A STUDY OF THE GEOLOCATOR ATTACHMENT EFFECTS AND MIGRATION TIMING OF LOUISIANA WATERTHRUSHES AND WORM-EATING WARBLERS

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ABSTRACT

As migratory bird tracking technologies advance, we can now follow movements of birds throughout a full-annual cycle. These breakthroughs are revealing information that was previously unknown for many species. Using light-level geolocators, my study follows Louisiana Waterthrushes and Worm-eating Warblers from four populations, from 2016 to 2019. The purpose of my research was to examine the potential effects geolocators have on body condition and survival, as well as to describe the migratory speed and duration of the populations. My results suggested that tracking Louisiana Waterthrushes and Worm-eating Warblers with light-level geolocators or other small markers weighing 0.5 g, using proper attachment methods, can be accomplished without deleterious impacts on the condition and survival of the birds, and the data revealed the birds employed a time-minimizing strategy during migration. Lastly, there was a cultural component of the project that connected communities on each end of Neotropical migration through an educational program.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BBL, Bird Banding Laboratory

GPS, Global Positioning System

HU, Harding University

PBA, Petén Birders Association

TRGT, Tennessee River Gorge Trust

TWRA, Tennessee Wildlife Resources Agency

USGS, United States Geological Survey

UT, University of Toledo

UTC, University of Tennessee Chattanooga

CHAPTER I

INTRODUCTION

Background

Nearly half of the bird species on Earth embark on seasonal movements between breeding and nonbreeding territories, better known as migration. This energetically demanding and risky behavior allows individuals to escape harsh environmental conditions or exploit more favorable conditions elsewhere (Moore et al. 1995). In the Western Hemisphere, species that migrate from South and Central America, Mexico, and the Caribbean to the United States and Canada are known as Neotropical migrants. These Neotropical migrants breed in their northern territories over the spring and summer, then return to their southern wintering grounds in the fall. Therefore, these migratory populations are only present in their seasonal territories for less than half of the year, with the remainder being spent in migration or on their nonbreeding areas. This exodus and absence create an enigma surrounding each local population of migrants. Researchers, conservationists, and wildlife enthusiasts have pondered over and investigated where these migratory birds travel for centuries. From identification markers (e.g., leg bands) to tracking technologies, we are still attempting to answer many questions regarding bird migration.

In order to achieve a comprehensive understanding of the life history of migratory birds, we must understand both the geographic places they inhabit throughout the year as well as the timing (i.e., migration length, duration, and time of year) associated with these distinct geographic spaces and pathways. The timing of migration is a critical component of a migrant's full annual life cycle and can provide valuable information for the conservation of migratory birds. Through the aforementioned technologies (e.g., geolocators, GPS tracking technology, stable isotope analysis), scientists can infer where local populations of migratory birds travel seasonally and when they do so.

A migration, especially an intercontinental migration such as the ones performed by many land birds, is dangerous and energetically costly. Although there are always exceptions and permutations, avian migratory strategies pertaining to energy output and time spent in migration can be generalized into two groups: energy maximizers and time minimizers (Lindstrom and Alerstam 1992). Although there is no distinct line that separates these two groups, species can be broadly associated with one of the two. By using migratory data, such as those from geolocator studies, we can infer which type of migratory strategy a species or local population employs.

Awareness of species' migratory strategies is critical in understanding population dynamics and to inform appropriate conservation action. For instance, birds that employ a relatively fast-paced migration subsequently use minimal stopover sites and spend only short durations at these sites. Therefore, it may be particularly important that these few stopover sites have available resources. Stopover sites with insufficient habitat could theoretically cause the individual to spend more time at the site, eventually altering the migratory strategy employed by lengthening time spent in migration. If an individual spends the same amount of time at a stopover site regardless of habitat quality, insufficient habitat could cause the individual to not refuel enough to meet its energetic demands, ultimately continuing on the migration with inadequate energy reserves. These examples demonstrate the importance of understanding the migratory behavior of bird species. With information on migratory timing, conservation action along the migratory pathways can be better informed in order to prioritize efforts.

Quality habitat also plays a vital role in migratory strategies. Having habitat that allows for the buildup of excessive fat reserves is essential to the success of a seasonal migration. These fat reserves provide the energy required for migration, and often also provide a margin of safety in case the birds' stopover sites do not hold sufficient food supplies or if an unexpected delay occurs (e.g., headwind, major storm) (Newton 2006). For individuals that partake in an exceptionally fast migration (i.e., time minimizer), obtaining adequate fat reserves prior to departure or along the few stopover locations can make or break the journey. A case can be made that time minimizing species, in particular, require especially energetically productive breeding and nonbreeding habitats in the fall and spring in order to build up the appropriate levels of fat reserves.

Migratory connectivity refers to connecting local populations with the distinct geographic areas they reside in during each stage of their life cycle. From species-level observations, we have a relatively comprehensive understanding of the migratory connectivity of each Neotropical migratory species. However, there are many voids in our understanding of where these birds migrate to from the perspective of local populations. The tasks of connecting a specific local population or individual bird with its corresponding seasonal grounds or uncovering their migratory pathways are arduous undertakings. Difficulties arise when tracking individuals over long distances, such as technological restraints, time and resource limitations, and the unpredictable nature of marking and recapturing animals. Marking individuals with identification tags, tracking technologies, or stable isotope analysis have proven to be the primary means in which researchers gather this type of migratory connectivity information.

Due to extensive efforts and integrated reporting, bird banding data have played a large role in providing information on migratory connectivity of bird species. Bird banding refers to the practice of attaching aluminum leg bands with unique identification information to individual birds, and the information is entered into a collective database. Whenever a researcher recaptures a banded bird, that information is also entered into the database. Recapture data is useful for many topics, including seasonal movements and site fidelity. Bird banding can also provide limited migratory connectivity data when individuals have been banded on one seasonal territory, then recaptured on their corresponding territory or on their migratory pathway. Although this information is valuable, these occurrences are far too infrequent to provide discernable information for all the migratory species. For instance, 17,223 Louisiana Waterthrushes have been banded throughout their breeding, migratory, and wintering ranges since 1964, but only 148 have been recovered away from their original banding location (USGS 2021). Tracking technologies (e.g., global positioning system tracking units, light-level geolocator data loggers) or stable-isotope analysis can glean where marked or sampled individuals travel throughout their full-life cycle. These technologies are being highly utilized by ornithologists to develop new understandings of migrant species. Global positioning system tracking units generally provide the most detailed data and often do not require recapturing the individual, however they can be expensive and their relatively heavy weight limits their use on smaller species. Geolocator data loggers are usually lightweight, less expensive than GPS technology, and provide generalized routes and locations, however they require the individuals to be recaptured after deployment in order to obtain any information. Stable isotope analysis does not require the individual to be marked and recaptured and is more affordable, yet it provides the least amount of detail when compared to the aforementioned methods. Geolocators discern these global positions by collecting ambient light-levels in reference to time of day. Algorithms in statical programs can then extrapolate estimated coordinates by determining the time of sunrise, sunset, and midday.

Objectives of the Study

Until recently, uncovering and describing the migrations of distinct populations of small songbird species would have been unfeasible. Thanks to the recent miniaturization of migratory tracking technologies, more and more of these enigmatic songbird migrations are being brought to light. The full-life cycle data gleaned from these devices offer important information regarding the understanding and conservation of these species. Thorough investigation into the effects of attaching tracking devices to species for the first time followed by thoughtful and detailed descriptions of the outcomes is critical. These descriptions should include any and all effects on the marked individuals from a physiological or behavioral standpoint, as well as descriptions of the novel information recovered from the tracking units themselves. Once a bird species is tracked for the first time, ensuing efforts from the ornithological community can begin to further demonstrate the feasibility, safety, and functionality of tracking particular species. However, detailed data and information sharing is necessary.

In this thesis research, I investigated potential effects of geolocator markers on the body mass, return rates, and pairing ability on male Louisiana Waterthrushes (*Parkesia motacilla*) and Worm-eating Warblers (*Helmitheros vermivorum*) by comparing treatment (marked with geolocators and leg bands) and control (marked with only leg bands) groups. My study serves as an initial steppingstone in tracking Louisiana Waterthrush and Worm-eating Warbler migration with light-level geolocator data loggers. Attaching foreign devices to wild animals requires comprehensive consideration of any effects the device may cause to the individual. This examination of marker effects is important from an ethical, conservation, and practicality standpoint.

In this study, I aimed to describe the migratory timing (i.e., migration departure and arrival times, migration duration) of male Louisiana Waterthrushes from 4 distinct populations. To my knowledge, this research project describes the migratory timing of Louisiana Waterthrush for the first time. The information provided here offers a glimpse into the migratory strategies and behaviors of the Louisiana Waterthrush. This study is part of a larger-scale study that will answer more of the questions pertaining to the two species' migration ecology.

Part of the funding for this research project included support for an educational program to be implemented in communities on each end of neotropical bird migration. The objectives pertaining to the cultural exchange program were straightforward in theory, yet complex in practice. The goal was to establish a cultural and educational connection between two communities that share the presence of Louisiana Waterthrush, Worm-eating Warbler, and other migratory birds. We sought to establish a connection between the Chattanooga, Tennessee area (a location within the breeding ranges of both focal bird species) and a region in which these bird species spend the nonbreeding season. Through the combination of Tennessee-based geolocator migratory data, focal species range maps, and interested partners, we established a connection with two bird-related groups and an international organization's field office in the Petén Region of Guatemala (Petén Birders Association, Caoba Birders Club, Wildlife Conservation Society Flores, respectively).

Focal Species

The Louisiana Waterthrushes (*Parkesia motcilla*) and Worm-eating Warblers (*Helmitheros vermivorum*) are Nearctic-Neotropical migratory wood warblers (Parulidae). They are both typically socially monogamous species that breed and raise offspring in the eastern United States during the spring and early summer. Their wintering grounds span southern Mexico through Central America, and the Caribbean. The habitat requirements of both species are also similar. The species breed in primarily hilly terrain among deciduous forests. The Worm-eating Warbler is associated with steep slopes characterized by mid to late successional forest cover that also includes a dense understory. Louisiana Waterthrushes are exclusively associated with small- to medium-sized streams. Both species are ground nesters, with Louisiana Waterthrushes nesting in detritus and vegetation on streambanks and Worm-eating Warblers nesting on steep slopes under dense vegetation (Holland Youngman, unpubl. data). The steep slopes associated with Worm-eating Warblers are often in close proximity or directly adjacent to the small to mid-sized tributary streams which define Louisiana Waterthrush habitat. Therefore, the species can often be found in the same areas. A primary reason these species were selected for this collaborative research project was due to varying population trends. Over the past 30 years, Louisiana Waterthrush populations have been increasing in Tennessee but are declining in Arkansas, Ohio and Pennsylvania. The sympatric Worm-eating Warbler is experiencing opposing population trends (i.e., declining in Tennessee and Pennsylvania while increasing in Ohio and Arkansas). Obtaining migratory data on these species will allow the collaborators to investigate these opposing trends and identify potential nonbreeding locations contributing to population declines (Figures 1 and 2).

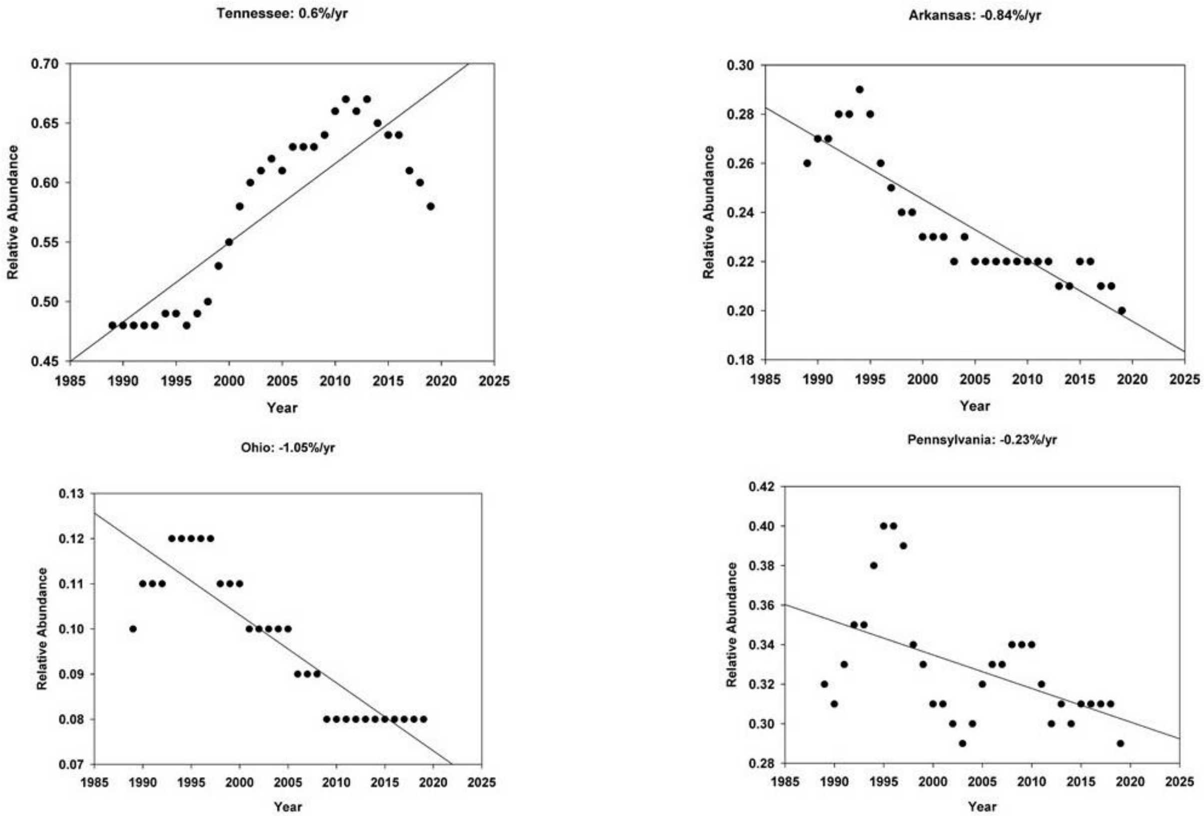

Figure 1 30-year Breeding Bird Survey trends for Louisiana Waterthrushes in the four populations studied. The overall trends are depicted by a line of best fit added to data retrieved from the 30-year Breeding Bird Survey (US Geological Survey)

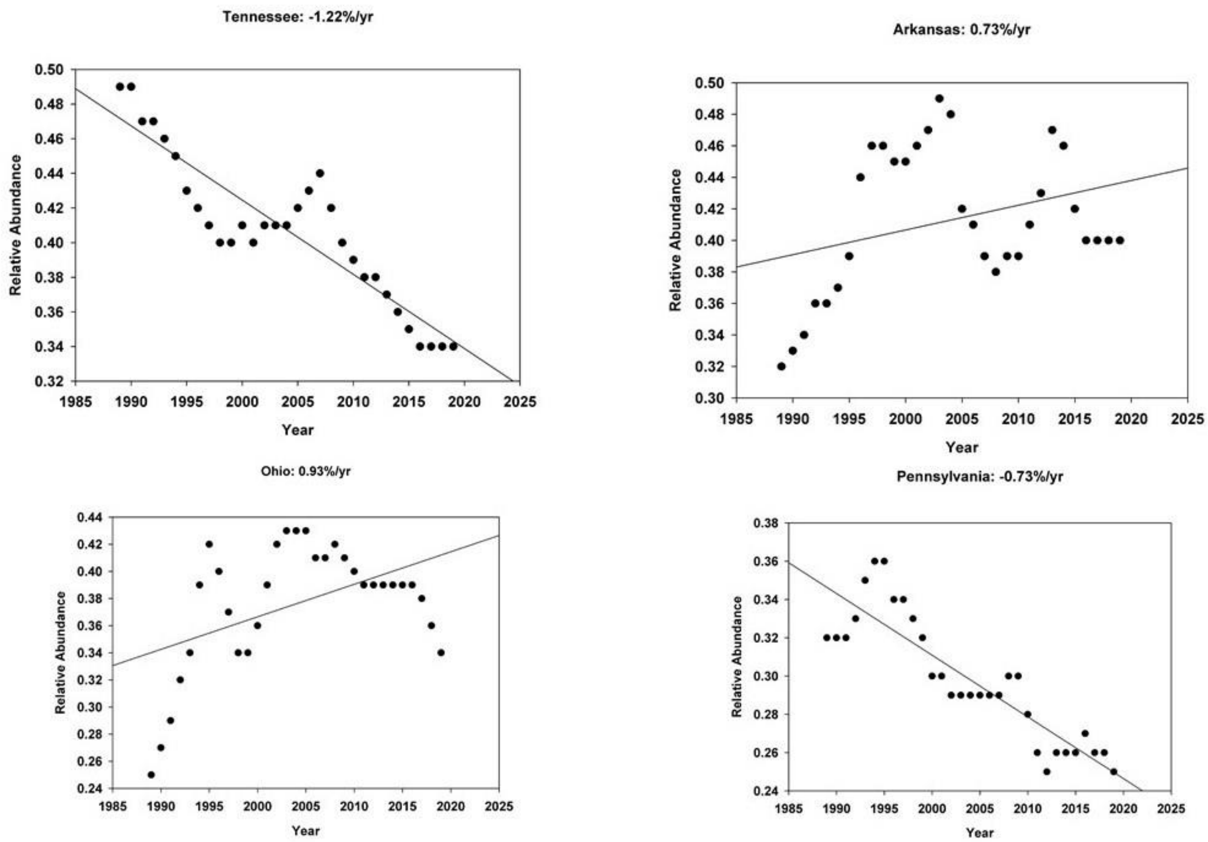

Figure 2 30-year Breeding Bird Survey trends for Worm-eating Warblers in the four populations studied. The overall trends are depicted by a line of best fit added to data retrieved from the 30-year Breeding Bird Survey (US Geological Survey)

Geolocator Data Loggers

As is the case with any mark and recapture wildlife study, sampling large numbers of birds can be exceedingly time and resource intensive. Some of these technologies, such as many GPS tracking units or stable isotope analysis, allow researchers to discern annual movements by only capturing the individual a single time. Other technologies, such as light-level geolocator data loggers (hereafter; geolocators), require individuals to be recaptured in order to retrieve the data recorded on the device. In general, geolocators can function at lower weights than GPS tracking units due to fewer necessary components. The downside is that the units must be physically retrieved in order to extract any data recorded on the device. Thanks to the relatively low weight options provided by geolocators units, smaller migratory species can be safely tracked with geolocators that would be ineligible to be equipped with a heavier GPS-based unit. Neotropical migrants vary greatly in size, such as large individuals from hawks and waterfowl to the smallest hummingbirds. Following the general rule set by the Bird Banding Laboratory (BBL) of foreign markers not to exceed 3% of the total body mass of the individual, all but the smallest of these species (i.e., >16.7 g) can be tracked with modern geolocator units. For instance, modern lightweight geolocators weigh roughly 0.5 g, which means they can be attached to birds weighing roughly 16.7 g. The BBL occasionally permits researchers to track certain bird species with units that weigh slightly more than the standard maximum marker mass limit. An impetus behind this allowance is to ensure that marker mass regulations are based on empirical evidence as the miniaturization of geolocator technology progresses. The BBL permitted this thesis research project to mark a songbird species (i.e., the Worm-eating Warbler) with markers not to exceed 5% of total body mass as an experimental authorization.

I conducted research on the effects of geolocator attachment methods and the migration ecology of Louisiana Waterthrushes (*Parkesia motcilla*) and Worm-eating Warblers (*Helmitheros vermivorum*). Both species are Nearctic-Neotropical migratory wood warblers (*Parulidae*) with similar habitat requirements and overlapping breeding and nonbreeding distributions. The project entailed fitting individuals from each species with light-level geolocators and equivalent control individuals (i.e., handled in the same way, but no geolocator is attached) to glean data pertaining to the migratory behavior of the two species from four geographically distinct local populations (i.e., southeast Tennessee, northwest Arkansas, southern Ohio, and southeastern Pennsylvania). Additionally, the effects of the tracking units on breeding site fidelity, breeding success, and health were assessed. This project is a collaborative project between the University of Tennessee Chattanooga (UTC), University of Toledo (UT), Harding University (HU), and the Tennessee River Gorge Trust (TRGT; a 501(c)(3) land trust).

In the spring and summer of 2017, a pilot study was completed to assess the methods and materials used to attach the geolocator to Louisiana Waterthrushes, as requested by the United States Geological Survey's BBL (i.e., the federal permitting body for avian research in the United States and Canada). The results demonstrated that the attachment methods and devices did not cause apparent harm to the migratory species and showed similar return rates to breeding sites from other studies marking birds in the *Parulidae* family with geolocators (Rick Huffines, unpubl. data). The BBL subsequently granted approval to mark 120 individuals (60 LOWA and 60 WEWA) with geolocators in 2018. In the spring and summer of 2018, 30 individuals were marked with geolocator devices and leg bands (15 of each species) and 30 (15 of each species) control individuals were marked with only leg bands at each of the four study sites. In the following spring and summer of 2019, the research teams completed an exhaustive search for all returning marked individuals. This thesis research will analyze the data associated with the effects of marker attachment of the two species and the migratory timing of Louisiana Waterthrushes.

Cultural Component

This project also included a human component to coordinate efforts between groups working in the bird conservation and environmental education fields on each end of the focal species' migration. Neotropical migrants have distinct winter and summer homes. Therefore, comprehensive conservation efforts should focus on all of the areas that migratory species utilize over the full annual cycle (i.e., wintering grounds, breeding grounds, and the migratory pathways between the two). We believe conservation efforts should extend beyond habitat protection and research to include the human residents of the communities that reside in the same areas as the target bird species.

Study Areas

Tennessee River Gorge, Tennessee

We studied male Louisiana Waterthrushes and Worm-eating Warblers on breeding territories along tributary streams of the Tennessee River in the Tennessee River Gorge, Tennessee, USA (35.10° N, 85.41° W). The Tennessee River Gorge comprised a ~42 km section of the Tennessee River flowing through Hamilton and Marion counties, Tennessee. The elevation of the study sites varies between ~195-545 m. Study sites consist of steep, forested mountain slopes surrounding tributaries ~2-15 m wide. Land cover surrounding the tributaries is predominately extensive stands of upland deciduous forests dominated by oaks (*Quercus* spp.), hickories (*Carya* spp.), maples (*Acer* spp.), pines (*Pinus* spp.), American beech (*Fagus grandifolia*), and Sweetgum (*Liquidambar styraciflua*), and to a lesser extent, rhododendron (*Rhododendron* spp.), mountain-laurel (*Kalamia latifolia*) and eastern hemlock (*Tsuga canadensis*). The tributaries were low-volume creeks with gradients ranging from ~18-217 m/km.

Racoon Creek Watershed, Ohio

This study site included Louisiana Waterthrush and Worm-eating Warbler breeding territories along tributary streams of Racoon Creek in Vinton County, Ohio, USA (39.33° N, 82.35° W). The area was primarily closed-canopy mature second growth deciduous forest in the foothills of the Appalachian Mountains. The elevation of the study sites ranged from ~210-300 m. Study sites consisted of forested slopes along tributaries ~1-5 m wide. Land cover surrounding the tributaries was predominately deciduous forests dominated by oaks (*Quercus* spp.), hickories (*Carya* spp.), maples (*Acer* spp.), American beech (*Fagus grandifolia*), and pines (*Pinus* spp.). The tributaries were low-volume creeks with gradients ranging from ~14-26 m/km.

Little Piney and Big Piney Creek Watershed, Arkansas

This study site included breeding territories along tributary streams of Little Piney Creek and Big Piney Creek, in the Boston Mountains ecoregion of the Ozark National Forest, Arkansas, USA (35.54° N, 93.21° W). The elevation of the study sites ranged from ~175-450 m. Study sites consisted of steep, forested slopes surrounding tributaries ~2-15 m wide. Land cover surrounding the tributaries was predominately extensive stands of upland deciduous forests dominated by oaks (*Quercus* spp.), hickories (*Carya* spp.), maples (*Acer* spp.), pines (*Pinus* spp.), and Sweetgum (*Liquidambar styraciflua*).

Schuylkill River Watershed, Pennsylvania

This study site included breeding territories along tributary streams of the Schuylkill River in Berks County, Pennsylvania, USA (40.23° N, 75.80° W). The elevation of the study sites ranged from ~153-300 m. Study sites consisted of forested slopes along tributaries ~1-20 m wide. Land cover surrounding the tributaries was predominately deciduous forests dominated by oaks (*Quercus* spp.), maples (*Acer* spp.), pines (*Pinus* spp.), and to a lesser extent, rhododendron

(*Rhododendron* spp.), mountain-laurel (*Kalamia latifolia*) and eastern hemlock (*Tsuga canadensis*). The tributaries were low-volume creeks with gradients ranging from ~8-20 m/km.

CHAPTER II

LITERATURE REVIEW

Geolocator Data Loggers

Light-level geolocator data loggers measure ambient light levels in reference to time in order to estimate the position on Earth. These devices do not remotely transmit any information back to researchers, but rather store the information internally to later be interpreted through various software packages. Therefore, the devices necessitate physical recovery from the marked animal in order to obtain the data. Although GPS tracking technologies can provide superior accuracy and may not require physical recovery, they generally weigh more than geolocator devices. Since weight is a major limiting factor for which devices can be attached to certain species, the lightweight nature of geolocators allow for use with all but the smallest avian species.

Geolocator capabilities, as well as the methods to analyze these data (e.g., open-source software packages), are constantly improving (Rakhimberdiev et al. 2017). Rakhimberdiev et al. (2016) compared the accuracy of geolocation data to GPS tracking technology by marking individuals with both types of devices. The study showed that FLightR estimates (the same open-source software package used in this thesis research) “deviated by 43.3 ± 51.5 km (great circle distance with equinoxes included),” while estimates from GeoLight (another open-source software package) “deviated from the individual's true position by 495.5 ± 1031.2 km (great circle distance with equinoxes excluded)” (Rakhimberdiev et al. 2016). This FlightR package has proven to be a widely used and effective open-source software package for interpreting geolocation data by ornithologists (Rakhimberdiev et al. 2017; Streby et al. 2015a). Another study investigated geolocation data accuracy by "ground-truthing" the calibration and deployment sites (i.e., researchers compared geolocation estimates of a site with data physically recorded with GPS devices) (McKinnon et al. 2013). The study found differences between latitude versus longitude estimates and between deploying geolocators on tropical nonbreeding grounds versus breeding grounds (McKinnon et al. 2013). Overall, latitude estimates ranged from 365 ± 97 km to 180 ± 48 km from the actual site, while longitude estimates were 66 ± 13 km (McKinnon et al. 2013). Furthermore, deploying geolocators on nonbreeding grounds in the tropics yielded more accurate data than deployment on breeding grounds (McKinnon et al. 2013). In summary, modern lightweight geolocators have opened the door to tracking small migratory bird species. The relative affordability and sufficient accuracy have allowed researchers to finally obtain full-life cycle movement data on migratory bird species in an efficient manner (Stutchbury et al. 2009).

Although the technological innovations that have allowed smaller songbirds to be marked with geolocator data loggers occurred relatively recently, there is still an abundance of geolocator-based studies on smaller members of the *Parulidae* family. However, there are no published studies in which Louisiana Waterthrush nor Worm-eating Warblers were tracked with geolocator data loggers to our knowledge. Therefore, there is a gap in knowledge regarding the full-life cycle of these two focal species as well as the effects of marking them with geolocators. By applying relevant literature on similar species (e.g., Golden-winged Warbler; Streby et al. 2015b), studies utilizing similar foreign markers (e.g., radio telemetry), and broader research on songbird migration, we can better discern the implications of this thesis research.

Ornithologists around the world are tapping into geolocator technology to better understand the full life cycle of migratory songbirds. However, the attachment of any foreign marker to a wildlife species has the potential to cause adverse effects to the animal's health or fitness. Our understanding of the effects of geolocators is becoming evident as more and more ornithologists assess the impacts of attaching geolocators or similar devices to a variety of bird species (Barron et al. 2010). Thanks to regulatory entities, such as the Bird Banding Laboratory, field ornithologists are obligated to carefully observe any deleterious effects arising from the attachment of a foreign device. Barron et al. (2010) completed a meta-analysis of 84 studies on transmitter effects on avian behavior and ecology. The researchers identified significant negative impacts on birds wearing transmitter devices, particularly pertaining to energy expenditure and likelihood to nest (Barron et al. 2010). Other studies have shown different results that indicate certain species can safely wear such devices with little to no consequences (e.g., Peterson et al. 2015). These varying results highlight the fact that close consideration of any species-specific responses is obligatory for each project that equips a bird species with foreign devices.

Overall, the effects of attaching geolocators to Louisiana Waterthrushes and Worm-eating Warblers specifically remains unknown due to a lack of study. Mattson et al. (2006) described a unique response by Louisiana Waterthrush parents when nestlings were equipped with radio telemetry devices. Adult Louisiana Waterthrushes were documented to fatally expel young from the nest that were marked with radio telemetry devices (Mattsson et al. 2006). These results indicate some level of aversion to foreign markers by Louisiana Waterthrush adults. Overall, the study serves as a valuable reminder that unique responses may be exhibited by certain bird species in the presence foreign devices. Literature, like that of Mattsson et al. (2006), can be used to infer yet another need for thoughtful discretion when marking Louisiana Waterthrush, and similar species, with foreign markers.

We have established that species specific responses to foreign markers warrants proceeding carefully when attaching markers to bird species even if studies on similar species showed no evidence of deleterious impacts to the individuals. In this thesis research, we came to the determination that the species were eligible for geolocator research. Multiple studies on Golden-winged Warblers (Peterson et al. 2015; Streby et al. 2015b) and Cerulean Warblers (Delancey et al. 2020) demonstrate that small members of the *Parulidae* family can be safely marked with geolocators. These studies described return rates, interannual territory fidelity, and body masses, that were comparable between treatment (marked with a geolocator) and control groups (marked with only leg bands) suggesting that the presence of a geolocator did not negatively affect the ability of an individual to survive the rest of the annual cycle and return to the capture site (Delancey et al. 2020; Peterson et al. 2015; Streby et al. 2015b). Many ornithologists use the return rate parameter as an indication of interannual survival. Although return rates are not identical to interannual survival, they do offer a conservative estimate into the survival of the individuals. When marked individuals return to the capture site, researchers can confirm interannual survival. However, using this estimate often classifies individuals that were not recaptured as not surviving when in reality these individuals could have survived and altered their seasonal territory or were overlooked by the field researchers. Nevertheless, it offers a valuable glimpse into the correlation of interannual survival and marker effects. These studies, along with others, support the decision to carefully mark members of the *Parulidae* family with geolocators.

The specific attachment method used for tracking devices also plays a significant role in the potential deleterious effects experienced by the marked individual. A meta-analysis found that distinct attachment methods played a role in whether "device-induced mortality" was experienced by marked individuals (Barron et al. 2010). Variations of the leg-loop harness have become common for attaching backpack-style devices to smaller passerines. This attachment method was first described in Rappole and Tipton (1991) where the researchers described a new adaptation which uses figure-eight shaped leg loops that place the device over the bird's synsacrum (fused vertebrae on birds' lower back) (Rappole and Tipton 1991). Rappole and Tipton (1991) described the process being difficult and taking up to one hour, however researchers have recently demonstrated that this process can be considerably streamlined (Streby et al. 2015b). One study identified modifications to harness materials (i.e., elastic cord) and preparation efforts (i.e., pre-assembled harnesses already attached to tracking devices) that minimized handling time to as little as 20-60 seconds per bird (Streby et al. 2015b). These continuous improvements, coupled with tracking technology innovations, are making it more feasible to attach tracking units to a wider variety of species.

Migration Ecology

Each spring and fall, Neotropical migratory songbirds embark on a seasonal journey known as migration. As previously mentioned, migration is presumed to allow individuals to escape harsh environmental conditions or exploit more favorable conditions elsewhere. Nevertheless, many facets of avian migration remain an enigma. The basics of this perilous undertaking are understood as a whole, but several gaps in knowledge arise as we scale down to individual species' or local population's migratory behaviors. Due to a variety of factors (e.g., time, resources, technology), many avian species exist that have never been tracked throughout a full annual cycle or any existing sample sizes are small. An in-depth understanding of a species' migratory strategy is necessary to inform effective management decisions, and therefore, obtaining these data is a critical step in migratory bird conservation.

Data relating to migratory timing (e.g., departure, arrival, migration duration), is important information and is not well understood when applied to individual species. This information is critical in order to achieve a comprehensive understanding of a species and to inform managers on conservation-related issues (Cooper et al. 2017). There are many factors that affect migratory timing, such as weather events, climate, and stopover habitat availability. For Warblers (*Setophaga kirtlandii*), departure time was the strongest predictor of arrival time, but the total migration distance and stopover usage played important roles as well (Cooper et al. 2017). This study suggested that the observed correlation between departure and arrival dates can be used to "provide a plausible mechanism for previously documented carry-over effects of winter rainfall on reproductive success in this species" (Cooper et al. 2017). This is just one example of how migratory timing information can be used to identify factors contributing to conservation-related issues.

Weather events can often dictate the arrival, departure, and durations of migration. It is well established that migratory birds cue into weather patterns and may cater their migratory strategy to utilize favorable conditions (Akesson and Hedenstrom 200; Lack 1960). For instance, Cooper et al. (2017) showed that a loop migration exhibited by Kirtland's Warblers (i.e., different routes are taken by the individual in fall and spring migration) may have been a response to "seasonal variation in prevailing winds" (Cooper et al. 2017). Additionally, Golden-winged Warblers (*Vermivora chrysoptera*) exhibited an atypical avoidance of an approaching tornadic storm in which obligate migrants (a migratory species that migrates on a regular cycle) demonstrated a facultative migration (a migration resulting from a cue such as a weather event) (Streby et al. 2015a). With such a variety of factors impacting departure and arrival times, it is critical that researchers obtain large, species-specific datasets in order to understand each species' unique migratory strategy and the influences that may be responsible for variation in migratory behavior.

Migratory connectivity refers to the geographic connection of the respective breeding and nonbreeding grounds used by a migratory individual or population throughout a full year. At the population scale, the level of migratory connectivity varies by species. Many local populations of birds have been shown to have a strong level of migratory connectivity (specific breeding populations spend the nonbreeding season in the same general location) (Knight et al. 2008; Kramer et al. 2017). Weak levels of migratory connectivity have been documented; breeding populations of Purple Martins (*Progne subis*) did not exhibit a strong level of migratory connectivity on nonbreeding grounds (Fraser et al. 2017). Habitat usage on nonbreeding grounds also differed from breeding territories (Fraser et al. 2017). This is an example of the type of migration ecology information that is useful to conservation managers when selecting priority areas for conservation action. Migratory connectivity is a critical piece of information for conserving migratory bird populations since it may identify the priority areas for a given local population.

Data relating to the habitat preferences of migratory birds at their breeding territories, nonbreeding territories, and migratory route are essential in order to comprehensively protect these populations. Migratory pathways and stopover locations are critical pieces of information when addressing conservation issues yet can be difficult to detect on a population scale (Knight et al. 2018). Migratory pathways can identify critical habitat as well as inform researchers and managers of more complex dynamics such as reproductive isolation (Delmore et al. 2012). A study on Swainson's Thrushes (*Catharus ustulatus*) suggested that local populations used divergent migratory routes; and these migratory divides supported the notion that “divergent migratory behavior could contribute to reproductive isolation between migrants” (Delmore et al. 2012). Any conservation efforts for a migratory bird population that solely focus on one seasonal ground, without knowledge of the other geographic areas used by the population and how it may affect population ecology is at risk of experiencing futile results. In order to create empirically informed conservation management strategies, researchers must continue to obtain data on each species’ migratory behavior then establish known migratory networks to prioritize areas for focus (Knight et al. 2018).

CHAPTER III

METHODOLOGY

Capture Methods

We captured male birds using mist nets (30 mm mesh). We targeted males by broadcasting conspecific calls and songs of the respective species with an electronic callback unit. The calls were used in combination with decoy birds representing the respective species. We used 12-meter or 6-meter mist nets. Males were the only sex used in the study since they tend to have higher breeding site fidelity and are territorial, and therefore, easier to lure into the net with conspecific songs and calls. Residency status was ensured prior to capture by observation of signs of residency such pairing with a mate, regular territoriality, nesting activities, or time of year. Birds were extracted upon capture then either equipped with the geolocator and bands or underwent marker removal depending on the project phase. Field researchers followed all standard wild bird handling protocols defined by the BBL.

Marker Deployment

We attached 16 Biotrack geolocators (ML6140 V3878, Biotrak Ltd., Wareham, UK) to adult male Louisiana Waterthrush during March-June 2016 exclusively at the Tennessee River Gorge study site. In March-June 2018, we attached 121 Migrate Technology geolocators (Intigeo-W55Z9-DIPv10, Cambridge, UK) to 61 male Louisiana Waterthrushes and 60 male Worm-eating Warblers across 4 distinct study sites. In 2018, we deployed 15 geolocators on

Louisiana Waterthrush and 15 on Worm-eating Warblers at each study site: Tennessee River Gorge, Northwest Arkansas, Southern Ohio, and Southeastern Pennsylvania. Comparable control groups were marked (i.e., individuals marked with only leg bands). Prior to initial deployment, we documented evidence of breeding status by signs of nesting (e.g., observation of nest construction, regular territoriality, the presence of an active nest), pairing with a female, or time of year in reference to breeding stages of the two species. This effort was done to ensure residency in order to avoid marking non-resident birds (i.e., birds moving through during migration) which would affect estimates of apparent inter-annual survival. Once residency was confirmed, we broadcasted conspecific songs and calls in combination with a decoy to lure males into mist nets.

Upon capture, geolocators were attached to geolocator-marked birds using a true leg-loop harness (Rappole and Tipton 1991) following the improved methods described in Streby et al. (2015b) (Figure 3). The harnesses were composed of a 0.5 mm diameter polyurethane cord (Stretch Magic, Pepperell Braiding Company, Pepperell, Massachusetts, USA) with straightened inside loop length of 19 mm (measured according to the methods described in Streby et al. 2015b). We also marked all birds with a standard U.S. Geological Survey band and a single plastic color band for easier visual detection at later stages. In addition, we marked a control group of adult male Louisiana Waterthrushes and Worm-eating Warblers with only a U.S. Geological Survey band and a plastic color band. We weighed all geolocator-marked birds (minus the geolocator) and control birds prior to release using a digital scale. The geolocator devices and color leg bands were removed from all recaptured individuals. The same capture and data collection methods were used throughout the study across all sites. All capture and attachment methods were carried out in accordance with approved IACUC protocol #19-01.

Figure 3 Light-level geolocator data logger in hand (left) and attached to a Louisiana Waterthrush (right)

Data Recording

We recorded standard physiological measurements (wing chord, tail length, body mass, fat score), observational parameters pertaining to paired status (pairing with mates), and assessed areas in contact with the geolocator and harness. All data were recorded by hand in the field, then recorded digitally upon return to the labs and field stations. Geolocators were kept in dry, room temperature storage until the data was extracted and saved digitally.

Geolocator Data Analysis

We analyzed raw light-level data following the methods described in Kramer et al. (2017). We used the BASTrak software (Biotrak, Wareham, UK) and IntigeoIF Interface software (Migrate Technology, Cambridge, UK) to extract light-level data and then performed the rest of our analyses in R (v. 3.3.0; R Core Team 2016). The BAStag Package was used to identify transitions (i.e., sunrises and sunsets) using a light-level threshold of 1. We used FLightR (v. 0.3.6; Rakhimberdiev et al. 2015) to calibrate our data using the period following deployment until 30 June (i.e., when the individual was known to be at the breeding sites). We also estimated the locations of geolocator-marked birds using the same methods detailed in Kramer et al. 2017. The generalized migration routes were inferred from a combination of longitude, latitude, and timing (Delmore et al. 2012; Kramer et al. 2017). We considered an individual to begin migrating when a noticeable shift in the raw light-level data corresponded with a consistent and permanent movement from the breeding site (breeding longitude may be used if shading errors resulted in estimates north or south of the known breeding location; Kramer et al. 2017). We considered migration to cease when the point estimates of an individual approach within +/- 1° latitude and longitude of the central core of the nonbreeding probability density function and remained at the same longitude for the remainder of the nonbreeding period (Kramer et al 2017).

Assessment of Condition

Upon recapture, we assessed the physical condition of geolocator-marked and control individuals. Condition assessments comprised returning status (i.e., if the bird was successfully recaptured at the breeding territory), paired status with a female, a body mass index (i.e., body mass (g)/wing cord (mm)), and visual inspection of areas in contact with the geolocator harness. The conditions for captured geolocator-marked and control Louisiana Waterthrushes and Worm-eating Warblers were assessed following consistent methodology across all study sites. However, paired status was only recorded for individuals from 2018 and 2019.

We visually assessed geolocator-marked and control individuals for any signs of irritation in areas that come in contact with the geolocator or harness cord and noted chaffing, sores, aberrant redness, or swelling. Control groups were assessed in the case of unrelated chaffing or abrasions for the species in areas that could be thought to be caused by a geolocator or harness. These assessments were done as a visual inspection while handling the bird.

Investigation on Effects of Geolocator Attachment

Body Mass and Wing Cord

A body mass index was used to compare geolocator-marked and control individuals in order to discern any differences in body mass between the two groups. The body mass index was calculated by body mass (g)/wing cord (mm). All individuals were weighed on a digital scale to the nearest tenth (g). Birds were placed on the tared scales in cloth weighing bags or altered PVC pipe tubes. Geolocators and color leg bands were not incorporated into the body mass measurements since birds were weighed prior to geolocator and color leg band attachment in the deployment phases and geolocators and color leg bands were later removed before weighing recaptured individuals. Birds weighed in the recapture phases were still equipped with a metal leg band unlike the deployment phases, but interannual weights were not assessed so this was not an issue. Wing chord was measured in millimeters (mm) by placing the wing on a standard wing ruler. Wings were straightened along the ruler, but not flattened. Wing cords were measured to the nearest 0.5 mm or whole number (e.g., 70 and 70.5).

We conducted statistical analysis in SAS 9.4 (SAS Institute, Cary NC) to assess any significant differences in the body mass indices between geolocator-marked birds and control birds from 2016-2017 and 2018-2019. A two-sample *t*-test was used to compare the body mass indices of treatment groups with control groups.

Interannual Survival Estimate

Breeding site fidelity (i.e., interannual return rates to breeding sites by a specific individual) over a full year was used as a limited indication of apparent annual survival. This parameter does not entirely represent interannual apparent survival since some birds may breed on different territories that we are incapable of surveying or were overlooked by the field researchers. This parameter based on return rates serves as a useful, yet conservative indication of interannual survival.

I investigated any significant differences between the return rates (breeding site fidelity) geolocator-marked birds and control birds from 2016-2017 and 2018-2019. A Fisher's Exact Test of Independence was used to compare the return rates of treatment groups (geolocator-marked individuals) with control groups (individuals marked with only a leg band).

Pairing Status

We recorded the observed paired status of individuals in order to investigate potential effects of the markers on males' ability to pair with a mate. We used observational parameters to infer if an individual was paired with a female mate. Pairing with a female was determined by a visual observation of signs of breeding status. These signs of breeding status included evidence of nest construction, observed copulation, feeding or interacting with young, or two individuals of the same species regularly interacting with one another in an unaggressive manner (male individuals of the two focal species are aggressive towards other males and generally only interact with their mate or young during the breeding season). Individuals were put into one of two categories: "paired" and "unknown." Individuals were considered to be paired with a mate if any of the aforementioned observational parameters were met. Birds in the category of "unknown" were assumed to not be paired with a mate for the purposes of this study; this approach serves as a very conservative estimate of paired status.

I assessed any significant differences in the paired status of the treatment and control groups. A Fisher's Exact Test of Independence was used to compare the paired status of treatment groups (i.e., geolocator-marked individuals) with control groups (i.e., individuals marked with only a leg band).

Cultural Exchange Program

We sought to establish working relationships with international partners to allow for the sharing of resources and commence a collaborative approach to environmental education centered around bird migration. The Tennessee River Gorge Trust in partnership with La Paz Chattanooga (a 501(c)(3) Latinx and Hispanic family advocacy organization) served as the groups to carry out this cultural connection. After close review of geolocator data (2016-2017 dataset), feasibility of travel, and the presence of interested ornithology-related groups, Petén was chosen as the focal community and PBA, CBC, and the Wildlife Conservation Society of Guatemala (hereafter, WCS) as the partnering entities. La Paz Chattanooga (hereafter, La Paz) partnered with TRGT to help establish relationships with the Guatemalan partners and connect Petén communities with the growing Latinx and Hispanic communities within Chattanooga, Tennessee, a large portion of which is Guatemalan. While TRGT served as the authority on ornithology and conservation, La Paz took the lead on the culture aspects of the project.

The cultural component of this project included a trip to Petén, Guatemala by two members of TRGT and two members of La Paz. During the trip, the group met with WCS employees, PBA, and CBC leaders. The group traveled to a variety of village schools with PBA and CBC to take part in a series of lessons and discussions on migratory birds, particularly highlighting the fact that certain bird species spend roughly half of the year in Central America then the other half in North America. Further, TRGT participated in a joint presentation and discussion in which WCS researchers and TRGT researchers shared their respective projects. The group interacted with over 150 community members and established strong working relationships with PBA and CBC. The following year, 3 members of PBA were brought to Chattanooga, Tennessee for the second phase of the project. During this visit, the PBA representatives interacted with over 500 community members through classroom lessons (e.g., science and Spanish classes), community lectures, professional meetings, and a La Paz sanctioned family event at a local nature preserve.

CHAPTER IV

RESULTS

Effects on Body Mass for Louisiana Waterthrushes

The results of the two-sample *t*-test indicated that mean scaled body mass between treatment (geolocator-marked) and control Louisiana Waterthrushes was similar. We failed to reject the null hypothesis that body mass was the same between the treatment and control groups (p= 0.6144, df= 1).

Effects on Body Mass for Worm-eating Warblers

The results of the two-sample *t*-test indicated that mean scaled body mass between treatment (geolocator-marked) and control Worm-eating Warblers was similar. We failed to reject the null hypothesis that body mass was the same between the treatment and control groups (p= 0.0534, df= 1). However, this was a near significant result.

Effects on Return Rates of Louisiana Waterthrushes

Twenty-two of 77 geolocator-marked individuals returned to breeding territories in comparison to 17 of 56 returning control individuals. The results of a Fisher's Exact Test of Independence test indicated that the proportions of Louisiana Waterthrush recaptured at the breeding territory a year after deployment (return rates) was similar between treatment and control groups. We failed to reject the null hypothesis that the proportions of return rates were the same between treatment and control groups (p=0.8489, df=1).

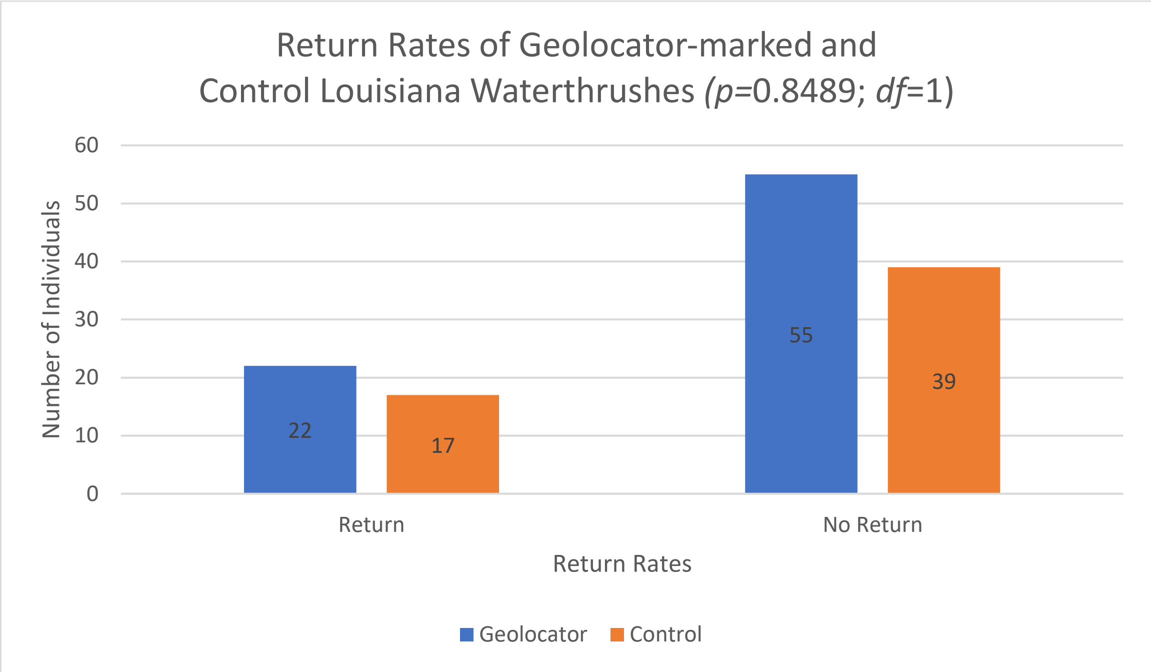

Figure 4 Return rates of geolocator-marked (n=77) and control (n=56) Louisiana Waterthrushes

Effects on Return Rates of Worm-eating Warblers

Twenty-one of 60 geolocator-marked individuals returned to breeding territories in comparison to 14 of 44 returning control individuals. The results of the Fisher's Exact Test of Independence test indicated that the proportions of Worm-eating Warblers recaptured at the breeding territory a year after deployment (return rates) was similar between treatment and control groups. We failed to reject the null hypothesis that the proportions of return rates were the same between treatment and control groups (p=0.8345, df=1).

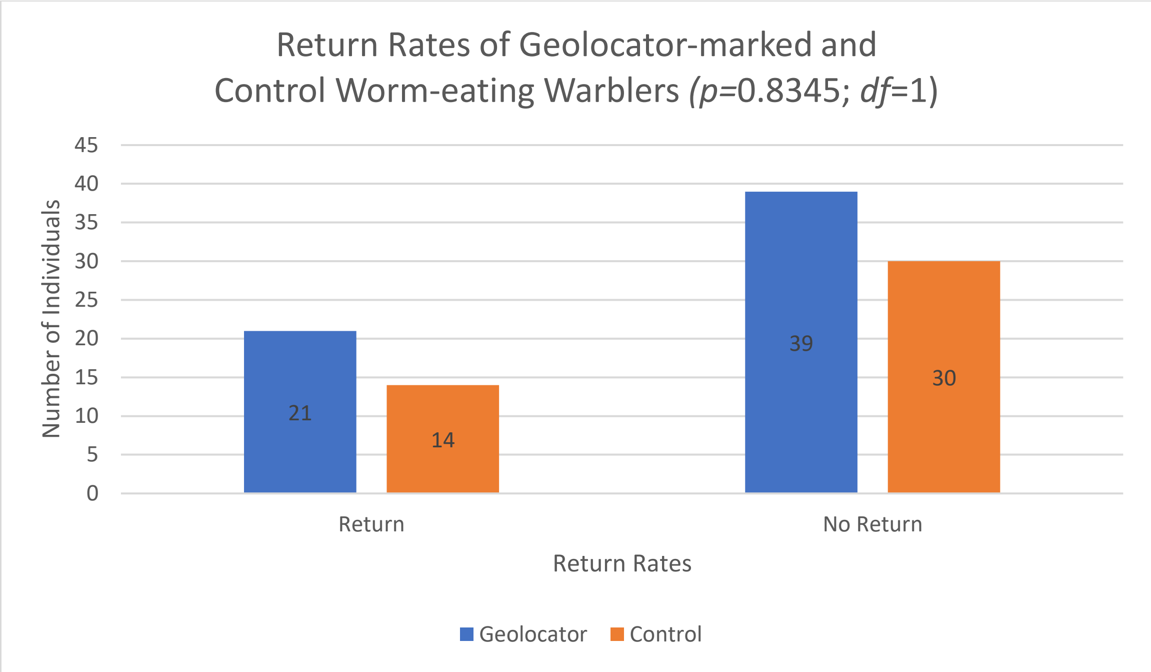

Figure 5 Return rates of geolocator-marked (*n*=60) and control (*n*=44) Worm-eating Warblers

Effects on Louisiana Waterthrushes' Ability to Pair with a Mate

Seventeen of 22 observed geolocator-marked individuals were paired compared to 10 of 17 control individuals. A Fisher's Exact Test of Independence suggested that pair-bonding success among geolocator-marked versus control Louisiana Waterthrushes was similar. We failed to reject the null hypothesis that the proportions of male birds paired with a mate were the same in the treatment and control groups (p=0.2994, df=1).

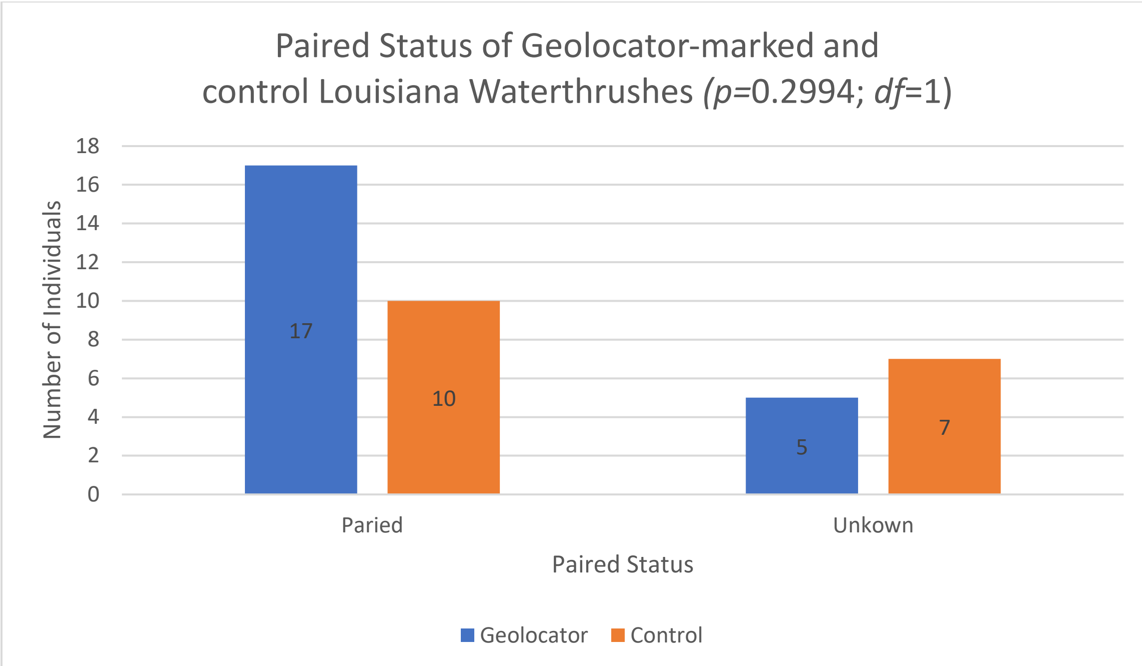

Figure 6 Pairing status of geolocator-marked (n=22) and control (n=17) Louisiana Waterthrushes

Effects on Worm-eating Warblers' Ability to Pair with a Mate

Six of 16 observed geolocator-marked individuals were paired compared to 7 of 14 control individuals. For Worm-eating Warblers, the results from a Fisher's Exact Test of Independence test suggested that pair-bonding success among geolocator-marked versus control groups was similar. We failed to reject the null hypothesis that the proportions of male birds paired with a mate are the same in the treatment and control groups (p=0.7131, df=1).

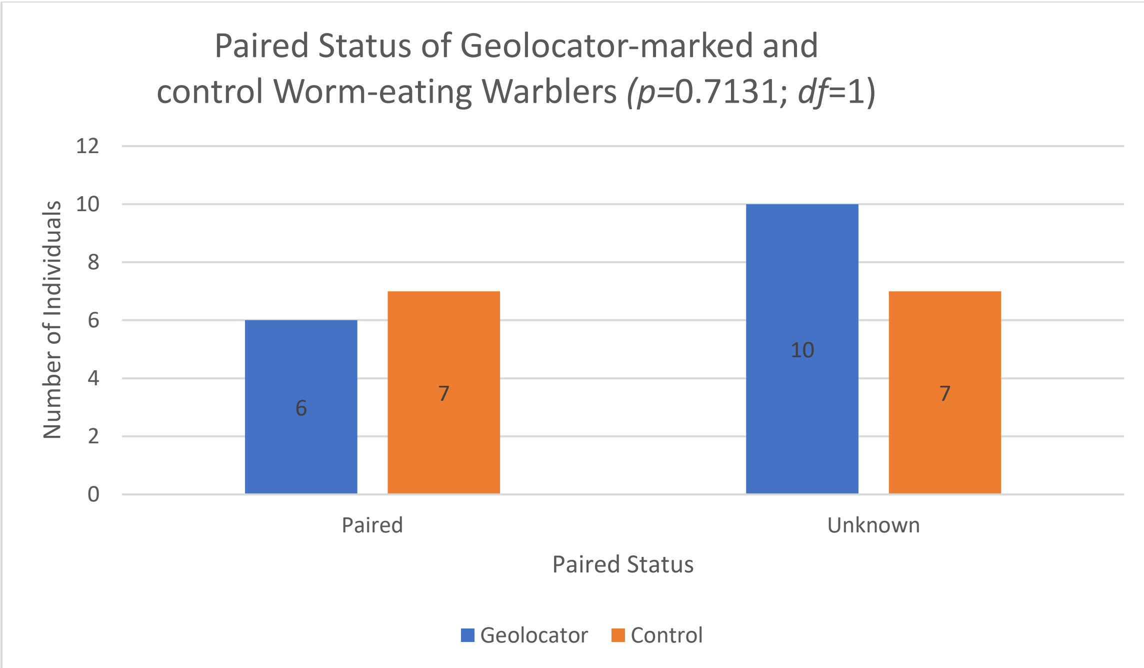

Figure 7 Pairing status of geolocator-marked (n=16) and control (n=14) Worm-eating Warblers

Effects on Skin Condition

Superficial callouses were observed on groups of returning geolocator marked birds. Fourteen returning geolocator-marked Worm-eating Warblers (n=17) and 17 returning geolocator-marked Louisiana Waterthrushes (n=22) experienced callousing under the geolocator. Specifically, these small callouses were located under the geolocator over the synsacrum and were featherless. One Louisiana Waterthrush had grown a callous around the harness cord on both sides of the geolocator. The harness cord was removed from the callous and no open wounds were present after removal. There was also a regular accumulation of feathers and oils that had adhered to multiple harnesses which did not appear to be associated with any signs of irritation to the skin.

Migratory Timing of Adult Males

Louisiana Waterthrush Migration Duration

The mean spring migration duration among all Louisiana Waterthrush (2016-17 sample and 2018-19 sample) was 26.7 days (n=19), while the mean fall migration duration was 12.7 days (n=21) (Table 1). The mean migration durations for the 2016-17 sample were lower than the durations from the 2018-2019 sample. The mean spring migration duration for the 2016-17 sample was 10.5 days (n=4), while the 2018-19 sample across all four sites was 30.4 days (n=15). The fall migration duration mean for the 2016-2017 sample was 6.6 days (n=5), while the 2018-19 sample across all four sites was 14.6 days (n=16) (Table 1). After comparing only individuals from one study site (Tennessee; the only study site used in both 2016-17 and 2018-19) across two full annual cycles, we found that mean spring migration duration from 2016-17 was 10.5 days (n=4) in comparison to 9.6 days for individuals from 2018-19 (n=5). There was a greater difference among the means of individuals from Tennessee; mean fall migration duration from 2016-17 (n=5) was 6.6 days in comparison to 40.8 days for individuals from 2018-19 (n=5). Specific migratory connectivity data will later be defined in subsequent research papers (Figure 8).

Table 1.

Estimated migration departures, arrivals, and durations of Louisiana Waterthrushes from 2016-2019

Geolocator ID	**State**	**Fall Departure Date**	**Fall Arrival Date**	**Fall Duration (days)**	**Spring Departure Date**	**Spring Arrival Date**	**Spring Duration (days)**
BK412	OH	8/14/18	8/25/18	12	Tag Died	Tag Died	Tag Died
BK414	OH	10/13/18	12/1/18	20	3/17/19	4/26/19	41
BK415	OH	8/3/18	8/27/18	25	3/21/19	4/20/19	31
BK416	OH	8/27/18	10/3/18	38	3/17/19	4/15/19	30
BK428	PA	8/15/18	8/17/18	3	2/23/19	3/20/19	26
BK434	PA	9/5/18	9/10/18	6	3/15/19	3/31/19	17
BK455	AR	8/23/18	9/2/18	11	2/16/19	3/31/19	44
BK459	AR	8/10/18	10/1/18	53	4/1/19	4/1/19	1
BK462	AR	8/11/18	8/15/18	5	2/17/19	3/19/19	31
BK463	AR	8/21/18	8/25/18	5	3/17/19	3/24/19	8
BK465	AR	8/20/18	8/26/18	7	3/11/19	4/2/19	23
BK607	TN	8/12/18	8/16/18	5	3/8/19	4/27/19	51
BK608	TN	8/23/18	8/29/18	7	1/15/19	3/9/19	54
BK612	TN	8/7/18	8/16/18	10	3/13/19	4/2/19	21
BK613	TN	7/25/18	8/14/18	21	2/19/19	3/18/19	28
BK618	TN	8/23/18	8/27/18	*5*	2/27/19	4/17/19	50
09	TN	8/16/16	8/31/16	16	2/19/17	2/25/17	7
16	TN	8/21/16	8/22/16	2	2/10/17	2/27/17	18
33	TN	8/20/16	8/24/16	5	3/16/17	3/26/17	11
38	TN	8/19/16	8/25/16	7	3/19/17	3/24/17	6
39	TN	8/22/16	8/24/16	3	Tag Died	Tag Died	Tag Died
Mean				**12.7**			**26.2**

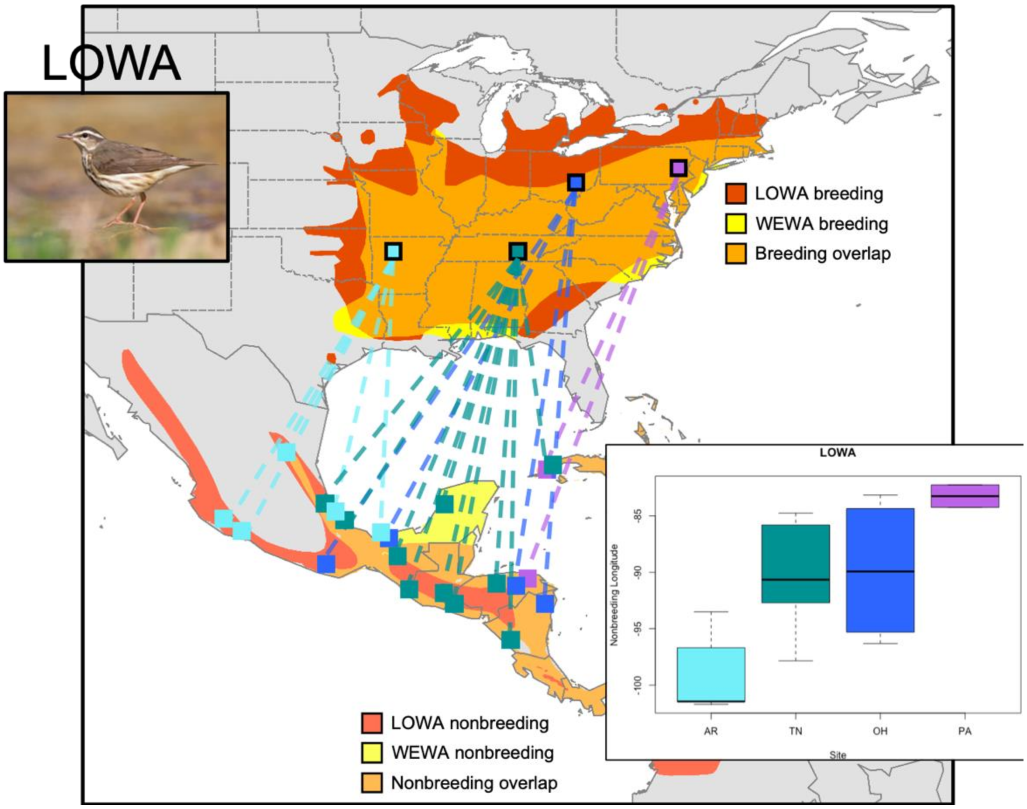

Figure 8 Migratory Connectivity of Louisiana Waterthrushes from 2018-2019 in the four study sites (figure prepared by Gunnar Kramer)

Cultural Exchange Program

Although the partnerships established between TRGT, La Paz, PBA, and CBA are ongoing, the results to date included various events and programs aimed towards environmental education and community outreach. Members of TRGT and La Paz traveled to Guatemala in September of 2018 followed by PBA members traveling to Tennessee in April of 2019 to implement the cultural exchange program. Highlights of the program included classroom presentations, a student pen pal program, community lectures, and the procurement of equipment for PBA. Much of the program's initiatives were in partnership with school groups ranging from elementary to high school classes (Figure 9). These environmental and cultural education efforts included presentations, discussions, and nature hikes with students. A particular focus was given to the concept that the communities of Petén, Guatemala and East Tennessee are connected through bird migration. More specifically, lessons incorporated the notion that we share the responsibility to protect wildlife and our environment, and our actions in one area may impact the environment in seemingly distant communities.

Community lectures and events were held in Chattanooga, Tennessee to engage a broader audience beyond school groups (Figure 10). These community events shared similar goals as the school-based educational efforts; the intent was to educate the public on bird conservation as well as foster the notion that conservation necessitates a collaborative approach that extends beyond political boundaries. TRGT and PBA also incorporated the partnership in their regular educational activities that followed the trips between Tennessee and Guatemala.

Over 650 individuals were directly engaged through the aforementioned methods. The organizations involved (TRGT, La Paz, PBA) plan to continue this partnership in a similar format as funding becomes available. These ensuing outcomes are further discussed in the discussion and conclusion section.

Figure 9 TRGT and La Paz staff joining a school group in Flores, Guatemala for an environmental education activity with PBA members

Figure 10 PBA members at a community presentation in Chattanooga, Tennessee sponsored by La Paz (left) and PBA's Marcial Cordova assisting with the capture of a Louisiana Waterthrush in the Tennessee River Gorge

CHAPTER V

DISCUSSION AND CONCLUSION

Impacts of Geolocator Data Loggers

Collection of migration data for small songbirds is becoming increasingly common due to the miniaturization of tracking technology and improvements to methods used to attach markers to birds. However, negative impacts on condition and survival have been reported for some species and with some marking methods. These results warrant careful assessment of potential marker effects in the early stages of any research marking certain species with tracking devices. Therefore, it is important to investigate and report the results from all geolocator-based studies on not only the migratory data, but also the effects of the devices to the individuals. A more comprehensive knowledge base regarding the attachment of tracking devices to small songbird species will allow for more ethically sound and productive full-life cycle research. The Louisiana Waterthrush has previously been marked with geolocators (Danny Bystrak, pers. comm.) which resulted in low return rates and poor physical condition for returning individuals. My thesis research used a distinctly different attachment method that has shown promising results from the 2016-2017 pilot study and on similar species (e.g., Streby et al. 2015b). To our knowledge, the Worm-eating Warbler had not been marked with light-level geolocators. Consequently, a study outlining the effects of marker attachment will be particularly useful for the ornithologists and governing bodies (e.g., USGS BBL, TWRA) to help guide future decisions regarding the tracking of these species.

Our data suggest that 0.5-gram geolocator data loggers attached with a leg loop harness following did not have discernable effects on the marked individuals when compared to control groups without geolocators in the three categories (i.e., body mass, return rates, ability to pair with a mate) with the exception of a near significant result for body mass of Worm-eating Warblers. This research project included the marking of 137 individuals with geolocators and 99 individuals as controls by 3 separate research teams. Although it is notably difficult to obtain large sample sizes in mark and recapture studies, this study contains relatively large sample sizes for mark and recapture studies on migratory songbirds. The results suggest that these geolocator devices did not have discernable negative impacts on body mass, interannual survival, or pairing ability. This study is of particular significance since an experimental authorization was granted by the USGS BBL to increase the standard marker mass restrictions of 3% to 5%. The total marker mass for the majority of Worm-eating Warblers (the smaller of the two focal species) marked in this study exceeded the standard 3% restriction. Since our results did not identify any adverse impacts, further research into these weight restrictions on similar species is justified.

Overall, these results suggest that certain members of the Parulidae family may be capable of carrying larger devices than previously permitted by the BBL without experiencing negative impacts to the individual's health or fitness. Extreme caution and meticulous study are necessary when increasing the weight load put on marked migratory birds. However, these results demonstrate that some weight restrictions prescribed by governing bodies (e.g., USGS BBL) could be altered for certain species. In an ideal world, robust datasets pertaining to each species' ability to carry devices of various weights would exist. Since we do not currently have this luxury, studies such as this one can be cautiously used to inform decisions when setting marker mass restrictions. Although time intensive and data dependent, a more comprehensive process by governing bodies which sets more distinct weight restrictions by taxonomic grouping is also a worthwhile endeavor. With modern technological innovations, a slight increase in the marker mass restriction could allow for more advanced markers that would ultimately yield much more detailed data. That being said, the evidence supporting any marker mass increase allowed by a governing body would have to be highly to persuasive for ethical, conservation, and productivity concerns. With the staggering avifaunal decline across the continent (Rosenberg et al. 2019), any information that helps us better understand bird species' full-life cycles or the research methods used to obtain data can help inform urgent conservation management strategies.

Sample Size of Exclusively Male Individuals

In this study, we exclusively captured male individuals on breeding territories. Male wood warblers have been documented to have a higher site fidelity than females (Greenwood 1980, Murphy 1996). This occurrence theoretically could be attributed to the fact that breeding males are more easily captured by the traditional target netting and callback strategies (i.e., males have apparent higher site fidelity only because they are more easily encountered and captured by researchers). Although a sample size of males and females would be ideal, including females with the methods used in this study would not have been feasible. It is possible that females would have different responses than males when marked with geolocators. In addition, backpack-style markers on females are generally avoided due to constraints on copulation (e.g., males may have difficulty mounting females during copulation). Therefore, the inferences of this study of marker effects and migratory timing are limited to only male individuals.

Return Rates

The site fidelity of a migratory bird refers to the frequency and likelihood that an individual bird will return to the same territory the following year after migration. Geolocators did not have a discernable effect on the return rates for both species. These interannual return rates can also be used as an indication of apparent annual survival, with the awareness that this parameter does not entirely represent apparent interannual survival since some birds may choose to breed on different territories that we are incapable of surveying. The possibility also exists that researchers may overlook returned individuals during field research. Breeding site fidelity still serves as a useful, yet conservative, indication of survival since returned birds can be positively confirmed as alive. This estimate therefore errs on the side of overstating negative impacts on return rates.

Any mark and recapture studies are at risk of unintentional, preferential selection of individuals for recapture efforts by field researchers. This research bias could result in higher apparent return rates for certain groups, such as geolocator-marked birds. This bias can be avoided by setting protocols to ensure every individual is given equal effort for recapture. However, the difficult question emerges of how to choose which individual territories to focus on when time and resources are limited, and some territories may yield valuable geolocation data while other sites with control individuals will yield less overall data. There is no evidence that these biases existed in this study, but it is a topic worthy of conversation and consideration. The results we provided are useful to make inferences on the impact of geolocator devices on the breeding site fidelity of the two species, but readers should still consider the aforementioned subjects when interpreting our results.

Breeding Success

Upon arrival to the breeding grounds in the spring, males select and defend a territory while courting potential mates. If pair-bonding is successful, the male will generally remain on that territory with the female throughout the spring and summer as they raise young.

We used paired status of males as an indication of breeding success for individuals. The results suggest that geolocators did not have a discernable effect on the pairing ability of males for both species. This estimate does not fully reflect the breeding success of an individual since paired mates may not successfully copulate or raise young. The estimate largely indicates if the presence of a geolocator negatively affects a male's ability to pair with a mate due to mate selection preferences by a female. Certain indicators of paired status, such as observation of parents with young, can more confidently address if the device has such effects on breeding. However, the sample size was not large enough to permit categorization of distinct breeding status indicators. It is possible that geolocators could have further effects on breeding success, such as deficiencies in the ability of parents to evade predation or acquire food for young. We can reasonably assume that most of these potential deficiencies would have impacted the results on the adult's body mass or return rates, however it is possible that geolocators could have impacts to overall breeding success that were not revealed with our methodology.

Our estimate of paired status was similar to our return rate parameter since it offered a conservative estimate of pairing with a mate. In other words, birds that were not observed to be paired were assumed to be not paired. It is plausible that many of these birds assumed to not be paired with a mate were in fact paired, but field researchers did not observe any indication of such status. This estimate errs on the side of underestimating paired status, and therefore, overestimates any negative impacts to males' ability to pair with a mate. We believe this conservative estimate allows us to make meaningful inferences on geolocators' impact on mate selection, and it offers valuable insight on potential impacts to overall breeding success. Our results indicated that the attachment of a geolocator device may not affect male Louisiana Waterthrushes' and Worm-eating Warblers' success in pairing with a female mate. In addition, Worm-eating Warblers have not been marked with geolocator data loggers, to our knowledge, and information on Louisiana Waterthrushes and geolocators is very limited. Therefore, assessing these potential impacts on breeding success is especially important to ensure there are not unique species-specific responses to geolocators in regard to mate selection.

Body Mass Indices

In order to assess geolocator effects on the physical health of individuals, we compared a body mass index among treatment and control groups. Mean body mass between geolocator-marked and control individuals was the same for Louisiana Waterthrushes. However, the results narrowly indicate that there was not a significant difference between the body mass indices of geolocator-marked and control Worm-eating Warblers, but this equivocal interpretation warrants further research. With a p-value of 0.0534, we almost rejected the null hypothesis that the body mass index was the same between geolocator-marked and control individuals. Additional research with a larger sample size may help more confidently reveal any impacts to the body condition of Worm-eating Warblers or lack thereof.

With a larger sample size, we could have conducted a more thorough analysis of impacts to body mass. For instance, we were not able to account for typical seasonal differences in body mass throughout the breeding season. A larger sample size would have permitted us to categorize individuals based on capture times into groups representing different phases of the breeding season (e.g., early breeding, mid breeding, late breeding periods). For example, the early breeding period could include the average arrival time from migration to clutch completion, while mid-breeding period may include the average date of first hatching to the average date of fledgling. It is reasonable to expect that adults may expend different levels of energy depending on the breeding and young rearing activities, as well as devote food resources to young rather than themselves. Migratory birds will also build up large fat reserves to supply the appropriate levels of energy prior to migratory departure. This buildup of fat could inflate the weights of birds recaptured later in the breeding season when compared to individuals captured earlier in the season. Consequentially, body masses may fluctuate in response to these changes in behavior throughout the season. Our sample sizes did not permit such in-depth investigations, but it is important to consider these issues when interpreting our results. We used the body mass index in order to account for variation in the body sizes of individuals. Combining body mass with wing cord length helped us more confidently compare body mass among individuals that may have varying body sizes (i.e., length and width). Lastly, the body mass index represents an assessment of physical health but has the potential to not reflect certain health impacts that would not be revealed with only body mass. Overall, the results from this study provide evidence that the presence of a geolocator for a full year does not impact the body mass of male Louisiana Waterthrushes yet further study is needed to reach a confident conclusion pertaining to Worm-eating Warblers.

Migratory Timing

The unearthing of the migratory timing exhibited by four local populations of Louisiana Waterthrush offers an empirical glimpse into the full life cycle of this species. Since no prior published data exist concerning to the individual migration duration and timing of Louisiana Waterthrush, this project serves as an early step in better understanding the Waterthrush's migratory strategy and behavior. Tracking the movements of migratory birds over the course of a full annual cycle can be time and resource intensive. These difficulties are amplified when studying smaller species that require lightweight tracking technologies that must be employed through a mark and recapture approach. These limiting factors make the types of data presented in this thesis research of notable value.

These data suggest that Louisiana Waterthrushes exhibit a relatively fast-paced migration for a songbird species. With an average migration duration of 12.7 days, these roughly 20-gram warblers can be broadly categorized into time minimizers. It is important to keep in mind that the migratory strategies employed over 2-4 migrations by 4 local populations may not be indicative of the entire species, but it serves as a useful indicator. Additionally, the analysis of geolocation data is not exact. 1 and 2 day migration durations were reported for 2 individuals (Table 1). These extremely fast-paced migrations are unlikely considering the physics of songbird migratory abilities. Errors with geolocation data could be attributed to shading at the birds' locations (e.g., the device did not receive ample ambient light levels needed for an accurate reading) or could be attributed to the analysis methods. Nevertheless, the short durations still provide evidence that the species employs a time-minimizer approach to migration.

The time minimizing strategy has many implications. First, individuals must have sufficient food supplies on their respective breeding and nonbreeding territories as they prepare for a migratory journey that will entail only a few stops to refuel. Further, individuals that minimally utilize stopover sites and spend short periods at these sites likely require quality stopover habitat that provides sufficient nourishment. Stopover habitat for any migratory species plays a critical role and needs to be of sufficient quality for obvious reasons. But with little time to spare foraging, it is reasonable to assume that stopover habitats for time minimizing species may need to be exceptionally productive to accommodate such a fast migration.

Birds have evolved to employ very specific migratory strategies in order to make migration possible and productive. Factors that alter these fine-tuned strategies, such as insufficient habitat on stopover sites, have the potential to fundamentally change the type of migration (i.e., speed and time spent in migration) employed by a bird. If we assume that species' have evolved to utilize the most efficient migratory strategies possible, such alterations to a strategy have the potential to affect the likelihood of a successful migration. Not much data exist on altering strategies to compensate for factors such as low-quality habitat on stopover sites, but it is reasonable to assume that factors which change the pace of a bird's migration, particularly a time minimizer, may have negative consequences. Further study will help address these concerns.

The information yielded from studies like these can be useful to international conservation efforts, particularly by notifying where and how funding should be allocated. The Tennessee Wildlife Resources Agency (TWRA) funded a portion of this study to better inform their own international conservation efforts. Funding is often allocated to state agencies to spend on conservation work at the wintering grounds of local populations of migratory birds that spend the breeding season in the respective state. With validated information on the wintering grounds of certain breeding populations, the state agencies can direct their funds to areas that they know their local populations utilize in the nonbreeding period. Migratory timing can also help influence these monetary decisions. For instance, species that spend many weeks in migration may utilize a number of stopover sites, and the conservation of these stopover sites is critical to enable successful migrations. On the other hand, time minimizing species may only use one or two stopover sites, which may deem these stopover sites as exceedingly vital for a successful migration.

Cultural Exchange Program

By heightening awareness of migratory birds' annual cycles, a shared sense of responsibility can be achieved among the people that live in critical conservation areas. A sense of shared responsibility over the status of these migratory birds is a critical step in gaining support for comprehensive conservation policy, awareness of the perils faced be migratory species, and even individual decisions that may affect habitats. A geographically and politically collaborative effort is essential for truly successful, long-term conservation action. Neotropical migratory songbird conservation therefore warrants an international approach in which all communities involved in the species' annual cycles work together to ensure the welfare of the migratory populations.

The Petén Birders Association (PBA) and Caoba Birders Club (CBC) are two grassroot groups located in the Petén region of Guatemala. Although there are slight distinctions, both groups focus on environmental education, eco-tourism, and promote habitat protection. A considerable portion of the people affiliated with these groups work as eco-tourism guides for part of the year then volunteer their time traveling throughout the region to lead environmental education efforts with school and community groups the remainder of the year. A main objective of their efforts is to raise awareness of Guatemala's unique biodiversity and instill a sense of responsibility over the welfare of local wildlife. The groups work together to actively mitigate threats to local bird populations ranging from dissuading school children from shooting birds with slingshots (i.e., a non-subsistence activity) to promoting eco-tourism as an alternative means to profit from family farms rather than selling the property to foreign agricultural production (e.g., palm oil production). Additionally, the groups' educational endeavors seek to simply bring awareness to an exceedingly imperiled natural treasure of Guatemala: unparallel avian biodiversity. Through deliberate action, PBA and CBC have demonstrated why birds are worth protecting to many villages and schools through lessons on ecosystem function and services, eco-tourism industries, regional pride, and environmental ethics. Whenever possible, researchers should consider incorporating the human communities that are involved in Neotropical bird migration. Such efforts will help shape the paradigm that we all share the responsibility to protect the habitats that these species rely on. Migratory birds do not take notice of political boundaries and efforts to protect them should not either. Conserving migratory wildlife is an arduous task, but it is one that we can achieve through a collaborative, international approach.

Recommendations for Future Research

Since no published data exists pertaining to marking either species with geolocators, the opportunity for a metanalysis is not yet possible. Once more published data emerges, we recommend that future research readdresses these questions with larger sample sizes in order to make more robust conclusions.

More compelling results could be reached pertaining to the geolocator effects on body mass with larger sample sizes. We recommend that future research efforts consider categorizing individuals into distinct breeding season stages to account for changing body mass. A deeper investigation into the breeding success of geolocator-marked individuals is also worthwhile. Future studies could attempt to identify more conclusive breeding success estimates on a larger scale, such as actual observation of a nest or the presence of young.

In order to inform land mangers on how to improve habitat for Louisiana Waterthrushes and Worm-eating Warblers, more questions need to be answered. Revealing facets of migratory strategies and behaviors are critical steps, but further study into the dynamics of these strategies and how they relate to stopover habitat dependence, geographical areas, and much more is needed. Investigation into the habitat quality at each breeding site could reveal a correlation between habitat quality and migration duration. Individuals at exceptionally productive breeding habitats may have enough fat reserves to complete a faster migration than those that prepared for migration on lower quality sites. For this project, the geographical connection of the four local populations with their respective breeding and nonbreeding grounds and the migration pathways will be released in subsequent research papers. This thesis research was part of a collaborative project between multiple universities and organizations. Each sub-group tackled different aspects of the project. I also believe there are many research opportunities to determine how stopover site quality may impact Louisiana Waterthrush migration. Studies that mark migrants with GPS tracking technology at stopover sites of various habitat quality levels can begin to determine how much factors like these affect the overall picture for a migration.

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VITA

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