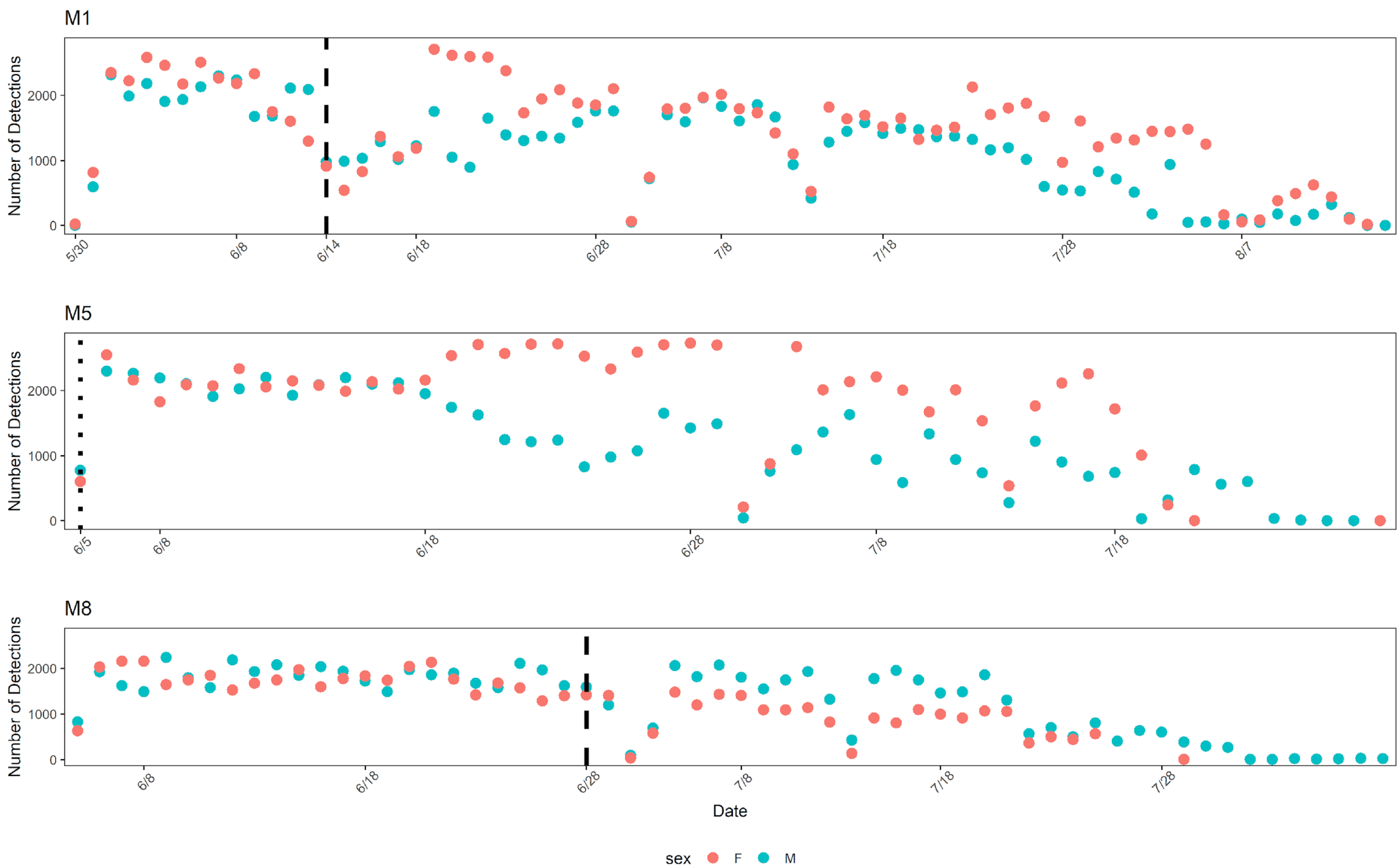


Figure F3. Number of daily detections for mated Common Terns that successfully hatched young in 2019 at Interstate Island (M1, M5, and M8). Hashed lines associated with M1 & M3 denote the date when young were first observed. The dotted line associated with M5 shows date of nest failure, but the pair successfully renested and hatched young.

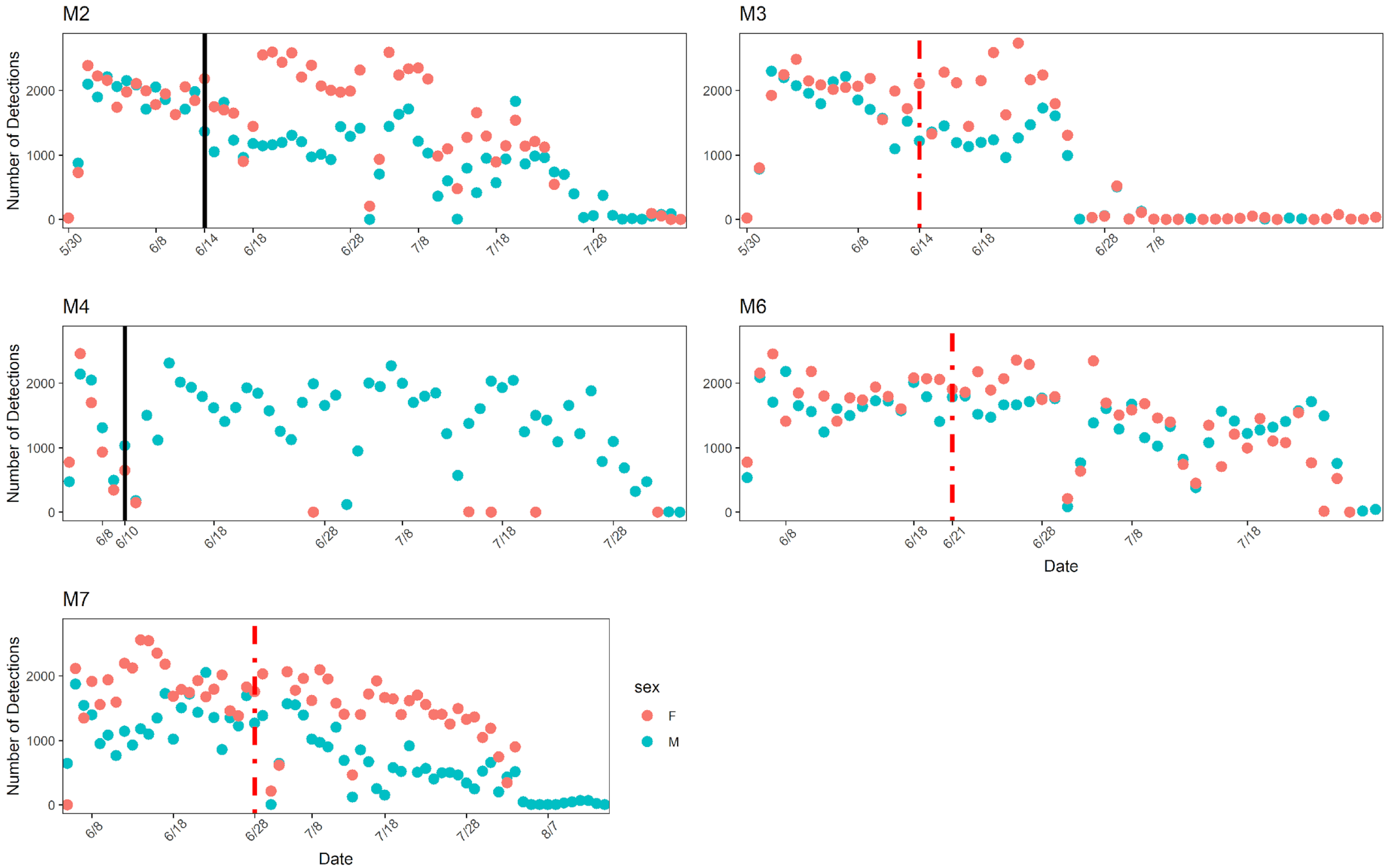


Figure F4. Number of daily detections for mated Common Terns that did not successfully fledge young in 2019 at Interstate Island (M2, M3, M4, M6, and M7). Solid lines associated with M2 & M4 denote the dates when nests failed. The red dot-dash lines associated with M3, M6, and M7 show dates when nests successfully hatched young but the chicks did not survive to fledge.