Ornithological Methods

Evaluating two avian monitoring tools for detecting relative abundance of species during autumn migration

Evaluando dos herramientas de monitoreo de aves para detector abundancia relativa de especies durante la migración de otoño.

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ABSTRACT. Detecting changes in abundance through time is important for understanding how factors like climate change or habitat conditions affect migrating populations and is limited by our ability to monitor them. We compared two widely used monitoring tools to determine whether they are comparable for detecting relative abundance of migratory birds. This study evaluated how flight calls detected by autonomous recording unit throughout the night compared to diurnal detections of birds captured via standard effort mist netting the following morning at three elevational sites in the Intermountain West. Across all species, mist netting performed better for characterizing species diversity. Among the 21 species detected at least once by both methods, increased detection of nocturnal flight calls was significantly ($p = 0.036$) but only moderately correlated ($r = 0.46$) with increases in mist-net captures the following day, demonstrating that the two methods are not adequately equivalent for tracking relative abundance. Each method has strengths as well as limitations, and the target species or project goal may dictate which monitoring method should be applied.

RESUMEN. Es importante detectar los cambios en la abundancia a través del tiempo para entender como los factores como cambio climático o condiciones del hábitat afectan las poblaciones migrantes y es limitada por nuestra habilidad de monitorearlos. Comparamos dos herramientas de monitoreo ampliamente utilizadas para detectar la abundancia relativa de aves migratorias y establecer si estas son comparables. Este estudio evaluó como las llamadas en vuelo detectadas por unidades de grabación automáticas a lo largo de la noche se comparan con detecciones diurnas de aves capturadas por medio de esfuerzos estándares de redes de niebla la mañana siguiente en tres sitios a diferentes elevaciones en el sistema inter-montañoso del Oeste. Incluyendo todas las especies las redes de niebla fueron más efectivas para caracterizar la diversidad de especies. Entre las 21 especies detectadas, al menos una vez por ambos métodos, el aumento en la detección de los llamados de vuelo nocturnos estuvo significativa ($p=0.036$), pero solo moderadamente correlacionada ($r = 0.46$) con incrementos en las capturas en redes de niebla al día siguiente, demostrando que los dos métodos no son adecuadamente equivalentes para rastrear la abundancia relativa. Cada método tiene sus fortalezas, así como sus limitaciones, y la especie focal o el objetivo del proyecto deben determinar el método de monitoreo que debe ser aplicado.

Key Words: *autonomous recording units; banding; fall; migration; mist net; mist netting; nocturnal flight calls; passive acoustic monitoring*

INTRODUCTION

Avian species migrate to exploit optimal environments for survival and reproduction (Dingle and Drake 2007). These changes in location occur biannually for most species during spring then autumn and are typically driven by seasonal environmental changes. Autumn migration is an evolutionarily critical portion of the annual cycle (Rappole 2013) but has received far less research attention than spring migration (Gallinat et al. 2015). Climate change adds complexity to understanding migration because of the shifting phenology of seasonal migratory patterns (Walther et al. 2002, Visser and Both 2005, Ellwood et al. 2015, Gallinat et al. 2015) as well as altered routes and stopover sites used by avian species (Cox 2010, Ellwood et al. 2015). Our ability to study populations that migrate is vital to our ability to effectively conserve populations.

Several methods are common for monitoring migrating populations and the goals of a study will best dictate which method may apply. A long-standing, well-practiced approach is using standard effort mist netting to capture and mark birds (Low 1957, Ralph and Dunn 2004), which is an effective tool for monitoring populations during autumn migration (Dunn et al. 1997, Benson et al. 2012). Unlike other monitoring tools, birds can be detected without reliance on vocalizations. Mist netting allows researchers to collect morphometric, demographic, and health data in addition to presence/absence information. While bird monitoring using mist nets is considered a safe practice, there is inherent risk associated with trapping and handling wildlife (Spotswood et al. 2012). Capturing birds is limited by the area nets cover, both by length and height, as well as net mesh size (Pardieck and Waide 1992). This limitation can skew or eliminate the ability to estimate population trends for species that spend significant amounts of time outside the reach of nets. Additionally, mist nets are more often set up in structured habitats (e.g., forest and riparian) than open habitats (e.g., grassland and desert) dictating the communities of birds available for capture.

Technological advances in recent decades have broadened our ability to study birds that migrate. An emerging approach to monitor migrating birds is bioacoustic monitoring using autonomous recording units (ARUs; reviews by Shonfield and Bayne 2017, Sugai et al. 2019, Pérez-Granados and Traba 2021).

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Many birds employ a nocturnal migration strategy (Libby 1899), making them especially difficult to study. Birds are typically far less vocal outside of the breeding season and, therefore, difficult to detect, even during stopover. Fortunately, many migratory passerines produce a species-specific flight call; this vocalization given during sustained flight can be recorded using ARUs. While flight calls are prevalent among songbirds, not all species produce them (La 2011). ARUs are programmable, non-invasive, and do not require the presence of researchers in the field to detect an individual. They also help fill in an important gap in our migration understanding since robust methods to monitor birds at night have only recently been introduced. ARUs come with challenges for estimating density or abundance, and distinguishing individuals is difficult (Pérez-Granados and Traba 2021). ARUs also collect vast data sets that require automated analysis of calls, a requisite that is still under development (Kahl et al. 2021).

Methods for monitoring animals are continually improving to maximize information from surveys while potentially minimizing time and cost. Studies have tested the performance of methods and evaluated a direct comparison between point counts and ARUs (Hutto and Stutzman 2009); point counts and line transects (Arizaga et al. 2011); point count and mist nets (Rappole et al. 1998, Blake and Loiselle 2001, Pagen et al. 2002, Wang and Finch 2002); ARU and Doppler radar density (Larkin et al. 2002, Farnsworth et al. 2004); ARUs and citizen science data (Bota et al. 2020), as well as ARUs and mist nets (Sanders and Mennill 2014). There are still considerable unanswered questions regarding direct comparisons between migration monitoring methods and to our knowledge, no studies have evaluated whether on-the-ground mist-netting captures at stopover sites during autumn migration is reflective of ARU flight call detections from the night prior.

Aside from the type of monitoring method used, other factors influence our ability to detect migrating birds. Habitat type, elevation, as well as the time of day/night can affect how a bird behaves (e.g., vocalizing and stopping over) which can influence detectability. Lower elevational river corridors and riparian habitat, especially in the arid west, are critical for migrating birds (Stevens et al. 1977, Delong et al. 2005, Skagen et al. 2005), but other montane habitats are important especially during autumn migration (Carlisle et al. 2004, 2005). High elevations have been shown to be important for migrating birds during the autumn season (Delong et al. 2005, Boyle and Martin 2015) and contain high-quality habitats for migrating birds (Evans Ogden et al. 2013). Additionally, the time of day and night can influence bird behavior, including frequency and reasoning for vocalization (La 2011). Studies have suggested nocturnal vocalizations play a role in selecting stopover habitat (Mukhin et al. 2008, Alessi et al. 2010), which may lead to increased call frequency as birds prepare to stopover.

The goal of this study was to evaluate how nocturnal flight call (NFC) detections from ARUs compare to standard mist-net captures on the ground the following morning during autumn migration. We examined eight years of monitoring data from banding stations and ARUs at three sites along an elevational gradient, and we compared mist-net captures to ARU detections across four different categories of twilight/night. We predicted a positive correlation between abundance estimates derived from ARU detections and mist-net captures (i.e., the magnitude of birds calling are comparable relative to the number stopping over and being captured in mist nets). We evaluated factors that might influence relative abundance relationships between detection methods including time relative to sunrise (i.e., twilight and night categories) as well as elevational changes (and, therefore, differences in habitat). We hypothesized that the twilight category just before daylight (i.e., civil twilight, 30–34 minutes before sunrise) would have the highest correlation due to an increase in vocalizations as birds prepare to rest and refuel. Additionally, we hypothesized that ARU detections at the lowest elevational site (i.e., riparian habitat) would be most predictive of mist-net captures on the ground the following morning due to the known critical importance of high-quality riparian corridors for refueling in migrant birds (Stevens et al. 1977, Delong et al. 2005, Skagen et al. 2005).

METHODS

Study sites
Mist nets and ARUs were set up on MPG Ranch (https://www.mpgranch.com/) outside Missoula, Montana, USA (46°40' N; 114°01' W) every autumn from 2013 through 2020. We collected data annually from the beginning of August through early-mid October at three sites of different elevations: low (967 m), mid (1154 m), and high (1694 m). Data were collected at all sites 2013–2015, then in 2016–2020 only at the low site. The low-elevation site is a riparian, floodplain forest comprised mainly of black cottonwood (*Populus balsamifera* ssp. *trichocarpa*), quaking aspen (*P. tremuloides*), ponderosa pine (*Pinus ponderosa*), willow (*Salix spp.*), rose (*Rosa spp.*), snowberry (*Symphoricarpos albus*), chokecherry (*Prunus virginiana*), red-osier dogwood (*Cornus stolonifera*), mountain alder (*Alnus incana*), Lewis's mock orange (*Philadelphus lewisii*), black hawthorn (*Crataegus douglasii*), and elderberry (*Sambucus cerulea*). The mid-elevation site is a seasonal creek draw containing quaking aspen, ponderosa pine, black hawthorn, serviceberry (*Amelanchier alnifolia*), and chokecherry. The high-elevation site contained primarily a coniferous mixed forest of western larch (*Larix occidentalis*), Douglas fir (*Psuedotsuga menzeisii*), and lodgepole pine (*P. contorta*) with an understory of mallow ninebark (*Physocarpus malvaceus*), rocky mountain maple *(Acer glabrum)*, birchleaf spirea (*Spiraea betulifolia*), and kinnikinnik (*Arctostaphylos uva-ursi*).

Mist-net captures
We captured birds using standard mist nets (12m long x 2.6m high, 30 mm mesh) at each of the three study sites. We operated mist nets an average of four days a week but ranged from two to five days a week depending on weather. We operated 10 nets at each site, with the exception of the mid-elevation site in 2013 where we only operated eight nets. During the sampling period, we opened nets 15 minutes before sunrise and closed them five hours later. Net locations were chosen based on vegetative structure and areas of concentrated bird movements to maximize efficient captures (Ralph et al. 1993). Net locations remained constant throughout the study period. Each captured bird was identified to species according to the Pyle Identification Guide to North American Birds (1997) and fitted with a U.S. Geological Survey aluminum leg band. We excluded non-migratory species and unidentified individuals from this comparative analysis.

Autonomous recording units

We deployed ARUs in the immediate vicinity of all three banding sites. ARUs consisted of a microphone connected to a passive recording unit (Song Meter SM2+; Wildlife Acoustics, Inc., Maynard, Massachusetts) attached to a post 4.5 meters above ground level. Each night from August through October units recorded 30 minutes before sunset to 30 minutes after sunrise at a sampling frequency of 22.05 kHz. From 2013 to 2015, we mounted omnidirectional microphones (SMX-II; Wildlife Acoustics, Inc., Maynard, MA, USA) with a built-in sensitivity of -32 to -40 dBV. Each microphone was installed at the center of a 30-cm² Plexiglas sound baffle to minimize the pickup of ground-based noise. In 2016, we began using directional microphones specifically designed for monitoring avian flight calls (Old Bird 21c; Old Bird, Ithaca, NY, USA). The microphone had a hypercardioid sensitivity pattern with acute directional sensitivity in the 2–10 kHz range in an inverted 60° cone expanding out from the direction it is aimed.

The ARUs stored nightly recordings as standard 16-bit resolution .wav PCM files. We imported the files into Vesper sound analysis software (version 0.4.10, H. Mills, Ithaca, NY, USA, https://github.com/HaroldMills/Vesper) and extracted flight calls from each recording using automated nocturnal flight call detectors (Old Bird, Ithaca, NY, USA). The "Tseep" detector extracted short bursts of high frequency calls (6–10 kHz), while the "Thrush" detector extracted longer duration, mid-frequency calls (2.8–5.0 kHz). We only included calls that occurred during the window of true night though twilight rise (dawn; Fig. 1). We used the Vesper platform to visually inspect each extracted clip, discard false positives or actual calls obscured by ambient noise, and then identify calls to the species level when possible. We only included accepted NFCs or calls indicative of migratory behavior. Species' NFCs that could not be differentiated from one another based on frequency and duration were grouped into accepted complexes (e.g., Evans and O'Brien 2002, Sanders and Mennill 2014, Evans 2021) for both detection methods (Appendix 1). Hereafter, we refer to these species' groups and individual species collectively as "species." We eliminated any calls from the same species within a 60-second window to calculate a minimum number of individuals passing (MIP) to avoid duplicating detections of the same individual (Evans and Mellinger 1999). In general, the use of vocal activity rate has been shown to have a significant relationship with estimating abundance for avian species (Pérez-Granados et al. 2019).

Most songbirds are nocturnal migrants and time of night can influence timing and frequency of vocalization. To investigate whether the relationship between time of night/twilight and the number of NFCs was correlated with capture data, we classified NFCs into four categories (Fig. 1) encompassing true night, astronomical (AT; sun is 18° below the horizon), nautical (NT; sun is 12° below the horizon), and civil (CT; sun is 6° below the horizon) twilight rise (dawn). The light categories used in this analysis (Fig. 1) change in length as the autumn season progresses. True night comprises the largest proportion of light categories (averaging ~81% or 7.5 hours) and has the largest shift throughout the season (minimum = 5.3 hours, maximum = 9.5 hours). Twilight categories are closest to sunrise and make up a smaller portion of the light categories (AT rise averages ~7% or 39 minutes; NT rise averages ~ 7% or 37 minutes; CT rise averages

~5.5% or 31 minutes) and have less variability (AT 35–49 minutes, NT 35–43 minutes; CT 30–34 minutes) throughout the autumn season. We excluded the time frame of twilight set in analysis based on studies that showed most birds take off about an hour after sunset (Bruderer 1994, Deppe et al. 2015) resulting in a lack of NFC detections during twilight set.

Fig. 1. Light categories used to determine correlation of birds caught during the day in mist nets and birds detected using autonomous recording units during true night and twilight rise (dawn) categories. Twilight set (dusk) categories were not used in comparative analysis. AT = Astronomical Twilight; NT = Nautical Twilight; CT = Civil Twilight. True night averages 7.5 hours and has the largest shift throughout the autumn season (August through October; ranges minimum = 5.3 hours to maximum = 9.5 hours). Twilight categories are closest to sunrise and make up a smaller portion of the light categories (AT rise averages 39 minutes; NT rise averages 37 minutes; CT rise averages or 31) and has less variability (AT 35–49 minutes, NT 35–43 minutes) throughout the season.
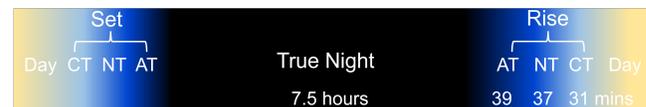
Statistical analysis

We compared data from mist nets and ARUs to evaluate consistency of detecting relative abundance of species in R (version 4.2.2; R Core Team 2020). We used total mist-net captures and total detections from ARUs of each species as proxies for relative abundance after adjusting for effort hours. ARU effort hours were calculated based on the number of hours an ARU was recording, beginning with the onset of night through civil twilight rise. We calculated mist-net effort from number of hours mist nets were open. We only examined data from dates with paired sampling sessions using both methods (i.e., ARUs operated during the evening before a mist-netting session). Standard mist-netting and ARU detection data were first logarithmically transformed for skewedness and then standardized by calculating a standard score for each species detected by both techniques to adjust for the scales of each method (Wang and Finch 2002). Linear regression analysis with standardized detection was performed for species detected by both techniques where the residuals were used as a measurement of the consistency between the two techniques. If the two techniques were consistent in estimating the relative abundance among species, points representing each species should fall on the regression line with zero deviation and have a perfect correlation ($r = 1$). We assigned mist-net detection as the dependent variable; a negative residual would indicate that mist netting resulted in a lower relative abundance measure than expected for a given species, while a positive residual indicates that mist nets provided a higher relative abundance estimate than expected.

We performed Pearson's correlations to compare all daily mist-net detections to the detections from the twilight/night before using detection data from each method corrected for effort hours per day (as described previously). For comparative analysis, we

Table 1. Overall number of detections using mist nets and autonomous recording units (ARU) during autumn migration at three different elevational (low, mid, high) sites. Data represents detections of species and species groups that were detected at least once by both methods across the entire study period (2013–2020). Data were collected using both methods at all three sites 2013 through 2015 and only at the low-elevation site 2016 through 2020.

Site	Light Category	Total ARU Detections	ARU Detections per Effort Hour	Total Mist-Net Detections	Mist-Net Detections per Effort Hour
Low		11,246	5.00	2748	2.39
	True Night	8012			
	Astronomical Twilight Rise	759			
	Nautical Twilight Rise	2309			
	Civil Twilight Rise	166			
Mid		1412	1.72	1006	2.33
	True Night	867			
	Astronomical Twilight Rise	79			
	Nautical Twilight Rise	430			
	Civil Twilight Rise	36			
High		933	1.27	527	1.28
	True Night	691			
	Astronomical Twilight Rise	65			
	Nautical Twilight Rise	168			
	Civil Twilight Rise	9			
Total		13,591	3.57	4,281	2.15

logarithmically transformed standard mist netting and ARU detection data and tested for correlations using all combinations of light and elevational site categories that included all ARU and mist-net detections from species that we detected at least once by each method. We partitioned the data by time period before (2013–2015) and after (2016–2020) due to equipment modifications in ARUs. We only collected data from the low-elevation site in 2016 through 2020, therefore, we analyzed each light category at the low-elevation site by these year groupings. Pearson's correlations were used to evaluate the annual means of daily species' relative abundance using data from species that were detected from ARUs and mist nets at least once for each year of the study. Additionally, we analyzed individual species with sufficient detections using both methods at the elevational and light category level using Pearson's correlations.

To determine if timing of passage detections were similar from mist-net data and ARUs, we followed Sanders and Mennill's (2014) approach and ranked all mist-net and acoustic detections by Julian date for each species. We then calculated the date at which 10%, 50%, and 90% of detections occurred for both mist-net and ARU detections, where we only included species that had at least five detections from both methods (Sanders and Mennill 2014). We calculated residuals of mist-net and acoustic of medial detection dates to a 1:1 line and then tested for correlation of the residuals and date.

RESULTS
We sampled a total of 250 nights/days using both methods, averaging 31 days each year over the course of this study. We detected 95 different migratory species by ARUs and mist nets (Appendix 1). We detected twelve species (12.6%) by ARUs that were never caught in mist nets and 62 species (65.3%) caught in mist nets that were never detected by ARUs. The 21 species (22.1 %) that we detected by both methods were all classified as migratory.

Detections varied by method, site, and light category (Table 1). Overall number of detections for species that were detected using both methods were highest in the low-elevation site, with 2748 mist-net detections and 11,246 ARU detections. Across both methods, detections decreased as elevation increased (Table 1). We collected data at the low-elevation site during all years of the study (2013–2020), and from 2013 through 2016 at the mid- and high-elevation sites. After adjusting for effort, the low-elevation site still resulted in more detections per effort hour than the higher elevations, with a more pronounced difference in the ARU detections at lower and higher sites (Table 1). Effort for all years of the study totaled 3805 hours for ARUs and 1994 hours for mist netting.

Species that we detected using both methods were moderately correlated (r = 0.460, SE = 0.204, p = 0.036) and the generalized linear model revealed little explanation for mist-net detections when compared with ARU detections from the night/twilight prior (R^2 = 0.210; Fig. 2). The two species with the value closest to one (Fig. 2) were the White-throated Sparrow (*Zonotrichia albicollis*) and the Chipping Sparrow (*Spizella passerina*), suggesting that the relative abundances of these species are estimated to be relatively equal between detection methods. For the other 19 species, mist nets underestimated expected relative abundance for eight species when compared with ARUs, while they were higher than expected for 11 species (Fig. 2). For the 21 species detected at least once using both methods, there was variation in the frequency of detection, time of year detected, and overall patterns between detection methods (Fig. 3).

All detections combined from ARUs and mist nets showed significant but weak evidence of correlation for the number of detections per day (Table 2; r = 0.276, SE = 0.031, p < 0.001). Within sites, the low-elevation floodplain site showed significant but weak support for comparable numbers of individuals detected by both methods (r = 0.287, SE = 0.037, p < 0.001), but there was no significant correlation for either the mid-elevation site (r =

Fig. 2. Relationship between species caught using mist nets and detected using autonomous recording units (ARU) during autumn migration from 2013–2020 in western Montana. Species that fall on the regression line (dashed line) with zero deviation have a perfect detection correlation (r = 1) for relative abundance.
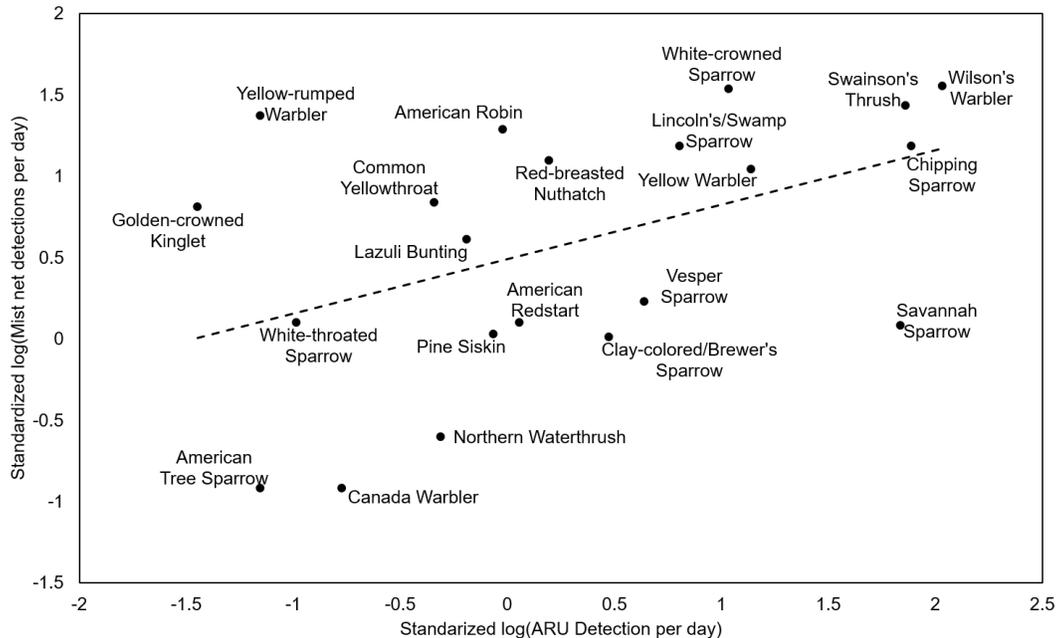
0.011, SE = 0.073, p = 0.883) nor the high-elevation site (r = 0.110, SE = 0.087, p = 0.209).

All significant correlations between site and light category were weak or moderate (Table 2). Only true night (r = 0.228, SE = 0.063, p < 0.001) and nautical twilight rise (r = 0.245, SE = 0.064, p < 0.001) resulted in any significant correlation among all sites. At the low-elevation site, true night and nautical twilight rise were the two categories with the highest number of ARU detections (Table 1). The low-elevation site had significant moderate correlation relationships with true night (r = 0.352, SE = 0.064, p < 0.001), nautical twilight rise (r = 0.237, SE = 0.068, p = 0.001), and civil twilight rise (r = 0.239, SE = 0.100, p = 0.019) light categories. There were no significant correlations with any light category at the two higher (mid and high) elevational sites.

Because we updated ARU methods beginning in 2016, we partitioned the data into two time periods (2013-2015 and 2016–2020). We analyzed each light category at the low-elevation site by time period. We found a significant relationship with detections between methods in all light categories when we used the earlier low-elevation dataset (2013–2015). True night had the strongest correlation (r = 0.497, SE = 0.102, p < 0.001), astronomical twilight rise (r = 0.368, SE = 0.149, p = 0.018), nautical twilight rise (r = 0.408, SE = 0.114, p = 0.001), and civil twilight rise (r = 0.427, SE = 0.185, p = 0.029) all had significant moderate correlations. The 2016–2020 time period only showed weak correlation with true night (r = 0.199, SE = 0.083, p = 0.017), negative weak correlation with astronomical twilight rise (r = -0.191, SE = 0.095, p = 0.046), and was not significantly correlated with the other light categories (Table 2).

We tested correlation for each of the 21 species with elevation and light categories. Only 16 species had enough detections to yield results, none of which had any significant correlation. Annual means of daily species relative abundance resulted in a strong relationship for 2015 (r = 0.529, SE = 0.140, p = 0.001) and a moderate relationship for 2018 (r = 0.405, SE = 0.159, p = 0.016). No other years showed any significant relationship (Table 3).

Analysis from seasonal timing of migration yielded no significant results. The 10th (r = -0.130, SE = 0.265, p = 0.631), 50th (r = 0.745, SE = 0.027, p = 0.745), and 90th (r = -0.204, SE = 0.262, p = 0.448) percentiles showed no relationship with the mist net and ARU data on the timing of passage.

DISCUSSION
This study evaluated whether a relationship between relative abundance estimated by NFC detections from ARUs and mist-net captures exists at a local scale. If data from ARUs and mist nets in our study revealed that NFC rates correspond to numbers of birds captured the next day, we could replace mist-netting with ARUs as an automated and less field intensive method of monitoring change in migrating populations. The potential to move toward automated technology to monitor migration seems both more efficient and modernized, however, our study demonstrates that even though there is a significant relationship (p = 0.036), there is not a statistically strong (r = 0.46) enough relationship to support substitution of one method with the other. While each of these methods have a place in research, nocturnal acoustic recordings are largely not reflective of on-the-ground mist-net captures.

Fig. 3. Twenty-one species detected at least once using mist nets and autonomous recording units (ARU) during autumn migration from 2013–2020 in western Montana. Detections were standardized on a log scale and adjusted for effort hour by method type. Shaded ribbons represent standard error. Data ranges from August 9 (Julian date = 221) to October 10 (Julian date = 284).
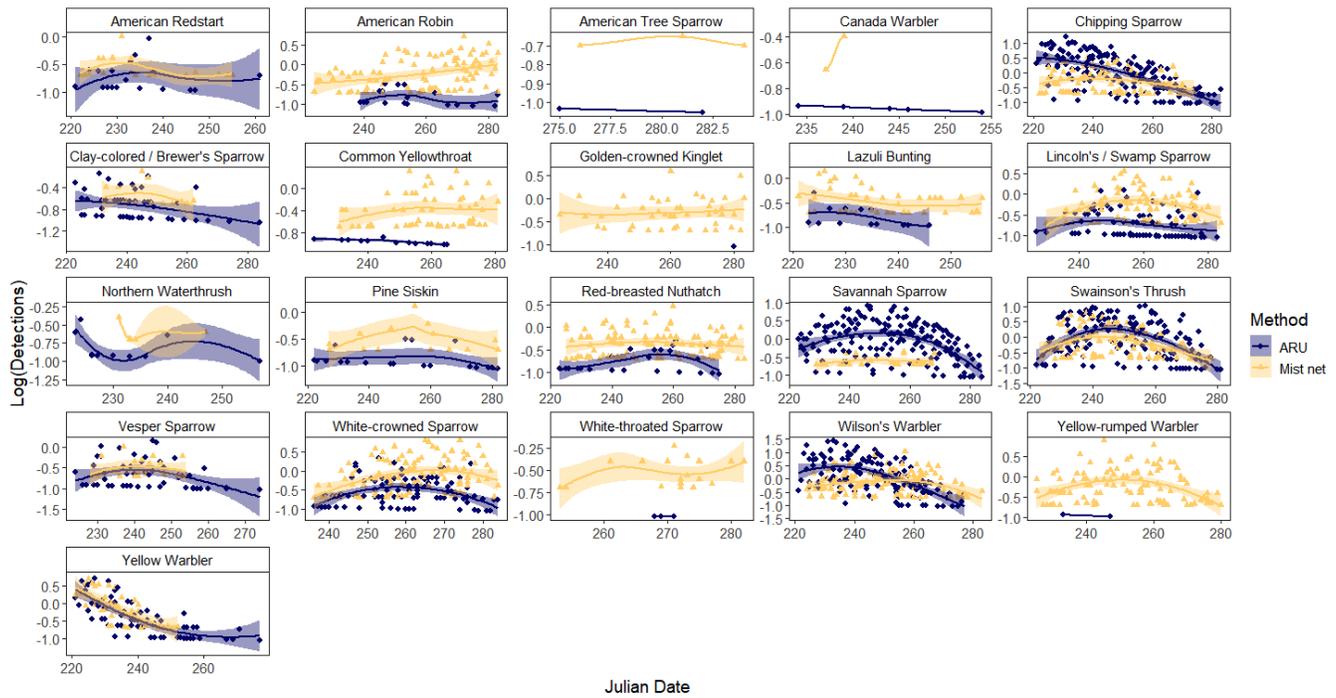
While this study paired mist nets and ARUs at small-scale locations, the option to implement microphone arrays across a landscape may increase the scope of ability to estimate bird abundance as well as bird densities (Pérez-Granados and Traba 2021). Automation of ARU data analysis is rapidly developing and machine learning allows for more accurate identification and streamlined analyses (Blumstein et al. 2011). And while ARUs have been used extensively to sample birds and other vocal animals, analytical and inferential limitations make quantifying birds difficult. More recently, researchers have successfully estimated distances to birds from ARU recordings to improve and standardize detection (Darras et al. 2018; Yip et al. 2020). As such, efforts to reliably estimate migrant numbers would profoundly improve the utility of bioacoustic migration monitoring (Bota et al. 2020).

Bird species detected by ARUs but never captured in mist nets represent 13% of species detected over the course of this study and include a diverse mix of rare species (e.g., Chestnut-sided Warbler (*Setophaga pensylvanica*)), secretive grassland species (e.g., Grasshopper Sparrow (*Ammodramus savannarum*), Upland Sandpiper (*Bartramia longicauda*)), and several waterbirds (e.g., Solitary Sandpiper (*Tringa solitaria*), Sora (*Porzana Carolina*), Virginia Rail (*Rallus limicola*); Appendix 1). Many of these species avoid the vegetation often associated with where mist nets are deployed, occur in open-water habitats, or migrate large distances in one flight and thus would avoid or pass by most mist-net stations. It may be that ARUs help detect species that are otherwise difficult to monitor - especially during migration. Further research could be undertaken to compare ARU

detections to various types of observational data. We suggest focusing on areas where observational data for migration are typically not available, particularly where stopover habitat is understudied or in areas that are difficult to access (e.g., deserts, large water bodies, high-altitude mountains).

In comparison, roughly 65% of species in our study were caught in mist nets and never detected by ARUs. Those species include flycatchers, wrens, hummingbirds, finches, vireos, woodpeckers, kinglets, and others (Appendix 1). We know that some species either migrate during the day or do not emit nocturnal flight calls, so mist nets can provide information on some species where ARUs cannot. At the local scale, mist netting provides a much more direct picture of migratory species using an area because birds are captured at the physical location they are using, whereas detections from ARUs could be individuals either passing over or preparing to use an area. For this study, we only included ARU detections from night through civil twilight rise to evaluate detections of NFCs from migratory species, but ARUs are capable of recording through all times of the day and could provide insight into additional species that are emitting diurnal calls or songs.

Relatively few of the 21 species were detected on more corresponding days/nights by both methods, than the numbers of days or nights by one method alone (Appendix 2). Only five species (Wilson's Warbler (*Cardellina pusilla*), Swainson's Thrush (*Catharus ustulatus*), White-crowned Sparrow (*Z. leucophrys*), Lincoln's / Swamp Sparrow (*Melospiza lincolnii /M. georgiana*), and Yellow Warbler (*S. petechia*)) had significantly higher number of paired days/nights where they were detected by both methods

Table 2. Pearson correlation test results for detections using mist nets and autonomous recording units (ARU) during autumn migration at three different elevational (low, mid, high) sites. Data represents detections of species and species groups that were detected at least once by both methods across the entire study period (2013–2020). Data were collected using both methods at all three sites 2013 through 2015 and only at the low-elevation site 2016 through 2020. Light categories were for when a bird was detected from an ARU unit based on the time of twilight rise (dawn) or night. Asterisk denotes significant p-value where r value shows at least moderate correlation (≥ 0.3).

Site	Light Category	r	SE	p-value	
All	All	0.276	0.031	<0.001	
Low	All	0.287	0.037	<0.001	
Mid	All	0.011	0.073	0.883	
High	All	0.110	0.087	0.209	
All	True Night	0.228	0.063	<0.001	
	Astronomical Twilight Rise	-0.075	0.076	0.325	
	Nautical Twilight Rise	0.245	0.064	<0.001	
	Civil Twilight Rise	0.150	0.094	0.112	
Low	True Night	0.352	0.064	<0.001	*
	2013-2015	0.497	0.102	<0.001	*
	2016-2020	0.199	0.083	0.017	
Low	Astronomical Twilight Rise	0.001	0.082	0.999	
	2013-2015	0.368	0.149	0.018	*
	2016-2020	-0.191	0.095	0.046	
Low	Nautical Twilight Rise	0.237	0.068	0.001	
	2013-2015	0.408	0.114	0.001	*
	2016-2020	0.125	0.084	0.141	
Low	Civil Twilight Rise	0.239	0.100	0.019	
	2013-2015	0.427	0.185	0.029	*
	2016-2020	0.132	0.120	0.277	
Mid	True Night	-0.025	0.121	0.839	
	Astronomical Twilight Rise	-0.109	0.176	0.540	
	Nautical Twilight Rise	0.158	0.127	0.220	
	Civil Twilight Rise	-0.026	0.224	0.908	
High	True Night	0.230	0.130	0.083	
	Astronomical Twilight Rise	-0.147	0.240	0.548	
	Nautical Twilight Rise	-0.012	0.151	0.938	
	Civil Twilight Rise	-	-	-	

Table 3. Pearson correlation test results for annual means of daily species abundance using mist nets and autonomous recording unit detections during autumn migration. Data represents detections of species and species groups that were detected at least once by both methods across the entire study period (2013–2020). Asterisk denotes significant p-value where r value shows at least moderate correlation (≥ 0.3).

Year	r	SE	p-value	
2013	0.217	0.213	0.320	
2014	0.140	0.161	0.390	
2015	0.529	0.140	0.001	*
2016	0.248	0.180	0.179	
2017	0.129	0.207	0.538	
2018	0.405	0.159	0.016	*
2019	0.032	0.186	0.866	
2020	0.338	0.192	0.092	

than on a day or night by a single method. The American Redstart (*S. ruticilla*) is the only species where the number of days/nights it was detected by both methods was roughly equal to the number of days or nights in which it was only detected by one method (Appendix 2). Seven species were more frequently detected only by ARUs, including the Chipping Sparrow and Savannah Sparrow (*Passerculus sandwichensis*) which were never detected

by mist nets without an ARU detection from the night prior. The final eight species were detected many more days by mist nets than nights detected by ARUs, except for the American Tree Sparrow (*Spizelloides arborea*) that was never detected both methods on a paired day/night and only detected separately on two nights by ARUs and three days by mist nets (Appendix 2).

The 21 species detected by both methods varied in the frequency of detection, time of year detected, and overall patterns between detection methods (Fig. 3). Many of the species appear to have similar detection patterns between the methods, however the estimated relative abundance relationships between methods are greatly influenced by time of year and number of detections. Several species (e.g., Swainson's Thrush, White-crowned Sparrow, Northern Waterthrush (*Parkesia noveboracensis*), American Redstart) did not have perfect correlative relative abundance estimates between the methods (Fig. 2) but exhibited similar overall patterns in phenology (Fig. 3). The Vesper Sparrow (*Pooecetes gramineus*) and Yellow Warbler have almost identical patterns for detections by both methods (Fig. 3), however, it is only maintained for part of the migratory season. The Clay-colored / Brewer's Sparrow (*S. pallida/S. breweri*) group shows a similar timing pattern as well. We detected these three species via ARUs throughout the season but only captured them in mist nets at the beginning of migration. This finding may suggest that late in the season, these species are passing by but not stopping at our sites. The Lazuli Bunting (*Passerina amoena*) displays the opposite

pattern where this species is being detected by mist nets throughout the season but are only being detected by ARUs at the beginning of migration. The Chipping Sparrow exhibited the highest correlation for estimated relative abundance (Fig. 2) and shows an overall similar detection pattern throughout the season between methods (Fig. 3). Although there were many nights where the Chipping Sparrow was only detected by ARUs, there were almost equal number of days/nights where we detected them by both methods (Appendix 2). The White-throated Sparrow also fell close to the line for high correlation of estimated relative abundance (Fig. 2) but exhibits a much different pattern. There were relatively few overall detections of the White-throated Sparrow (Fig. 3), most of which were from mist nets and was only detected on two paired day/night from both methods (Appendix 2).

When considering species detections across elevations, detections between methods varied significantly (Table 1). Across elevations, the detections from the low-elevation floodplain site seem to drive the overall patterns at all sites within species. This finding reinforces the importance of riparian areas during migration in the Intermountain West. At our mid- and high-elevation sites, Golden-crowned Kinglet (*Regulus satrapa*) and Red-breasted Nuthatch (*Sitta canadensis*) were both detected exclusively by mist nets. These species do occur year-round at these locations, and resident birds could be what was captured. Additionally, mist nets provided the only detections of the Yellow-rumped Warbler (*S. coronata*) at the high-elevation site and the White-throated Sparrow at the mid-elevation site. The Red-breasted Nuthatch is the only one of these four species we detected at the low-elevation site using ARUs, suggesting the other three species might be residents or they not emit an NFC frequently enough to be detected since they are detected in mist nets at all elevational sites. The Yellow Warbler and Savannah Sparrow are both only detected at the mid- and high-elevation sites via ARUs, suggesting that these species (a riparian and grassland species) may just pass over but not land at higher elevations.

Our ability to detect a bird using either method depends largely on the location or the time of day. This study showed that the number of birds being captured in mist nets is somewhat comparable to those being detected via ARUs at our low-elevation site throughout the night and twilight categories, particularly in the beginning of our study (2013–2015). Similar frequency of detection from both methods may be due to birds flying and calling at a lower elevation as they prepare to rest and refuel. Nautical and civil twilight rise categories showed the highest correlation for mist nets and ARU detections at low-elevation site for the twilight categories (Table 2), but less so when compared to true night. This could be because birds are beginning to land or are already on the ground as daylight approaches and no longer emitting NFCs.

With constantly improving technological advances, we opted to adapt our ARU equipment in 2016 which resulted in enhanced NFC detection performance. After accounting for effort, the number of detections per hour at a single site between 2016 and 2020 far outnumbered the detections per hour from all three sites in 2013–2015. This speaks to the importance of the equipment and the quality and quantity of the data it will yield. Omnidirectional microphones are used in the majority of ARUs

studies currently published (Pérez-Granados and Traba 2021), though when we switched to the OldBird 21c directional microphone in 2016, we found we had a richer data set and enhanced ability to detect NFCs. However, the more sensitive directional microphone likely captured migrants flying higher and/or farther away from the site where mist-netting took place, and potentially led to overall reduced correlation which may have important implications for comparative studies.

This study evaluated several factors that failed to explain a relationship between relative abundances estimated from ARU and mist-net data. First, there were no significant correlations at the two higher elevational sites, which could be attributed to a few reasons. Birds may preferentially be using lower elevations, resource-rich habitats over higher elevational areas when they land during migration. Additionally, the higher elevational sites we sampled during the first three years of the study yielded lower detection rates. Second, the majority of the years in this study showed no significant correlation in daily species abundance (Table 3). Seasonal means were expected to explain variation that could be due to annual changes in factors that might affect calling rate and stopover probabilities, but we did not observe that pattern. Third, in contrast to what Sanders and Mennill (2014) found around the Great Lakes region, we did not find a correlation in the timing of passage for the 21 species detected by both methods.

ARU and mist-netting methodologies both provide vital information about bird migration. Depending on the study objectives, one method may be better suited to answer particular research questions than the other. For example, a study designed to understand habitat selection, local stopover use, population migration monitoring, or refueling rates of birds would best be served by a mist-netting study. If a study is designed to investigate broad-scale movement patterns, detect elusive or rare species, collect data at remote field sites, sample species that exist in habitats where mist netting is not typically done, or study a species known to vocalize at high rates during migration, then ARUs would likely outperform mist netting. Finally, Gyekis et al. (2019) reiterates that the use of diurnal data alone without incorporating night flight calls may not accurately represent migratory phenology. Although not always financially or logistically feasible to run concordant monitoring programs, reducing overall effort on either method could allow for both practices to be implemented resulting in a more informative study of migration.

Data Availability:

The data/code that support the findings of this study are openly available in github at https://github.com/maggierblake/ARU_Mistnet.git. This research was conducted in compliance with the Guidelines to the Use of Wild Birds in Research and under the University of Montana Institutional Animal Care and Use Committee protocol #010-20EGDBS and United States Geological Survey Banding Permit # 23206.

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Appendix 1. All migratory species and grouping of species detected through mist netting (net) and autonomous recording units (ARU) from autumn migration 2013 through 2020. Some species could not be differentiated from one another from their nocturnal flight call; therefore were grouped those species into complexes (i.e., Group below) for both detection methods.

Group	Method of Detection	Common Name	Scientific Name
	Net	Alder Flycatcher	*Empidonax alnorum*
	ARU	American Coot	*Fulica americana*
	Net	American Goldfinch	*Spinus tristis*
	Net	American Kestrel	*Falco sparverius*
	ARU	American Pipit	*Anthus rubescens*
	Both	American Redstart	*Setophaga ruticilla*
	Both	American Robin	*Turdus migratorius*
	Both	American Tree Sparrow	*Spizelloides arborea*
	Net	Black-chinned Hummingbird	*Archilochus alexandri*
	Net	Black-headed Grosbeak	*Pheucticus melanocephalus*
	Net	Blackpoll Warbler	*Setophaga striata*
	Net	Blue-headed Vireo	*Vireo solitarius*
1	Both	Brewer's Sparrow	*Spizella breweri*
	Net	Brown Creeper	*Certhia americana*
	Net	Brown Thrasher	*Toxostoma rufum*
	Net	Brown-headed Cowbird	*Molothrus ater*
	Net	Bullock's Oriole	*Icterus bullockii*
	Net	Calliope Hummingbird	*Selasphorus calliope*
	Both	Canada Warbler	*Cardellina canadensis*
	Net	Cassin's Finch	*Haemorhous cassinii*
	Net	Cassin's Vireo	*Vireo cassinii*
	Net	Cedar Waxwing	*Bombycilla cedrorum*
	ARU	Chestnut-sided Warbler	*Setophaga pensylvanica*
	Both	Chipping Sparrow	*Spizella passerine*
1	Both	Clay-colored Sparrow	*Spizella pallida*
	Both	Common Yellowthroat	*Geothlypis trichas*
	Net	Cooper's Hawk	*Accipiter cooperii*
	Net	Dark-eyed Junco	*Junco hyemalis*
	Net	Dusky Flycatcher	*Empidonax oberholseri*
	Net	Eastern Kingbird	*Tyrannus tyrannus*
	Net	European Starling	*Sturnus vulgaris*
	Net	Evening Grosbeak	*Coccothraustes vespertinus*
	Net	Flammulated Owl	*Psiloscops flammeolus*
	Net	Fox Sparrow	*Passerella iliaca*
	Both	Golden-crowned Kinglet	*Regulus satrapa*
	ARU	Grasshopper Sparrow	*Ammodramus savannarum*
	Net	Gray Catbird	*Dumetella carolinensis*
2	ARU	Greater Yellowlegs	*Tringa melanoleuca*

	Net	Hammond's Flycatcher	*Empidonax hammondii*
	Net	Hermit Thrush	*Catharus guttatus*
	ARU	Horned Lark	*Eremophila alpestris*
	Net	House Wren	*Troglodytes aedon*
	Both	Lazuli Bunting	*Passerina amoena*
	Net	Least Flycatcher	*Empidonax minimus*
	ARU	Least Sandpiper	*Calidris minutilla*
	Net	Lesser Goldfinch	*Spinus psaltria*
2	ARU	Lesser Yellowlegs	*Tringa flavipes*
	Net	Lewis's Woodpecker	*Melanerpes lewis*
3	Both	Lincoln's Sparrow	*Melospiza lincolnii*
	Net	MacGillivray's Warbler	*Geothlypis tolmiei*
	Net	Marsh Wren	*Cistothorus palustris*
	Net	Mountain Bluebird	*Sialia currucoides*
	Net	Mourning Dove	*Zenaida macroura*
	Net	Nashville Warbler	*Oreothlypis ruficapilla*
	Net	Northern Flicker	*Colaptes auratus*
	Net	Northern Saw-whet Owl	*Aegolius acadicus*
	Both	Northern Waterthrush	*Parkesia noveboracensis*
	Net	Orange-crowned Warbler	*Oreothlypis celata*
	Net	Ovenbird	*Seiurus aurocapilla*
	Net	Pacific Wren	*Troglodytes pacificus*
	Net	Pacific-slope Flycatcher	*Empidonax difficilis*
	Both	Pine Siskin	*Spinus pinus*
	Net	Red Crossbill	*Loxia curvirostra*
	Both	Red-breasted Nuthatch	*Sitta canadensis*
	Net	Red-eyed Vireo	*Vireo olivaceus*
	Net	Red-naped Sapsucker	*Sphyrapicus nuchalis*
	Net	Rock Wren	*Salpinctes obsoletus*
	Net	Ruby-crowned Kinglet	*Regulus calendula*
	Net	Rufous Hummingbird	*Selasphorus rufus*
	Both	Savannah Sparrow	*Passerculus sandwichensis*
	Net	Sharp-shinned Hawk	*Accipiter striatus*
4	ARU	Solitary Sandpiper	*Tringa solitaria*
	Net	Song Sparrow	*Melospiza melodia*
	ARU	Sora	*Porzana Carolina*
4	ARU	Spotted Sandpiper	*Actitis macularius*
	Net	Spotted Towhee	*Pipilo maculatus*
	Both	Swainson's Thrush	*Catharus ustulatus*
3	Both	Swamp Sparrow	*Melospiza georgiana*
	Net	Tennessee Warbler	*Leiothlypis peregrina*
	Net	Townsend's Solitaire	*Myadestes townsendi*
	Net	Townsend's Warbler	*Setophaga townsendi*

ARU	Upland Sandpiper	*Bartramia longicauda*
Net	Veery	*Catharus fuscescens*
Both	Vesper Sparrow	*Pooecetes gramineus*
ARU	Virginia Rail	*Rallus limicola*
Net	Warbling Vireo	*Vireo gilvus*
Net	Western Palm Warbler	*Setophaga palmarum palmarum*
Net	Western Screech-Owl	*Megascops kennicottii*
Net	Western Tanager	*Piranga ludoviciana*
Net	Western Wood-Pewee	*Contopus sordidulus*
Net	White-breasted Nuthatch	*Sitta carolinensis*
Both	White-crowned Sparrow	*Zonotrichia leucophrys*
Both	White-throated Sparrow	*Zonotrichia albicollis*
Net	Williamson's Sapsucker	*Sphyrapicus thyroideus*
Net	Willow Flycatcher	*Empidonax traillii*
ARU	Wilson's Snipe	*Gallinago delicata*
Both	Wilson's Warbler	*Cardellina pusilla*
Both	Yellow Warbler	*Setophaga petechia*
Both	Yellow-rumped Warbler	*Setophaga coronata*

Appendix 2. All species and species groups detected by both mist net and autonomous recording units (ARU) at least once from autumn migration 2013 through 2020 in western Montana. Below are the total number of nights that a species was detected using ARUs; the number of nights that a species was detected only by ARUs and not by mist nets the following morning; the total number of days a species was detected using mist nets; the number of days a species was detected using only mist nets and not by ARUs the night before; and the number of paired nights/days that a species was detected by both methods.

Species	ARU	Only ARU	Mist net	Only Mist net	Both
American Redstart	23	11	23	11	12
American Robin	21	0	130	109	21
American Tree Sparrow	2	2	3	3	0
Canada Warbler	5	4	2	1	1
Clay-colored / Brewer's Sparrow	58	46	17	5	12
Chipping Sparrow	210	108	102	0	102
Common Yellowthroat	14	5	76	67	9
Golden-crowned Kinglet	1	0	44	43	1
Lazuli Bunting	14	1	55	42	13
Lincoln's / Swamp Sparrow	106	20	112	26	86
Northern Waterthrush	12	11	6	5	1
Pine Siskin	21	18	15	12	3
Red-breasted Nuthatch	27	5	106	84	22
Savannah Sparrow	227	203	24	0	24
Swainson's Thrush	199	72	130	3	127
Vesper Sparrow	72	51	24	3	21
White-crowned Sparrow	118	12	138	32	106
Wilson's Warbler	182	41	158	17	141
White-throated Sparrow	3	1	23	21	2
Yellow Warbler	97	40	63	6	57
Yellow-rumped Warbler	2	0	110	108	2