A Thesis

entitled

Post-fledging and Migration Ecology of Gray Vireos (*Vireo vicinior*) and Using ArtScience to Explore Gender and Identity

by

Silas E. Fischer

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the
Master of Science Degree in
Biology

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An Abstract of

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Many Neotropical migratory songbirds are experiencing significant population declines (Wilcove and Terborgh 1984, Robbins et al. 1989, Rosenberg et al. 2019), the majority of which remain critically under-studied, impeding informed, science-based conservation and management. To effectively implement conservation and management strategies, it is critical to understand population dynamics and demography, which are most informative when all stages of a species' life cycle are incorporated (Sillett and Holmes 2002, Anders and Marshall 2005, Streby and Andersen 2011, Peterson et al. 2016, Kramer et al. 2018). In migratory passerines, this means considering the full annual cycle, including periods that may be difficult to study (e.g., migration, the non-breeding season, and the post-fledging period; Sillett and Holmes 2002, Webster et al. 2002, Anders and Marshall 2005, Streby and Andersen 2011, Cox et al. 2014, Marra et al. 2015, Peterson et al. 2016, Kramer et al. 2018).

Knowledge of annual cycle ecology is especially limited for female songbirds, desert-dwelling songbirds, and other western USA Nearctic-Neotropical migrants (McKinnon and Love 2018, Bennett et al. 2019, Hedley 2019), which have experienced

community wide declines in the past century (Iknayan and Beissinger 2018). The Gray Vireo (*Vireo vicinior*) is a small (~11-14 g), under-studied migratory songbird that breeds primarily in piñon (*Pinus* spp.)-juniper (*Juniperus* spp.) savannas and structurally similar arid landscapes in the southwestern United States and northwestern Mexico (Barlow et al. 1999; but see Hargrove and Unitt 2017 for chaparral habitat associations of the likely-disjunct California population). Gray Vireos are currently listed as threatened in New Mexico (NMDGF 2018), as a species of Conservation Concern by US Fish and Wildlife Service (USFWS 2008), and as a Watch List Species by Partners in Flight (Rosenberg et al. 2016). These listings are likely due to a lack of demographical information (Schlossberg 2006), a restricted range, and a relatively small global population (estimated at ~400,000 individuals; Rosenberg et al. 2016).

Range-wide population trends for Gray Vireos are unclear because they occupy remote, inhospitable breeding habitats that are often away from roads and are therefore not well surveyed by Breeding Bird Survey (BBS) routes (Barlow et al. 1999, Schlossberg 2006, Sauer et al. 2014, Hargrove and Unitt 2017). The BBS data indicate that Gray Vireo numbers be increasing in New Mexico (though not statistically significant), but these trends may be misleading (Schlossberg 2006, NMDGF 2007, Sauer et al. 2017) because < 15% of routes in New Mexico detected the species (DeLong and Williams 2006). Compared to many other North American birds (e.g., wood warblers, Family Parulidae), there is a dearth of annual cycle data for Gray Vireos (see Figure A-1 for a brief illustration of the annual cycle). Studies of Gray Vireo breeding biology are severely biased towards the nesting stage (i.e., using nest success as the sole measure of productivity). However, incorporating demographic data from the post-fledging, migration, and nonbreeding periods is essential to determine full-season productivity, assess population trends, and ultimately identify potential limiting factors to population growth (Webster et al. 2002, Faaborg et al. 2010, Streby et al. 2014, Peterson et al. 2016, Kramer et al. 2017, Kramer et al. 2018). The post-fledging and migration stages have not been studied in Gray Vireos; fortunately, Bates (1987, 1992a-b) has studied the nonbreeding season in a portion of the species' range.

Causes for concern with Gray Vireos include habitat loss, climate change, brood parasitism by Brown-headed Cowbirds (*Molothrus ater*), and impacts of drought (Barlow et al. 1999, Walker and Doster 2009, Hargrove and Unitt 2017). The piñon-juniper habitat that most Gray Vireos and some other species of conservation concern (e.g., Pinyon Jays [*Gymnorhinus cyanocephalus*]) depend on during the breeding season is being continually altered for production of forage for agriculture, extensive juniper chaining, pine mortality, manipulation for firewood, and fire suppression, among other processes (Barlow et al. 1999, DeLong and Williams 2006, Schlossberg 2006, Walker and Doster 2009, Crow and van Riper 2010, Johnson et al. 2018). Chaining is the practice of using two coordinated bulldozers to drag a large chain across a shrubby landscape (e.g., piñon-juniper woodlands) for the purpose of game wildlife management, increasing land area to be used by livestock, and decreasing wildfire risk (Redmond et al. 2013). Juniper chaining has mixed effects on non-game wildlife (O'Meara et al. 1981) but may be detrimental to Gray Vireos and other piñon-juniper specialists (Crow and van Riper 2010, Johnson et al. 2018). Effects of oil and gas development are not known but may be more prevalent in northwestern New Mexico (Walker and Doster 2009). Impacts of woody shrub encroachment (i.e., the spread of junipers and other woody plants into native grasslands) and wildfire on Gray Vireos remain unclear (Walker and Doster 2009, Hargrove and Unitt 2017, but see Schlossberg 2006).

This thesis focuses on two major, unstudied portions of the annual cycle in Gray Vireos – the post-fledging period and migration. Both the post-fledging period and nonbreeding periods (including migration) can disproportionately affect population growth (Sillet and Holmes 2002, Streby and Andersen 2011), highlighting the importance of accurate, empirically derived estimates of fledgling survival and the need for understanding migratory ecology. In addition to studying the annual cycle of Gray Vireos, I also created a body of artwork, *Molt*, in response to this research that integrates scientific metaphors from my first two chapters with gender identity.

Migration, in a sense, is about returning and homecoming, and the urge to migrate can present as anxious restlessness (i.e., *zugunruhe*) induced by the endocrine system. Prior to and even during their migrations, Gray Vireos and other migratory songbirds must prepare for their journeys by molting their feathers among other processes. Molting is a profound disturbance of endogenous metabolism, a process whereby animals shed worn tissue, such as feathers, hair, and exoskeletons, that is often prompted by life cycle stages such as the transition from the breeding season to migration. In the series *Molt*, I drew parallels between my transition through hormone replacement therapy (i.e., testosterone) as a queer, transsexual person and the transition between songbirds' annual life cycle stages. Both migration and testosterone injections cause profound physiological changes, or *molting*, of the past, and both involve repeated "homecoming". I used multimedia techniques in glassblowing and kiln casting to explore gender and queerness while engaging viewers with wildlife science and conservation.

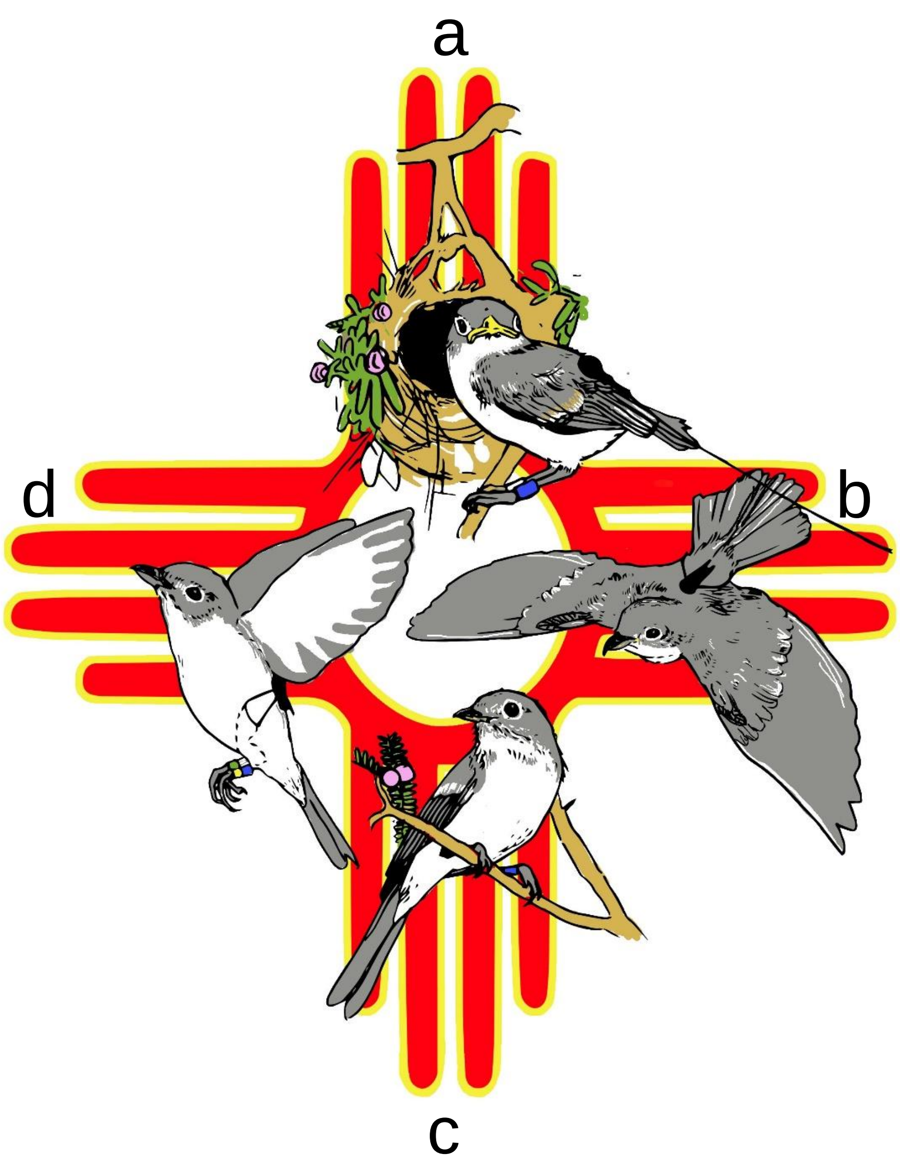

Figure A-1: Illustration of the full annual cycle in Gray Vireos (*Vireo vicinior*) in New Mexico, including a) the breeding period (i.e., nesting and post-fledging stages), b) migration from breeding to nonbreeding sites, c) the nonbreeding period, and d) migration from nonbreeding sites back to breeding sites. (© Silas Fischer)

For fellow trans and gender non-conforming scientists, and for the "dullest, drabbest bird in North America," the Gray Vireo.

Acknowledgments

I acknowledge that this field research was conducted on the land and territories of indigenous Mescalero Apache, Pueblos, and Ute people.

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Thank you to my therapists, who continually remind me that self-care is an important and necessary component to success in graduate school and life in general. Thanks to my dad, who sparked my interest in studying birds, and to my mom, the most empathetic person that I know.

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Chapter 1

Post-fledging Ecology of Gray Vireos at Sevilleta National Wildlife Refuge, New Mexico

1.1 Introduction

Traditionally, due to lack of appropriate technology, many studies that quantify reproductive success of songbirds include only the nesting stage, thereby excluding the post-fledging period. However, these two components of full-season productivity can be interdependent, and either measure alone can be misleading (Anders and Marshall 2005, Streby and Andersen 2011, Streby et al. 2014). Importantly, annual population growth (λ) in birds may be particularly sensitive to juvenile (hereafter, fledgling) survival in addition to nonbreeding period (including migration) survival, but these two portions of the annual cycle are studied least often (Anders and Marshall 2005, Streby and Andersen 2011, Cox et al. 2014).

Gray Vireo nesting success (i.e., the probability of completing a nesting attempt with ≥ 1 nestlings fledging) at the Sevilleta National Wildlife Refuge (NWR) is typically ~25% (S.E. Fischer, K. Granillo, and H.M. Streby, unpublished data), which is relatively low compared to other estimates in New Mexico (DeLong and Williams 2006). A variety of factors may contribute to this low nesting success, such as brood parasitism by Brown-headed Cowbirds (*Molothrus ater*; hereafter, cowbird) a songbird that lays its eggs in the nests of other species, leaving their young to be raised by the host, and nest predation (Barlow et al. 1999, DeLong and Williams 2006). Average Gray Vireo clutch size is ~3 eggs (Barlow et al. 1999), and nests at Sevilleta NWR have all been in oneseed juniper trees (*Juniperus monosperma*; S.E. Fischer, K. Granillo, and H.M. Streby, unpublished data). Gray Vireos may make up to six nesting attempts per year, and can sometimes produce second broods (i.e., nest again after having successfully nested once; Hargrove and Unitt 2014), although it remains unclear if double brooding occurs at Sevilleta NWR and whether this species can raise two fledged broods to independence in a single year.

The post-fledging period, or the stage after fledglings leave the nest and prior to migration, is critical to assessing avian productivity and population growth (Wightman 2009, Streby 2010, Cox et al. 2014); however, this stage has not been studied in Gray Vireos (Barlow et al. 1999). The survival of fledglings is important for population growth, and annual variation in survival can cause population fluctuations (Sullivan 1989, Robinson et al. 2004, Anders and Marshall 2005, Streby and Andersen 2011, Tarwater et al. 2011, Cox et al. 2014). Fledglings of relatively large songbirds (e.g., Wood Thrush [*Hylocichla mustelina*]; 40-50 g) were first tracked with radio telemetry >25 years ago (Anders et al. 1997, 1998) and the technology is now sufficiently small with adequate battery life to track tiny songbirds (e.g., Golden-winged Warbler [*Vermivora chrysoptera*]; 7-10 g). However, because this technology is new compared to the ability to find and monitor nests (Bendire 1889), and because of the expense and difficulty in collecting data on individual fledglings, the post-fledging period remains one of the most poorly understood portions of the full annual cycle, along with migration (Baker 1993, Cox et al. 2014). In the Northern Hemisphere, many post-fledging studies have been conducted in temperate forests (e.g., Anders et al. 1997, Anders et al. 1998, Streby and Andersen 2011, Vitz and Rodewald 2011, Chandler et al. 2012, McKim-Louder et al. 2013, Streby and Andersen 2013, Jenkins et al. 2017, Vernasco et al. 2017, Delancey and Islam 2019, Raybuck et al. 2020), grasslands (e.g., Yackel Adams 2006, Fisher and Davis 2011), and riparian areas and wetlands (e.g., Vormwald et al. 2011). Southwestern desert and arid land systems are under-represented in the literature of fledgling movements and survival (see Cox et al. 2014).

The post-fledging period is generally divided into the dependent stage, during which fledglings are attended to by parents, and the independent stage, or the stage of independence from adult care prior to migration or dispersal (Dybala et al. 2013, Cox et al. 2014, Goguen 2019). The length of these stages varies among and within species (Tarwater and Brawn 2010, Cox et al. 2014). Fledgling survival is generally lowest during the first week after departing from the nest, likely because of immobility and increased vulnerability to predators and exposure (Sullivan 1989, Anders et al. 1997, Yackel Adams et al. 2006, Fisher and Davis 2011, Vitz and Rodewald 2011, Tarwater et al. 2011, Lloyd and Martin 2016). Distance traveled from the nest and minimum straight-line daily distance traveled generally increase with age (Cohen and Lindell 2004, Vitz and Rodewald 2010, Fisher and Davis 2011, Vormwald et al. 2011), and many factors may influence movements (Jenkins et al. 2017). After fledging, some species move from their breeding habitats to different cover types and/or areas of higher vegetation density when available (e.g., Anders et al. 1998, Streby et al. 2011, Streby and Andersen 2013, Delancey and Islam 2019, but see Fischer and Davis 2011, Vormwald et al. 2011, Goguen 2019). These movements are often associated with access to food (i.e., invertebrates or fruit) and predator avoidance in increased cover (Marshall et al. 2003, Streby et al. 2011). Independent post-fledging movements, or “explorations” may be linked to the need for orientation prior in migratory species in addition to finding food and other resources (Morton et al. 1991, Baker 1993).

We used radio telemetry to study post-fledging movements, survival, and habitat associations of fledgling Gray Vireos, a species of conservation concern for which few annual cycle data are available. We hypothesized that fledgling survival and movement distances would be lowest in the first few days outside the nest, similar to other passerines (Cohen and Lindell 2004, Fisher and Davis 2011, Vormwald et al. 2011, Cox et al. 2014). In addition, we hypothesized that fledglings in areas of sparser tree cover (i.e., low density of trees and shrubs) would experience greater rates of predation compared to denser areas because predators might have greater search efficiency and greater opportunity to detect fledgling movements in less structurally complex areas. Lastly, we expected fledglings to be independent of adult care within four weeks of fledging, consistent with other passerines (Cox et al. 2014).

1.2 Methods

1.2.1 Study Area

Sevilleta NWR is a 93,000-ha, limited-access refuge in Socorro County, New Mexico, USA that protects a massive arid land ecosystem at the northern limit of the Chihuahuan Desert and is managed by the United States Fish and Wildlife Service

(USFWS 2012). Sevilleta NWR also hosts several other concurrent and long-term research projects through the Sevilleta Long-Term Ecological Research (LTER) program. We conducted this study on the eastern side of Sevilleta NWR within the foothills of Los Pinos Mountains (mean elevation ~1785 m), where Gray Vireos are known to breed. Vegetation in the study area was predominantly juniper savanna comprised mainly of juniper (*Juniperus monosperma*), creosote bush (*Larrea tridentata*), and other shrubs (e.g., *Quercus* spp., *Rhus* spp., and *Cercocarpus montanus*), grasses (e.g., *Bouteloua* spp.), and succulents (e.g., *Yucca* spp., *Cylindropuntia* spp., and *Opuntia* spp.), with piñon pines (*Pinus edulis*) at higher elevations (see Stevens and Fischer 2018).

Annual precipitation in the study region averages ~250 mm, and is seasonal and generally bimodal, with most rain falling during monsoons of July – September and additional precipitation (rain and snow) occurring in winter months (Notaro et al. 2010, Baez et al. 2013, Muldavin et al. 2014, Petrie et al. 2014, Kwiecinski et al. 2020). Mean annual temperature is ~13.2 °C (Kwiecinski et al. 2020) and temperature from May to August ranges from ~ 15-38 °C.

1.2.2 Nest Searching and Monitoring

Marking and monitoring fledglings required first finding and monitoring the nests from which they would fledge. We searched for nests in May-July 2017-2019 by following Gray Vireos exhibiting breeding and nesting behavior (e.g., singing males, males or females carrying nesting material) and by radio tracking females to their nests during day and night, as radio telemetry can help reduce potential confirmation bias in traditional searching methods (Powell et al. 2005, Peterson et al. 2015). Nest locations were recorded using handheld GPS devices with waypoint averaging to improve accuracy. After locating nests, we monitored them every 3-4 days to record adult activity, nest contents (i.e., presence and number of eggs or nestlings of vireos and cowbirds) and nest condition. During the late nestling stage, we observed nests daily to determine fledge date and begin tracking fledglings.

1.2.3 Capturing, Banding, and Radio Transmitter Attachment

To our knowledge, our study is the first to employ radio transmitter attachment on Gray Vireos. We used 0.6-g radio transmitters (~5% of body mass; Blackburn Transmitters, Nacogdoches, TX) with a modified figure-eight leg-loop harness (Rappole and Tipton 1991, Streby et al. 2015) that has been successfully implemented in other studies of small migratory songbirds with no apparent deleterious effects (e.g., Streby et al. 2013, Peterson et al. 2016). Nestlings were removed from nests 2-3 days prior to expected fledging and marked with one color band and one metal U.S. Geological Survey numbered band. All nestlings within each year received the same band color, with different colors according to years for cohort identification (i.e., red in 2017, white in 2018, and blue in 2019). We randomly selected between one and four nestlings from each nest and fitted them with radio transmitters. We recorded mass and took blood samples (< 1% body mass) from all nestlings from the brachial vein using sterile 27-gauge needles and heparinized capillary tubes for future analyses. Following sampling and marking, all nestlings were returned to their nest.

To capture adult Gray Vireos, we used 12-m mist-nets and conspecific song and call playback to elicit aggression and territorial responses. All adults were marked with unique combinations of 3 color bands and one metal U.S. Geological Survey numbered band. We recorded standard morphometric data, including mass, age, wing length, and tail length. Adult sex was determined by both breeding condition (e.g., cloacal protuberances and brood patches) and behavior. We marked and tracked 23 adult female Gray Vireos (*n* = 11 in 2017, *n* = 7 in 2018, *n* = 3 in 2019) with radio transmitters (see marking methods above) to find additional nests. In 2017, we also marked 23 adults, both males and females, with light-level geolocators for a migration study (see Chapter 2); some of which were also caring for radio-marked fledglings. We took blood samples from adults using the same methods as with nestlings (see above). All work was approved and conducted under the University of Toledo IACUC protocol #108708. All sampling and marking methods were identical among years.

1.2.4 Radio Tracking Fledglings

We used standard ground-based telemetry methods to track each fledgling daily in 2017 and 2018 and monitor survival, space use, and habitat associations. We used VHF handheld receivers (Model R410, Advanced Telemetry Systems, Isanti, MN, USA) and directional antennas (Model RA-23K flexible “H”-type, 148-154 MHz, Telonics Inc., Mesa, Arizona, USA) for all radio telemetry. In 2019, due to logistical constraints from a large sample size, we reduced tracking frequency to once every 3 days after fledglings reached 12 days post-fledging. Inclement weather sometimes prohibited daily tracking (e.g., when roads were washed out), but the logistic exposure survival analysis we used incorporates variable interval lengths (Shaffer 2004). We tracked all fledglings until confirming or suspecting mortality, transmitter failure, or signal loss. Upon locating each fledgling using radio telemetry, we recorded their locations using GPS units with waypoint averaging for accuracy of < 5 m. In addition, we recorded fate (i.e., alive or dead), other fledglings and/or adults observed nearby, activity of adults and fledglings (e.g., foraging, feeding), vocalizations (e.g., begging), fledgling height from ground, and vegetation data (i.e., substrate and lateral vegetation density). We measured lateral vegetation density using a 2-m tall by 0.25-m wide profile board divided into eight squares, which we hung from a collapsible stand at each fledgling point (i.e., where the fledgling was initially observed when tracking; see Streby et al. 2013a, 2016). We visually estimated percent cover in each of the eight squares from 10 meters North and 10 meters East of the profile board. All 16 values were then averaged to obtain one estimate of lateral vegetation density at each fledgling location (see Streby et al. 2013a, 2016).

We followed similar methods to Streby et al. (2016) and Yackel Adams et al. (2006) to identify potential predator types (i.e., small mammals, avian predators, etc.) of Gray Vireo fledglings following radiotracking if we were unable to confirm the predator species. We attributed predation to small mammals if transmitter signals emanated from underground burrows, or if we recovered transmitters along with appendages (i.e., legs and feet) or leg bands that had been removed (see Streby and Andersen 2011). We acknowledge that when fledglings were located underground, we were unable to rule out predation by snakes, which often use small mammal burrows (Kinlaw 1999) and are known to depredate birds. We assumed avian predators if we recovered transmitters that were kinked and/or located in a pile of plucked feathers. We assumed non-predation (i.e., apparent exposure) when we observed in-tact carcasses (see Yackel Adams et al. 2006) with no sign of carnage or feather loss, or when otherwise undamaged carcasses were covered by ants, which we assumed occurred following death by exposure.

1.2.5 Analysis of Fledgling Movements and Brood Division

We obtained high-resolution digital orthophotography (National Agricultural Imagery Program [NAIP] available through New Mexico Resource Geographic Information System [RGIS]) to visualize our study areas. Because some radio-marked females selected nest sites outside of where we searched, and because we could not predict where fledglings would travel, we established the boundaries of our study sites post hoc such that the area included all nest and fledgling locations with a buffer of ~100 m. We used supervised classification in ArcMap (v10.7.1) to differentiate shrubs and trees (e.g., juniper, pinyon pine, oaks, creosote) from bare ground, rock, and smaller vegetation (e.g. forbs) to create a measure of tree cover. Grasses and other plants were excluded from tree cover classification because fledglings were not observed using those substrates. We imported the classified raster for use in QGIS, an open-source mapping software (QGIS Development Team 2020). We classified the raster tree layer in QGIS as binomial (i.e., tree or not tree), such that percent area covered by tree could be calculated for any area to estimate tree cover.

We created 25-m radius buffers around each fledgling location (during the first 12 days post-fledging) and nest location. We selected the 25-m radius (~1,964 m^2) buffer by consulting literature for home range sizes of small mammals in the Southwest USA, the assumed predominant predators of Gray Vireo fledglings at Sevilleta NWR. We assumed this 25-m buffer size was biologically relevant based on potential predators and small enough to describe potential variation in survival among areas used by fledglings. Small mammals in this ecosystem occupy home ranges from ~200-2000 m^2 (e.g., 486 m^2 in *Neotoma albigula,* Macêdo and Mares 1988; 220 m^2 in females and 1900 m^2 in males in *N. micropus*, Conditt and Ribble 1997. We generated 600 random points and associated 25-m buffers within study site polygons to compare post-fledging and nest habitat associations with non-used but presumably available areas. Within each buffer, we used the classified raster tree layer and extracted the percentage of tree cover using zonal statistics by dividing the sum (# of tree pixels) by the count (total # of pixels) and multiplying by 100. Tree cover percentages from buffers were then added as covariates in survival models.

We calculated minimum daily distance traveled and daily distance from the nest using the Haversine (i.e., shortest distance between daily points on the sphere) method using the geosphere package in R (v.1.5-10; Hijmans 2019). We included only distances between consecutive daily locations because it is inappropriate to interpolate minimum distance moved during periods shorter than that observed (e.g., minimum distance over two days cannot be divided by two to estimate daily distance unless the individual moves constantly in one direction). To avoid pseudoreplication in all movement analyses, we averaged all daily movement values for broods in which broodmates fledged at the same age from hatching. Within these broods, if daily data were not available for some broodmates, we used data (if available) from other broodmate(s). To account for variation in ages from hatching in all other broods, we randomly selected one fledgling for analyses, unless we had more observation data for one broodmate, in which case we chose that fledgling to include in analyses. We acknowledge the possibility that broodmates with more observation data were more likely to be observed and may have moved shorter distances; however, broodmates tended to move similar distances to one another. In broods that exhibited clear brood division, we considered movement data from female-reared fledglings to be independent from those of male reared fledglings. We defined brood division conservatively as clear spatial segregation between adult males and females and their associated fledglings. Therefore, we accounted for the minimum percentage of brood division and acknowledge that this phenomenon may be more prevalent than was detectable (e.g., inconspicuous or smaller differences between adult males and females in terms of space use, especially for broods in which we tracked fewer fledglings). We present median distances instead of means because movement data were not normally distributed.

Many previous studies have defined fledgling age in terms of days after leaving the nest (but see Cohen and Lindell 2004). However, Gray Vireos fledged from their nests 9-15 days after hatching and this variation was not attributable to variable growth rates (i.e., birds that hatched 14 days ago were developmentally indistinguishable regardless of whether they had fledged yet). We therefore used age from hatching in our movement analyses (see Cohen and Lindell 2004) and survival models (see below) to account for the wide range of development at the time of fledging.

1.2.6 Fledgling Survival and Logistic Exposure Modeling

Prior to running survival models, we used Winterstein's Chi-squared test of independence to assess interdependence among fledglings within broods in which we monitored >1 fledgling (Winterstein 1992). Winterstein *P*-values < 0.05 indicate that survival among broodmates in non-independent and individuals should not be treated as independent samples (Winterstein 1992), warranting inclusion of brood as a random effect in our models.

We used logistic exposure models (i.e., modified generalized linear models; Shaffer 2004) to estimate fledgling survival and to allow covariates and hypothesis testing following Mayfield’s exposure methods (1961, 1975). Covariates for fledgling survival models included year, ordinal date, age from hatch, fledgling height from ground, elevation, substrate lateral vegetation density, and tree cover within a 25-m radius. In these models, we included only the first 12 days post-fledging because we did not observe any mortalities after day 11 in any year. We censored non-predation mortalities (i.e., apparent exposure) from analysis of habitat associations with survival because those mortalities were clearly associated with annual climatic conditions and not with vegetation variables (S.E. Fischer, unpublished data). Birds that died on day-1 post-fledging due to non-predation were therefore excluded from these vegetation models altogether, and those that died of exposure after day-1 were censored on the day they died. We included a random effect of brood in fledgling survival models to account for interdependence among individuals from the same nest following a Winterstein’s Chi-squared test of independence ($P = 0.003$). We considered $\alpha \leq 0.05$ to be statistically significant and models were ranked and chosen using Akaike’s Information Criterion adjusted for small sample sizes (ΔAICc; Burnham and Anderson 2002). We considered a parameter to be uninformative if a model including that parameter was otherwise identical to the highest-ranking model and was within 2 AICc (Arnold 2010).

To describe overall fledgling period survival from 2017-2019 for demographic applications and comparisons, we used all types of mortality in our model to generate daily survival estimates. For the first few days post-fledging, we used a correction in the daily survival estimate for the proportion of fledglings in the sample each day because some fledglings departed the nest at different ages from hatch (range: 9-15 days, median and mean = 12 days).

1.3 Results

1.3.1 Fledgling Survival and Habitat Associations

We tracked a total of 90 fledglings (*n* = 30 2017, *n* = 19 in 2018, and *n* = 41 in 2019) from 42 nests (*n* = 13 in 2017, *n* = 8 in 2018, *n* = 21 in 2019). Overall, fledgling survival was 0.51 (*n* = 44 mortalities total), including data from 2017-2019 and all mortality types. Fledging dates ranged from 14 June to 19 July (mean = 29 June ± 8 days SD) and mean nestling stage length (i.e., the age from hatch at which a fledgling departed the nest) was 12 ± 1 days SD but ranged from 9-15 days (Figure 1-2). Of the 44 mortalities, 48% (*n* = 21) were due to predation and 52% (*n* = 23) due to exposure. Of the 21 predation mortalities, 62% (*n* = 13 of 21) were presumably due to small mammals or snakes, 29% were attributed to avian predators (*n* = 6 of 21), and 10% (*n* = 2) were due to unknown predators. We identified 2 predators and one probable predator; we tracked one transmitter to a Swainson's Hawk (*Buteo swainsoni*) nest, one to a desert striped whipsnake (*Masticophis taeniatus taeniatus*), and one to a pile of feathers under a tree on which we observed a Loggerhead Shrike (*Lanius ludovicianus*) on the same day.

Focusing on predation, daily survival of fledglings was positively associated with age (Figure 1-1). Two models slightly outperformed the age-only model, one including age and hatch date and one including age and ordinal date. These models suggested a tendency toward lower survival later in the season. However, 95% confidence intervals around the effects of hatch date and ordinal date included zero. Other apparently competitive models likely included non-informative parameters because those models included only one addition parameter and ΔAICc was < 2 for each (Arnold 2010). Fledgling survival was lowest during the first 2 days post-fledging (i.e., between ages 10-13 days from hatching) with no observed mortality after day 11 from fledge (i.e., ~21-24 days from hatching) in any year. We were unable to determine the date upon which fledglings became independent from adult care due to logistical constraints, as many were still observed with parents as late as 45 days (i.e., ~58 days after hatching) and some transmitter batteries began expiring around ~28-36 days of use. We observed wing fluttering behavior and confirmed adults feeding fledglings as late as 43 days post-fledging (54 days after hatching).

During the first 12 days post-fledging at the 25-m-radius scale, Gray Vireo fledglings used areas of denser tree cover (mean 15 ± 9%) compared to random points (mean 9 ± 9%; $t = -10.6$, $df = 1206.5$, $P < 0.001$). At the same spatial scale, fledglings and nests (mean 15 ± 10%) were in areas of similar tree cover ($t = -0.5$, $df = 194$, $P = 0.6$). Including data from the entire monitoring period, fledglings occupied juniper in 88% of observations (951 of 1078 observations, $n = 90$ individuals; Figure 1-6). For the remaining 12% of observations (127 of 1,078 observations), fledglings were found most often in oaks (*Quercus* spp.; 37 observations), alder-leaf mountain mahogany

(*Cercocarpus montanus*; 23 observations), and creosote bush (*Larrea tridentate*; 20 observations), and <10 observations in each of sumac (*Rhus microphylla*, *R. trilobata*, or *Rhus* spp.), piñon pine (*Pinus edulis*), cholla (*Cylindropuntia* spp.), red barberry (*Mahonia haematocarpa*), and dead vegetation (Figure 1-6). Over the entire monitoring period, fledglings used locations with a mean of 60 ± 24% lateral vegetation density, which did not differ from that of nest locations (mean 56 ± 26%, n = 118 nests; t = 1.6, df = 135.8, P = 0.1). As fledglings aged, they used slightly decreasing lateral vegetation density but with considerable variation; fledglings used a mean of 61 ± 23% lateral vegetation density until 20 days post-fledging and 58 ± 24% after 20 days post-fledging with a statistically significant slope but no apparent biologically significant change (R^2 = 0.006, df = 1076, P = 0.02). Many fledgling locations were on north-facing slopes and/or near or in arroyos (S.E. Fischer, personal observation), or ephemeral, intermittently dry drainage channels (Waters and Haynes 2001) that are often associated with larger and more numerous shrubs compared to surrounding areas presumably due to increased soil moisture (Balding and Cunningham 1974).

1.3.2 Fledgling Movements and Brood Division

The minimum daily distance traveled, distance from nests, and variance associated with these measures, increased with age in Gray Vireo fledglings in all three years (Figure 1-3 and 1-4). There was a pronounced increase in the variance around minimum daily distance and distance from nest at ~40 days after hatching, attributable to a combination of some birds making relatively large movements at that time and our relatively small sample size of older fledglings. We confirmed brood splitting by clear spatial separation of male- and female-reared fledglings in 2 broods. We do not know what percentage of broods were split because we did not mark all fledglings from many broods and we did not account for broods that may have been split with regard to parental sex but did not segregate spatially or for broods in which fledglings attended to by only one parent may have been the only fledglings that survived the early post-fledging period. In the two broods that were clearly divided, females and their associated fledglings traveled away from the nesting territory, while males and their associated fledglings remained near the nest. Spatial separation in split broods occurred ~9 days after fledging. In 2017, we observed one case of brood division in which an adult female and one fledgling moved west and separated from the male and the associated fledgling between days 8-9 post-fledging (Figure 1-5-a). In 2018, we observed one pair dividing their brood (Figure 1-5-b). The adult female and the associated fledgling moved away from the natal area around day 9, after which they gradually traveled > 2.5 km from the nest and maintained a small area; the adult male and the associated fledgling maintained a larger area around the nest. In 2019, we did not observe any apparent cases of brood division.

1.4 Discussion

1.4.1 Fledgling Survival and Habitat Associations

The post-fledging period in Gray Vireos was similar in many ways to that of other songbirds. Overall fledgling survival (0.51) in Gray Vireos is somewhat average in the context of a post-fledging survival meta-analysis (range 0.23-0.87; Cox et al. 2014). Compared to other small songbirds, post-fledging survival was lower than Willow (*Empidonax traillii*, 0.74) and Dusky Flycatchers (*E. oberholseri*, 0.72; Vormwald et al.

2011), Western Bluebirds (*Sialia mexicana*, 0.64; Wightman 2009), and Golden-cheeked Warblers (*Setophaga chrysoparia*, 0.73; Trumbo 2019), but was higher than a suite of other species, such as Cerulean Warblers (*Setophaga cerulea*, 0.48; Raybuck et al. 2020) and Sprague's Pipits (*Anthus spragueii*, 0.29; Fisher and Davis 2011). Survival was similar to Golden-winged Warblers (*Vermivora chryoptera*, 0.52, Streby et al. 2016).

We observed the highest mortality during the first few days post-fledging, which is consistent with other passerines (Sullivan 1989, Anders et al. 1997, Cohen and Lindell 2004, Yackel Adams et al. 2006, Vitz and Rodewald 2011, Vormwald et al. 2011, Cox et al. 2014, Goguen 2019, Raybuck et al. 2020). Our model indicated that survival approached 1.0 at ~17 days after hatching (or ~5 days post-fledging), which is relatively earlier compared to other songbird species according to a meta-analysis of post-fledging survival by Cox et al. (2014), which shows that survival becomes relatively constant after ~20 days with most mortality occurring during the first 10 days post-fledging. We found that age was the only significant predictor of survival among the covariates that might be associated with predation, consistent with ~50% of other post-fledging studies (Cox et al. 2014). Hatching date and ordinal date each had nonsignificant trends towards lower survival later in the breeding season, but confidence intervals around their effects included zero. We contend that age from hatch is a more biologically relevant measure of age or development compared to age from fledging and should be considered in other studies when nestling stage length varies among nests or when hatching or fledging dates are variable within broods. Because our objective was to describe post-fledging survival in the context of habitat variables, further research is needed to assess the influence of additional environmental covariates, such as annual climatic differences, on survival, especially because arid lands are sensitive to climate variability (see Collins et al. 2014).

Small mammals or snakes accounted for the majority of Gray Vireo fledgling predation at Sevilleta NWR. Identifiable predators of fledglings included Swainson's Hawk, desert striped whipsnake, and likely Loggerhead Shrike (also documented in Barlow et al. 1999). Potential, but unconfirmed predators included small mammals *Neotoma albigula*, *Neotoma micropus*, *Spermophilus variegatus*, *Ammospermophilus interpres*, *Xerospermophilus spilosoma*; mesocarnivores including coyotes (*Canis latrans*) and gray foxes (*Urocyon cinereoargenteus scottii*; Hanna 1944, Barlow et al. 1999); other avian predators such as Woodhouse's Scrub Jay (*Aphelocoma woodhouseii*; known predator of Gray Vireo nestlings, S.E. Fischer personal observation), Northern Mockingbird (*Mimus polyglottos*), and Scott's Oriole (*Icterus parisorum*); and several other snake species.

Lateral vegetation density at fledgling locations and tree cover around fledglings were not associated with whether fledglings were depredated. This suggests either that predation on Gray Vireo fledglings is independent of vegetation density or that it is associated with characteristics we did not measure. Given the somewhat homogeneous nature of vegetation across our study area, it is possible that variation in predation rates occurs at larger geographic scales among sites or regions. In general, fledglings occupied juniper-dominated cover types that were similar to the nesting site, which has also been observed in Willow Flycatchers (a riparian-obligate; Vormwald et al. 2011), Sprague's Pipits (a grassland-obligate; Fisher and Davis 2011), and Black-capped Vireos (*Vireo* *atricapilla*, juniper-oak shrubland species; Martinez et al. 2019), species that could be considered habitat specialists like Gray Vireos. However, our observations are presumably based solely on dependent fledglings, whose habitat associations may differ from those of independent fledglings (e.g., Black-capped Vireos [*Vireo atricapilla*], a relatively closely related species; see Dittmar et al. 2014, 2016). Future research on survival, habitat associations, and behavior during the independent fledgling stage in Gray Vireos would be beneficial and fill additional annual cycle knowledge gaps.

1.4.2 Fledgling Movements and Brood Division

Gray Vireo fledgling movements increased with age as predicted and consistent with other passerines (Morton et al. 1991, Cohen and Lindell 2004, Vormwald et al. 2011, Streby and Andersen 2013, Cox et al. 2014, Jenkins et al. 2017, Raybuck et al. 2020). Longer daily movements and associated variation both increased between days 25-30, which is around the age when many other songbirds become independent from adult care (e.g., 23-29 days in Ovenbirds (*Seiurus aurocapilla*), Streby and Andersen 2013, Vitz and Rodewald 2010, Jenkins et al. 2017; ~30-40 days in White-crowned Sparrows [*Zonotrichia leucophrys*], Morton et al. 1991;) or disperse from the natal area (dispersal after ~31 days in White-throated Thrushes; Cohen and Lindell 2004). We observed greater variation in fledgling distance from the nest compared to minimum daily distance traveled, which was likely associated with variation in both brood division behavior (i.e., when broods split, some fledglings remained in the natal territory while others made substantial movements away from the nest) and movements back to the nest site, as observed in Willow and Dusky Flycatchers (Vormwald et al. 2011) and Cerulean

Warblers (Raybuck et al. 2020), and also due to our lower sample size as the season progressed.

We were unable to determine the length of the dependent period in Gray Vireos, as we observed older fledglings begging and being fed by parents. Similarly, Cohen and Lindell (2004) observed older White-throated Thrush fledglings (> 60 days since leaving the nest) being fed by parents and speculated there may be variation in the length of their dependent period, which we suspect may be true in Gray Vireos as well. Future research on Gray Vireo fledgling survival, habitat associations, and movements during the independent period, migration, and the nonbreeding period, though logistically challenging, would be valuable for filling additional annual cycle knowledge gaps.

To our knowledge, we present the first evidence of brood division behavior in Gray Vireos, a phenomenon that may be related to decreasing predation vulnerability (McLaughlin and Montgomerie 1985) and mate guarding (Vega Rivera et al. 2000) among other factors. However, most Gray Vireo family units either did not divide, or division was unclear. Like Wood Thrushes, Gray Vireos appear to have multiple strategies for brood division or lack thereof that may depend on adult reproductive activity (e.g., double brooding; see Vega Rivera et al. 2000). Harper (1985) suggested that brood division may be more common when additional nests are not attempted, and less common when food is abundant, but we do not have enough data to make these conclusions.

Similar sex-specific patterns in which adult females and their fledglings travel farther from the nest (or disappeared, potentially indicating significant movements, Linkhart and Reynolds 1987) have been observed in Lapland Longspurs (*Calcarius lapponicus*, McLaughlin and Montgomerie 1985), Flammulated Owls (*Psiloscops flammeolus*, Linkhart and Reynolds 1987), Hooded Warblers (*Setophaga citrina*, Evans Ogden and Stutchbury 1997, Rush and Stutchbury 2008), and Golden-winged Warblers (*Vermivora chrysoptera*, Peterson et al. 2014, 2016). Interestingly, Peterson et al. (2014, 2016) showed that adult female and male Golden-winged Warblers exhibited similar space use until days 9 and 10 (though not taking age from hatching into account), when females began to make directed movements away from the nest territory; we observed similar patterns in a very different study species and system. Description of brood division was not a primary goal of our study, and further research is needed to assess how factors, such as weather, food abundance, and re-nesting attempts could potentially influence brood splitting behavior occurrence in Gray Vireos and other species.

1.4.3 Management Implications

Our management recommendations may be population-specific or at least may have better application in the central section of the Gray Vireo Recovery Plan Management Units, which include Socorro, Valencia, Bernalillo, Santa Fe, Los Alamos, Torrance, and portions of Cibola, San Miguel, Lincoln, Taos, Rio Arriba, Colfax, Guadalupe, and Catron counties of New Mexico (NMDGF 2007), or in areas of similar juniper-dominated cover type and elevation. Fledgling survival on Sevilleta NWR may be higher than in other parts of New Mexico, considering Sevilleta NWR has not been grazed since 1973 and is not being actively fragmented like many other juniper-dominated areas in the state (K. Granillo, personal communication). Fledgling survival was not associated with the habitat variables we measured, but nests and fledglings were located in areas with significantly denser vegetation cover compared to random points across the study area. This suggests that Gray Vireos might benefit from maintenance of relatively dense areas of juniper, especially on North-facing slopes and in and along arroyos, consistent with some findings by Wickersham et al. (2016), but these observations may be site-specific. Specifically, areas used for nesting and raising fledglings at our study site had ~15% juniper cover within a 25-m radius and areas not used generally had <10% juniper cover. Fledglings used juniper in almost 90% of observations with ~60% average lateral vegetation density. Because we found both nests and fledglings in junipers of varying lateral vegetation density, we suggest maintaining juniper heterogeneity in terms of size, individual tree density, and tree cover. Doing so may benefit other birds of conservation concern, such as Pinyon Jays, a species that is experiencing significant population declines and has been shown to use areas of relatively denser cover than Gray Vireos (Johnson et al. 2015).

If juniper chaining, fire, herbicide treatments, or other vegetation management strategies are prescribed, we recommend limiting such management to areas with relatively sparse juniper cover (i.e., <10% within 25-m radii) to limit potential negative impacts to Gray Vireo habitat. If habitat alteration must occur, we recommend taking junipers in areas where they are invading historical grasslands, especially edges, and/or avoid taking many wider, taller (i.e., older) junipers that have been shown as important nesting trees at sites similar to Sevilleta NWR (Johnson et al. 2015, Wickersham et al. 2016, Harris et al. 2020, but see Schlossberg 2006).

It will be important to quantify Gray Vireo reproductive success, including nest productivity and fledgling survival, before and after habitat management to assess how various management actions affect this species of conservation concern. Studying the post-fledging period can be logistically challenging; if empirical estimates of fledgling survival are not available, we recommend at least including both lower, more conservative estimates and a range of such estimates in population modeling, as survival can vary annually (Anders and Marshall 2005, Streby and Andersen 2011). Equating nesting success with productivity while ignoring the post-fledging period may produce nescient conservation outcomes and misunderstandings in the context of the annual cycle (Anders and Marshall 2005, Streby and Andersen 2011).

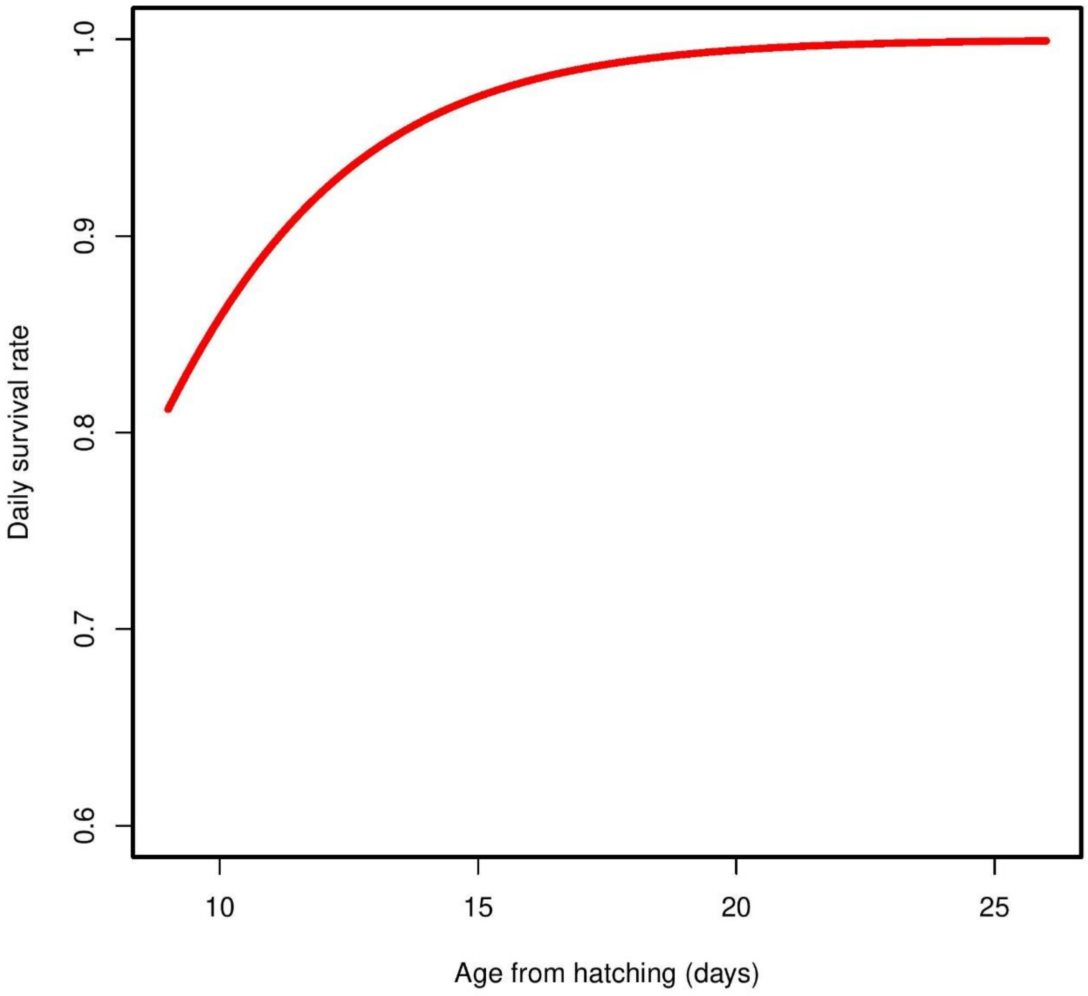

Figure 1-1: Daily survival rate of Gray Vireo fledglings during the post-fledging period at Sevilleta National Wildlife Refuge, New Mexico, from 2017-2019. Estimates were produced from the best-supported logistic exposure model using only fledglings that died due to predation (i.e., excluding fledglings that died due to exposure), with a random effect of brood, and age from hatching as the sole covariate.

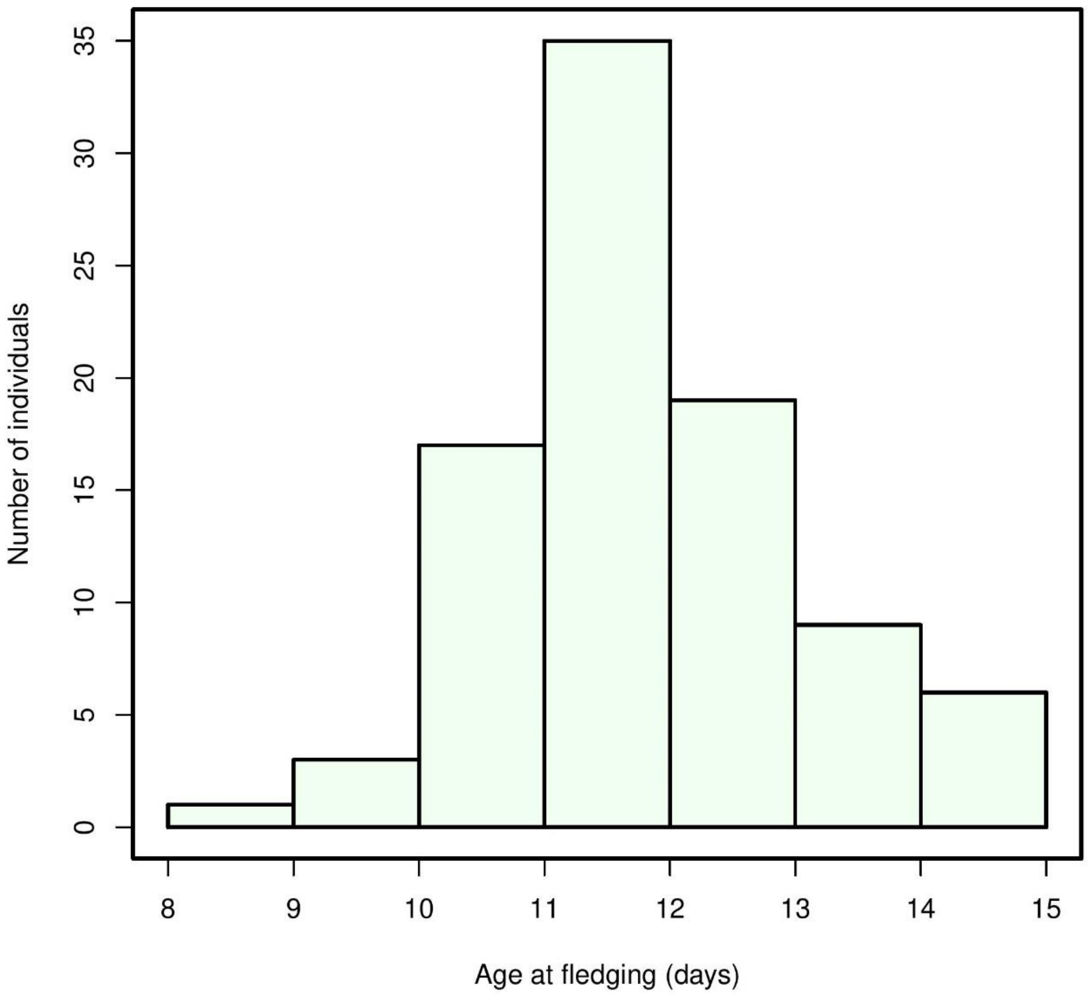

Figure 1-2: Distribution of ages at fledging (i.e., nestling stage length) for Gray Vireo fledglings on the Sevilleta National Wildlife Refuge, New Mexico, from 2017-2019.

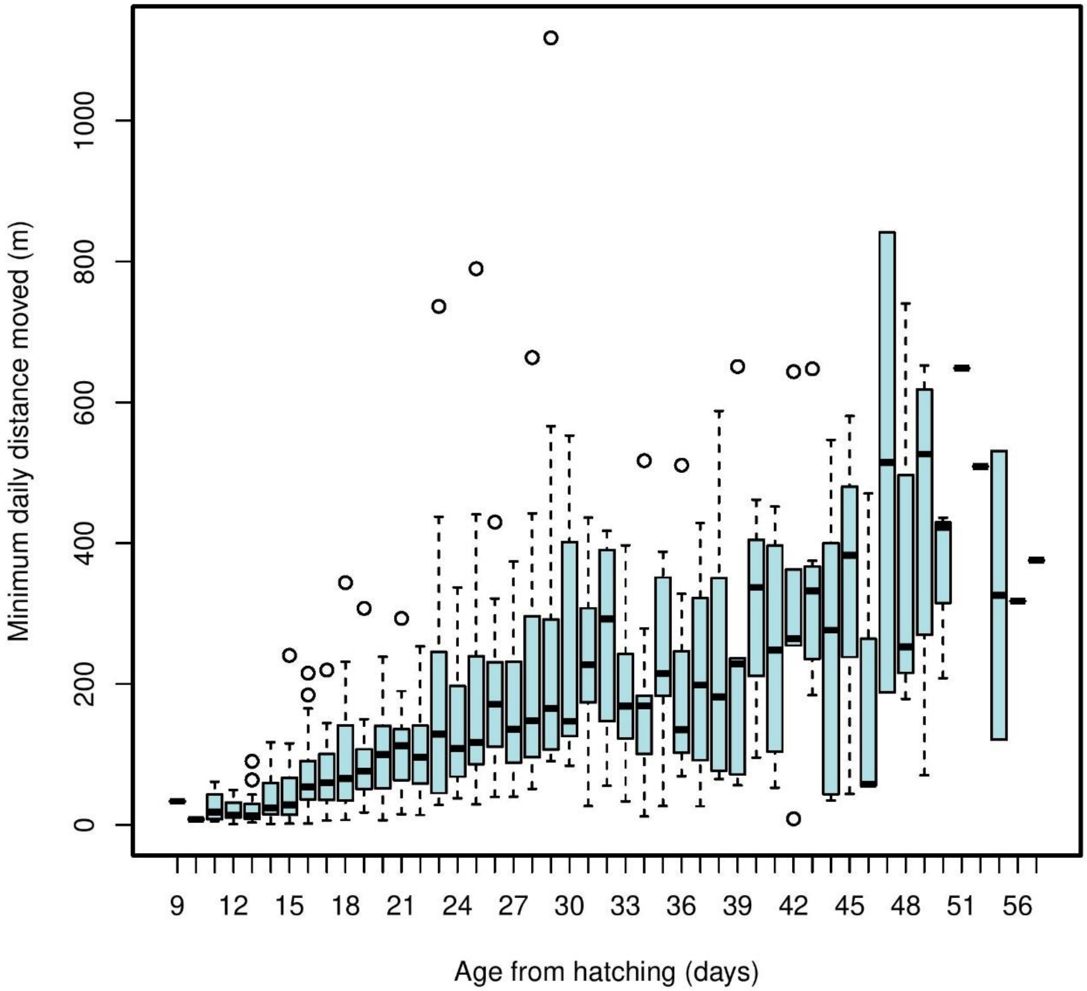

Figure 1-3: Minimum daily distances traveled (m) presented as medians among Gray Vireo fledglings (*n* = 45, *n* = 591 locations) from 2017-2019 at Sevilleta National Wildlife Refuge, New Mexico, USA. Time is shown as fledgling age in days from hatching.

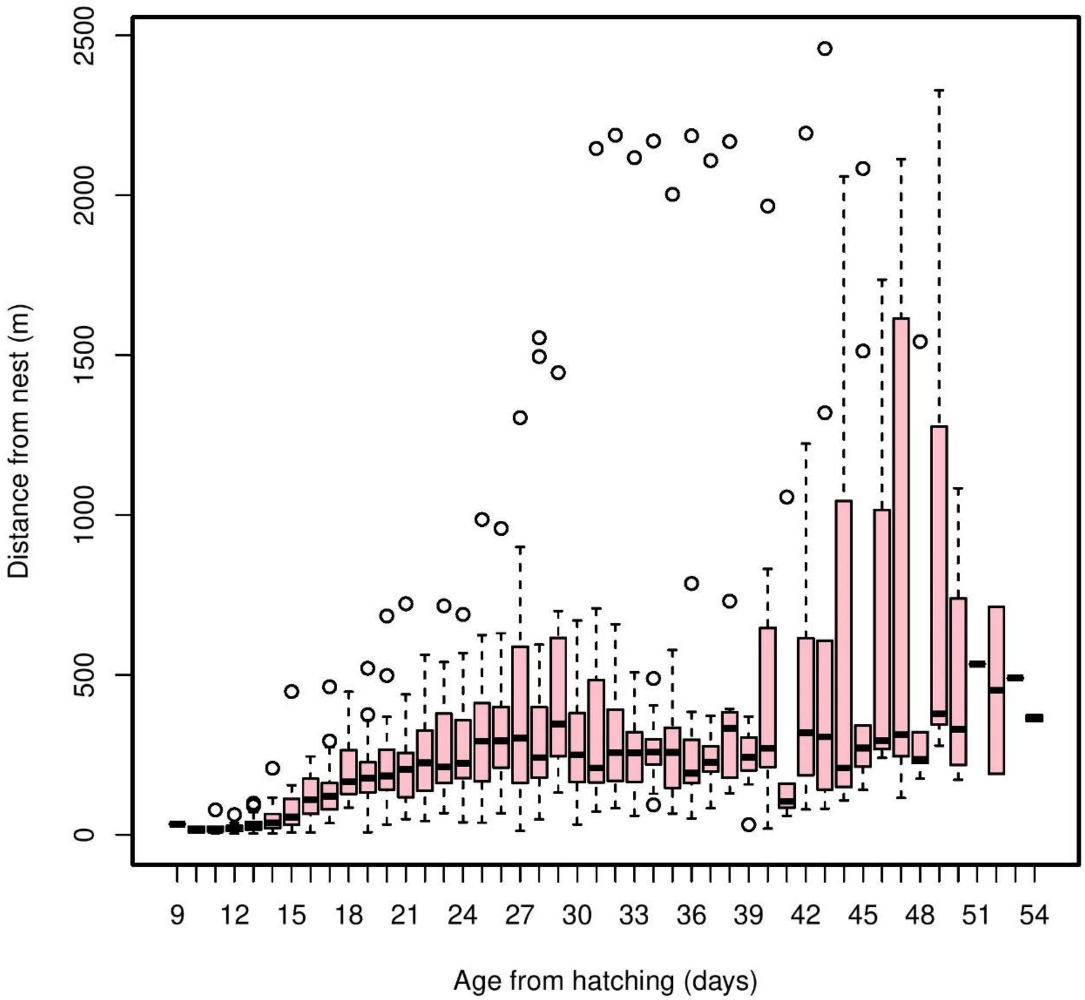

Figure 1-4: Median daily distances from nest (m) among Gray Vireo fledglings (*n* = 45, *n* = 697 locations) from 2017-2019 at Sevilleta National Wildlife Refuge, New Mexico. Time is shown as fledgling age in days from hatching. These estimates include data from divided broods, undivided broods, and broods in which division status was unknown.

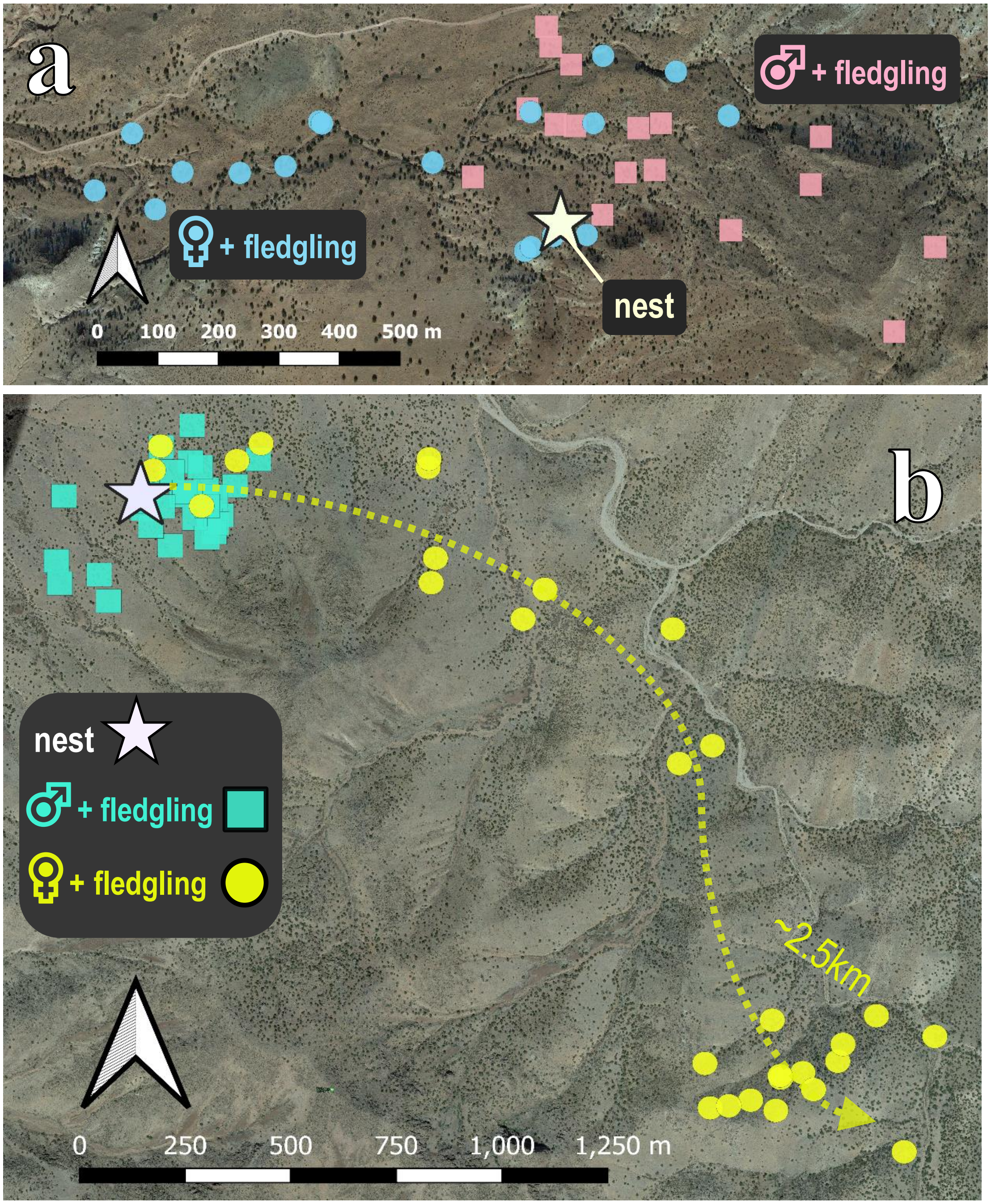

Figure 1-5: Examples of brood division behavior in Gray Vireo pairs during the post-fledging period in 2017 (a) and 2018 (b) at Sevilleta National Wildlife Refuge, New Mexico. Stars indicate the nest site and colored circles represent daily observations of fledglings.

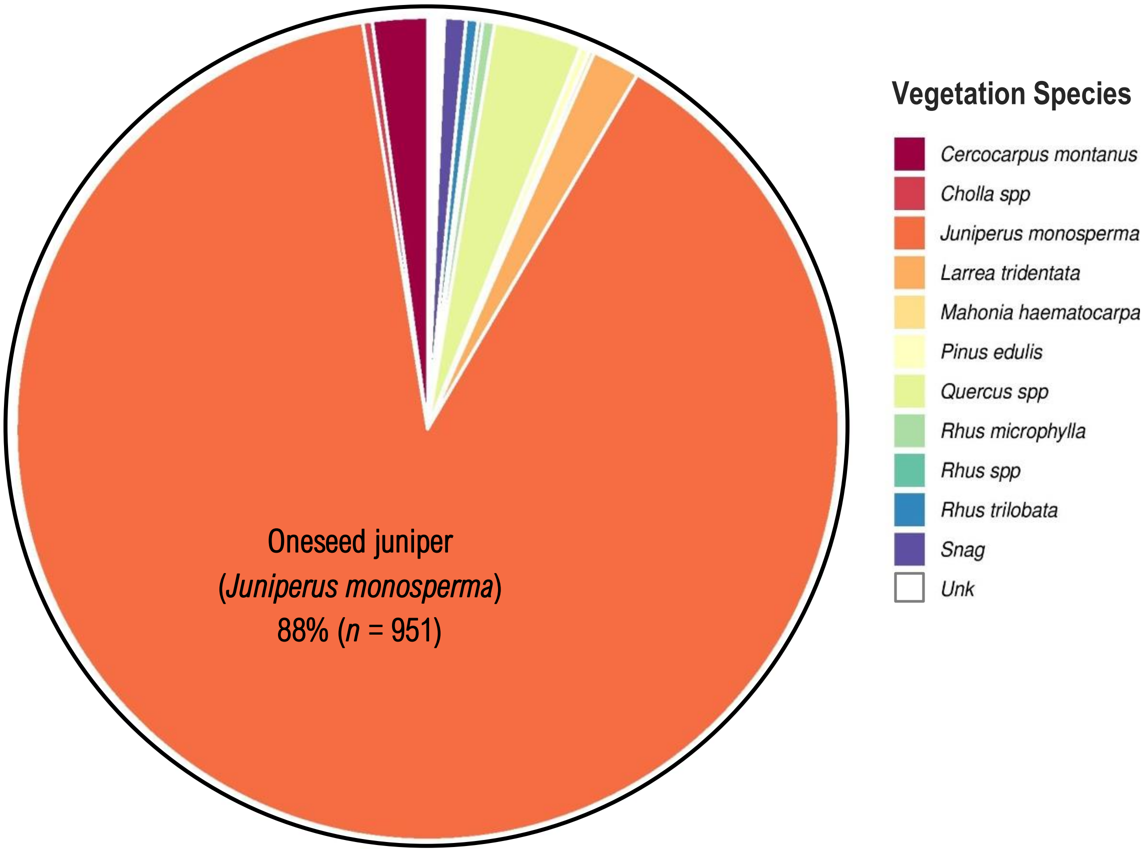

Figure 1-6: Proportion of observations in vegetation substrates for Gray Vireo fledglings during the post-fledging period at Sevilleta National Wildlife Refuge, New Mexico, 2017-2019, including data from the entire tracking period. Each color indicates either a different vegetation species or genus.

Table 1.1 Logistic exposure models of Gray Vireo daily fledgling survival at Sevilleta National Wildlife Refuge, New Mexico, 2017-2019 ($n = 451$ observations). All models excluded mortality due to non-predation (i.e., exposure, such as starvation) and excluded ages from hatching > 21 d (i.e., >12 d post-fledging). All models included a random effect of brood to account for interdependence among fledglings from the same nest. Age was the number of days from hatching (i.e., includes nestling and fledgling days). Models with ΔAICc < 5 are shown below.

Model	**K**	**ΔAICc**	**ω**	**Log-likelihood**
Age + Hatch date [a]	4	0.00	0.16	-84.74
Age + Ordinal date	4	0.05	0.16	-84.77
Age [b]	3	0.35	0.14	-85.93
Age + Fledge date	4	0.52	0.12	-85.00
Age + 25-m^2 tree cover	4	0.98	0.10	-85.23
Age + Lateral veg density	4	1.33	0.08	-85.41
Age + Age^2 + Hatch date	5	1.43	0.08	-84.44
Age + Height from ground	4	2.35	0.05	-85.92
Age + Site	5	3.92	0.02	-85.69
Age + Year	5	4.28	0.02	-85.87

[a] AICc = 177.56

Chapter 2

Using Light-level Geolocators to Track Gray Vireos from Three Breeding Populations

2.1 Introduction

Tracking migratory animals across their annual cycles is critically important for filling knowledge gaps and determining causes of variation in population trends to ultimately implement effective conservation actions (Sherry and Holmes 1996, Calvert et al. 2009). Many migratory songbirds are declining and may be more susceptible to the effects of a changing climate compared to resident species, partly because of their reliance on multiple landscapes at different times throughout their annual cycles (Wilcove and Terborgh 1984, Robbins et al. 1989, Webster et al. 2002, Both et al. 2010, Klaassen et al. 2012, Horton et al. 2019, Rosenberg et al. 2019). Additionally, habitat and/or diet specialists, especially those that occupy patchy distributions, have responded negatively to climate change (i.e., decreases in precipitation) disproportionately compared to generalists (Iknayan and Beissinger 2018).

Importantly, recent studies have identified major limiting factors to population growth outside of the breeding season in many taxa (Sherry and Holmes 1996, Calvert et al. 2009, Hewson et al. 2016, Kramer et al. 2018). Differences in migratory behavior (i.e., routes, timing), connectivity, and non-breeding dispersion may manifest among breeding populations, age classes, sexes, and even individuals of the same population, potentially driving overall population trends and leading to ecological and evolutionary implications (Hewson et al. 2016, Kramer et al. 2017, Briedis and Bauer 2018, Kramer et al. 2018, Fraser et al. 2019). For example, Kramer et al. (2018) showed that *Vermivora* warblers exhibit strong migratory connectivity linked to differential breeding population trends due to land use changes in specific portions of their nonbreeding range. Importantly, some demographic groups (e.g., sexes) may contribute disproportionately to population growth (i.e., songbird populations are generally more female-limited; Dale 2001), underlining the importance of studying their annual cycles (Briedis and Bauer 2018).

Knowledge about most migratory songbirds is biased with respect to the annual cycle, with most research being breeding season- and/or male-centric, leading to potentially nescient scientific conclusions or uninformed management and conservation efforts (Faaborg et al. 2010, Marra et al. 2015, Bennett et al. 2019, Cooper et al. 2019). However, most Nearctic-Neotropical migratory songbirds spend only ~1/3 of their annual cycles at breeding sites and spend the rest of the year either migrating or at nonbreeding locations; and ~1/5 of the world’s bird species are known to migrate (Sillett and Holmes 2002, Faaborg et al. 2010, Klaassen et al. 2012). Information on annual cycles and other data (e.g., museum specimens) are especially limited for female birds (Bennett et al. 2019, Cooper et al. 2019) and for desert birds and other western USA Nearctic-Neotropical migrants (McKinnon and Love 2018, Hedley 2019), which have experienced community-wide declines in the past century (Iknayan and Beissinger 2018).

Sexual segregation during the nonbreeding period, sometimes called “differential migration” in migratory animals, is relatively well-studied, and may manifest as differences in timing, routes, site selection, habitat associations, and migratory connectivity (Ketterson and Nolan 1983, Briedis and Bauer 2018). Segregation trends can be vastly different among bird taxa (e.g., raptors exhibit different patterns than songbirds; Ketterson and Nolan 1983, Cristol et al. 1999). It is unclear why such segregation occurs despite many competing hypotheses (e.g., the body-size, arrival-time, and dominance hypotheses), but importantly, it may contribute to differences in survival and can even influence sex ratios (Ketterson and Nolan 1983, Komar et al. 2005, Morrison et al. 2016, Briedis and Bauer 2018). In songbirds, females usually migrate longer distances and occur further south during the nonbreeding period, potentially due to being outcompeted by males so that males can remain closer to breeding territories and arrive earlier (Ketterson and Nolan 1983, Komar et al. 2005, Kokko et al. 2006, MacDonald et al. 2015). However, for most species there is a paucity of data on sexual segregation and migration ecology in general, especially in arid land songbirds.

The Gray Vireo (*Vireo vicinior*) is a small (~11-14 g), migratory songbird that breeds primarily in juniper savannas and structurally similar arid landscapes in the southwestern USA and northwestern Mexico (Barlow et al. 1999). The species occupies a relatively small and patchy breeding distribution (Schlossberg 2006, Hargrove and Unitt 2017), with swaths of seemingly appropriate habitat unoccupied (DeLong and Williams 2006, NMDGF 2007). Relatively little is known about Gray Vireos throughout their annual cycle, and population- and sex-specific nonbreeding locations are not known (Barlow et al. 1999). Importantly, reliable range-wide population trend estimates do not exist for Gray Vireos because during the entirety of their annual cycle, they occupy remote, inhospitable areas that are often away from roads and are poorly surveyed by standardized population monitoring assessments (i.e., the Breeding Bird Survey; Barlow et al. 1999, DeLong and Williams 2006, Schlossberg 2006, Sauer et al. 2014, Hargrove and Unitt 2017). Gray Vireos are listed as “Threatened” and as a “Species of Greatest Conservation Concern” in New Mexico (NMDGF 2007, 2018) and range-wide are considered a "species of conservation concern” by the US Fish and Wildlife Service (2008) and Partners in Flight (Rosenberg et al. 2016).

Anecdotally, Gray Vireos overwinter in coastal arid lands that support high densities of fruiting elephant trees (*Bursera microphylla*; Bates 1987, 1992a-b), making them potential habitat and diet specialists. The current description of their nonbreeding distribution extends through the southern half of the Baja Peninsula, Mexico, and east to southern Arizona and Sonora, Mexico, with small populations at Big Bend National Park, Texas and in southern California (Bates 1987, Bates 1992a-b, Barlow et al. 1999, Unitt 2000). However, our current knowledge of their distribution may be somewhat biased by human occurrence and sampling effort (see Ferrer et al. 2016), which is presumably more common in species that inhabit rural areas.

Gray Vireos have high overwintering territory site fidelity (73% in one year; Bates 1987; Barlow et al. 1999). They are mainly frugivorous during the winter, consuming berries of the elephant tree, and are thought to be its main seed disperser (Bates 1987, 1992a). Nonbreeding site selection, and potentially even nonbreeding population density, may therefore be associated with availability of fruiting elephant trees

(Bates 1987, 1992a). Bates (1987, 1992b) described territorial behavior in both sexes and, based on museum specimens collected in a portion of their nonbreeding range (i.e., Sonora, Mexico), hypothesized that sexual segregation in nonbreeding sites does not occur in Gray Vireos. Additionally, Gray Vireos generally molt on the breeding grounds (Voelker 2000, S.E. Fischer, personal observation) unlike many western Nearctic-Neotropical migrants that undergo molt migrations in which they travel from breeding sites to monsoon-prone regions to exploit increased food availability (Voelker 2000, Rohwer et al. 2008).

We used archival light-level geolocators (hereafter, geolocators), devices that track ambient light levels across the annual cycle (Stutchbury et al. 2009), to estimate nonbreeding locations for adult male and female Gray Vireos from three sites in the eastern portion of their breeding distribution. Our objectives were to investigate whether there were population-specific or sex-specific patterns in nonbreeding locations, and if so, to determine if those patterns have implications for annual cycle conservation priorities. Because most migratory songbirds studied to-date exhibit weak migratory connectivity (Finch et al. 2017), we hypothesized that Gray Vireos from our study populations would be broadly dispersed and would mix across their nonbreeding range. Additionally, because previous observations and museum specimens suggest no sexual segregation in their nonbreeding distribution (Bates 1987, 1992b), we did not expect to find differences in our estimates of nonbreeding latitude and/or longitude of male and female Gray Vireos.

2.2 Methods

2.2.1 Study Area

We studied Gray Vireos from three breeding sites in New Mexico and Utah, USA. Sevilleta National Wildlife Refuge (hereafter, “Sevilleta”; 34.391°N, -106.562°W) and Kirtland Air Force Base (hereafter, “Kirtland”; 35.005°N, -106.409°W,) are in the northern Chihuahuan Desert of central New Mexico. Within these lands, our study sites are sky islands, mountain ranges characterized by isolation and are surrounded by lowland cover types (McCormack et al. 2009), occurring at ~1,785 m elevation along the foothills of Los Pinos Mountains (Sevilleta) and ~2,000 m elevation in the Manzanita Mountains (Kirtland). Our third site was in the southern foothills of the Abajo Mountains (hereafter, “Abajos”; 37.562°N, -109.7843°W) in southeast Utah at ~1,900 m elevation. The dominant cover type at all three sites was predominantly juniper savanna comprised mainly of juniper (*Juniperus monosperma* at Sevilleta and Kirtland; *J. osteosperma* at Abajos), creosote bush (*Larrea tridentata*), and other arid-land shrubs (e.g., *Quercus* spp., *Rhus* spp., and *Fallugia paradoxa*), succulents (e.g., *Yucca* spp., *Cylindropuntia* spp., and *Opuntia* spp.), and grasses (e.g., *Bouteloua* spp.), with piñon pines (*Pinus edulis*) at higher elevations (see Stevens and Fischer 2018).

2.2.2 Capturing, Banding, and Geolocator Deployment

During May - July 2017, we used recordings of conspecific songs and other vocalizations and 12-m mist nets to capture adult male and female Gray Vireos. We marked each bird with an aluminum U.S. Geological Survey numbered band and a unique combination of one to three plastic color bands. We recorded morphometric measurements (i.e., mass and wing length), sex, and age (second-year [SY], after-second-year [ASY], or occasionally after-hatch-year [AHY] when uncertain). We deployed 48, 0.41-g geolocators (Sevilleta and Abajos birds: Intigeo W55Z9-DIPv9, Migrate Technology Ltd, Cambridge, UK; Kirtland birds: Lotek model #ML6340, Lotek UK Ltd, Wareham, UK) on adult male and female Gray Vireos at Sevilleta (*n* = 23), Kirtland (*n* = 13), and Abajos (*n* = 12). Geolocators recorded ambient light levels at regular intervals (2 and 5 min for Lotek and Intigeo models, respectively). Data quality has been compared between these two rates with no distinguishable difference and both tag types are regularly used in migration studies (Lisovski et al. 2019).

We attached geolocators using a modified figure-eight leg-loop harness made of elastic jewelry cord (Stretch Magic: Pepperell Braiding Company, Pepperell, MA USA; Rappole and Tipton 1991, Streby et al. 2015). Including the harness, geolocator units were < 5% of the average mass of an adult Gray Vireo (male mean mass 12.29 g ± 0.75 SD, *n* = 85; female mean mass 12.96 ± 0.80 SD, *n* = 23; overall adult mean mass 12.41 g ± 0.81 SD, *n* = 108). All capturing, handling, and marking procedures were conducted under University of Toledo Institutional Animal Care and Use Committee protocol #108708) and USGS Bird Banding Laboratory permits #24072 (H.M. Streby; Sevilleta and Abajos) and #20617 (S. Cox; Kirtland).

2.2.3 Geolocator Recovery

During the following breeding season (spring 2018), we systematically searched for returning geolocator-marked vireos at all three sites and for control vireos at Sevilleta (see below). We searched previous capture locations and areas within a ~500-m radius and returned multiple times and at different times of the day to minimize the chance of a returned vireo going undetected (Kramer et al. 2017). Upon detecting a returning vireo, we attempted to use similar methods as the previous year to lure individuals into mist nets. Due to difficulties re-capturing some geolocator-marked vireos, we also set passive nets around trees in which they were attending nests. Three vireos carrying geolocators were collected by Museum of Southwestern Biology (MSB) personnel during their collection activities under USFWS permit MB094297, NMDGF permit #3217, and University of New Mexico MSB IACUC protocol #16200406MC; specimens were deposited in the MSB, University of New Mexico, USA (MSB Bird catalog numbers 60601-60603; available at http://arctos.database.museum/guid/MSB:Bird:60601, http://arctos.database.museum/guid/MSB:Bird:60602, http://arctos.database.museum/guid/MSB:Bird:60603).

2.2.4 Testing for Marker Effects

Immediately following release of geolocator-marked vireos in 2017, we monitored each individual for ~20 min for apparent short-term marker effects on movement or behavior. To test for long-term marker effects (i.e., differences in apparent annual survival or variable selection on morphological traits [Taff et al. 2018]), we banded a control group of adult male and female Gray Vireos at one of our study sites (Sevilleta). Vireos in the control group were captured, handled, banded, and measured using identical methods as with geolocator-marked individuals except those in the control group were not marked with a geolocator. Individuals in both the geolocator-marked (n = 23) and control (n = 50) groups at Sevilleta were part of a demographic study in which we monitored territories, nesting ecology, and post-fledging survival during both years of this study.

2.2.5 Geolocator Analysis

We downloaded light-level data from units using software provided by the manufacturers (Migrate Technology Ltd, Cambridge, UK; BASTrak, Lotek UK Ltd, Wareham, UK). We analyzed all light-level data in R (v3.6.1; R Core Team 2018). Specifically, we processed the data using the TwGeos package to define sunrises and sunsets (i.e., twilights) (v0.1.2; Lisovski et al. 2016) and reformat drift-adjusted .lux files (Intigeo units) and .lig files (Lotek units) into 'TAGS' format using the BAStag package (v0.1.3; Wotherspoon et al. 2016). We selected a twilight threshold of one for all tags.

To identify migration timing and routes, and for redundancy in identifying nonbreeding locations, we used the template-fit method in FLightR (v. 0.4.9; Rakhimberdiev and Saveliev 2015) generally following the workflow outlined by Rakhimberdiev et al. (2017) and used in Kramer et al. (2017, 2018). We selected calibration periods (i.e., the time when a bird was stationary at a known location) for individual vireos by visually inspecting light images and location slopes (see Lisovski et al. 2019). We limited location estimates to an area incorporating both the breeding and nonbreeding distribution of Gray Vireos (18° to 43°N and -121 to -100°W) and prevented individuals from occurring over water when stationary (Rakhimberdiev et al. 2017). We also limited the maximum flight distance between subsequent twilights to 1200 km based on estimates derived from initial model runs (Rakhimberdiev et al. 2017, Lisovski et al.

2019). Final models were run with one million particles and outlier exclusion (see Rakhimberdiev et al. 2017).

We derived spatially explicit likelihood surfaces (see Kramer et al. 2017) for all twilight transition periods (i.e., sunrises and sunsets) between November 1 and February 28 ($n = 238$ twilights), or the subset of time when we assumed the bird was stationary at the non-breeding site (because both sexes of Gray Vireos are thought to defend winter territories; Bates 1987, 1992b). Some individuals ($n = 5$) appeared to experience significant environmental shading during extended periods of the nonbreeding period; in those cases, we chose a smaller subset of subsequent twilights (ranging from $n = 100$-325 twilights) during the nonbreeding period that were free of apparent environmental shading to derive more biologically plausible estimates (see Kramer et al. 2017). We averaged likelihood surfaces and divided by the sum of the surface to create nonbreeding probability density functions to visualize the most parsimonious nonbreeding location for each individual and associated error (see Kramer et al. 2017, 2018). We selected a nonbreeding location estimate for each vireo by extracting the highest probability latitude and longitude coordinates from the probability density function (see Kramer et al. 2018). We obtained Gray Vireo distribution maps from BirdLife International which we imported as .shp files into R for use in creating maps (BirdLife International 2018).

To determine migration timing (i.e., departure and arrival dates to and from the breeding and nonbreeding grounds) and associated error, we estimated when each vireo crossed latitude or longitude boundaries $> \pm 2°$ from the corresponding breeding and/or nonbreeding site. Most often, we used longitude because it is usually more accurate than latitude in geolocator analyses (Rakhimberdiev et al 2016); however, if there was significant noise in longitude data during migration, we used latitude boundaries. We used "stationary.migration.summary" function in FLightR to identify stopovers, or periods during migration during which birds were stationary (i.e., locations > or = 2 days using a probability cutoff of 0.1; Rakhimberdiev 2017). The movement model is more generous in detecting movement and stopovers with smaller probability cutoffs (e.g., more stopovers are detected in the model using a cutoff of 0.1 compared to 0.2). For one vireo we increased the probability cutoff to 0.2 to obtain a biologically reasonable estimate due to noise in the data (Rakhimberdiev et al. 2017, Lisovski et al. 2019).

2.2.6 Post Hoc Female-Male Comparisons

Because we detected an unexpected difference in female and male nonbreeding latitude, and because previous studies suggest that morphology can influence migration patterns and vice versa (Ketterson and Nolan 1983, Winkler and Leisler 1992), we conducted post hoc comparisons of wing chord, mass, and tail length between male and female vireos. For vireos that we captured and measured in two or more years, we averaged measurements. Because the eggs of female Gray Vireos can be ~17% of their body mass (mean fresh egg mass = 1.92 g, range 1.78-2.09 g; Hanna 1944, Barlow et al. 1999) and could therefore potentially confound female mass measurements, we divided females into three categories based on breeding season status at the time of capture: 1) unknown (i.e., we banded a bird but did not have associated breeding data), 2) laying (i.e., gravid), and 3) not laying (i.e., incubating, feeding brood or fledglings). Female vireos generally take 1-2 days to produce and lay each egg (Barlow et al. 1999) from fertilization to laying. Therefore, we considered females to be not laying (i.e., group 3) if we were reasonably certain that they were two or more days away from the laying stage, if they were incubating their full clutch for the nesting attempt, or if they were incubating 4 eggs, the maximum clutch size (Barlow et al. 1999, S.E. Fischer, K. Granillo, and H.M. Streby, unpublished data). We excluded females from comparison if they were placed in the “unknown” or “laying” groups.

2.2.7 Statistical Analysis

We used Welch two sample *t*-tests to compare migration characteristics between sexes, duration of fall versus spring migration, and wing chord and mass between geolocator-marked and control vireos. We used simple linear regressions, one-way ANOVA tests, and Tukey HSD post hoc tests to compare migration characteristics among the three breeding populations. We used Fisher’s exact test of independence to test for potential marker effects by comparing the apparent return rates in control and geolocator-marked individuals. We considered α-values of ≤ 0.05 to be statistically significant, and estimates are presented as means ± SD unless specified otherwise.

2.3 Results

Of the 48 Gray Vireos marked with geolocators in 2017, we re-sighted 38% (n = 18) in 2018, excluding one geolocator-marked male that returned carrying only the harness and was censored from all analyses. We retrieved 15 geolocators across all three sites (n = 9 at Sevilleta, n = 4 at Kirtland, and n = 2 at Abajos) and recovered usable data from 12 units (n = 7 Sevilleta, n = 3 Kirtland, n = 2 Abajos), of which nine were from males (n = 5 Sevilleta, n = 3 Kirtland, n = 1 Abajos) and three were from females (n = 2

Sevilleta, *n* = 1 Abajos). Three geolocator-marked individuals (*n* = 1 female Sevilleta, *n* = 1 male Kirtland, *n* = 1 male Abajos) returned but eluded capture in 2018. Overall, we found no measurable difference between return rates of control birds versus geolocator-marked birds at Sevilleta (Fisher's exact test, $P = 0.80$), even when comparing control vs marked males (Fisher's exact test, $P = 0.75$) and control vs marked females (Fisher's exact test, $P > 0.90$). Of the Sevilleta birds we marked with geolocators, the mass and wing chord of birds that returned and were detected in 2018 did not differ from vireos that did not return or returned but were not detected ($t = -0.53$, $df = 18.82$; $P = 0.60$; $t = -0.32$, $df = 16.49$, $P = 0.75$, respectively).

2.3.1 Nonbreeding Location Estimates

In general, Gray Vireos from Sevilleta wintered along the Baja Peninsula, Mexico and possibly the surrounding islands (Figure 2-1). Gray Vireos breeding at Kirtland wintered generally in Sonora, Mexico (Figure 2-1). Gray Vireos marked at Abajos wintered either on Guadalupe Island or in Southern California (Figure 2-1). Kirtland Gray Vireos wintered on average 5.5°, or ~600 km, farther east compared to those marked at Sevilleta (one-way ANOVA, $F_{2,9} = 6.6$, $P = 0.02$; post hoc Tukey test, $P = 0.05$) and 8.8°, or ~1000 km, farther east than those marked at Abajos (post hoc Tukey test, $P = 0.02$; Table 2.1). Gray Vireos from Abajos and Sevilleta occupied similar nonbreeding longitudes (post hoc Tukey test, $P = 0.37$; Table 2.1). We found no support for differences among populations in nonbreeding latitude (one-way ANOVA, $F_{2,9} = 1.4$, $P = 0.28$; Table 2.1). Regardless of population, deployment longitude and latitude did not correlate significantly with nonbreeding latitude (one-way ANOVA; $F_{1,10} = 1.73$, $P = 0.22$) or longitude (one-way ANOVA; $F_{1,10} = 2.97$, $P = 0.12$).

2.3.2 Migration Characteristics

Gray Vireos that bred farthest north (i.e., at Abajos) spent longest on the nonbreeding grounds (one-way ANOVA, $F_{2,8} = 5.78$, $P = 0.03$, Table 2.1) compared to Kirtland (Post hoc Tukey test, $P = 0.03$) and Sevilleta (Post hoc Tukey test, $P = 0.05$), which appears to be driven by a non-significant but potentially meaningful trend in which Abajos Gray Vireos departed nonbreeding grounds almost one month later ($P = 0.06$, Table 2.1). We did not find evidence for population-level differences in migration duration, migration timing, or great circle (i.e., Haversine) distance traveled between breeding and nonbreeding locations, although there was considerable variation in some factors and populations (all $P > 0.05$, Table 2.1).

Regardless of population, Gray Vireos departed the breeding grounds on September 7 ± 22 and took 26 ± 18 days to migrate in the fall ($n = 12$), arriving on October 3 ± 12. Similarly, Gray Vireos departed nonbreeding grounds on April 22 ± 17 and took 22 ± 18 days to migrate in the spring ($n = 11$), arriving on May 14 ± 19 to breeding sites. Only five vireos made stopovers in fall and only five in spring, three of which made stopovers during both fall and spring. Vireos made an average of only 0.4 ± 0.5 stopovers in fall with a mean duration of 20 ± 14 days and 1.0 ± 1.2 in spring with a mean duration of 38 ± 19 days.

2.3.3 Sexual Segregation

Female Gray Vireos wintered on average 4.7° farther north than males (female mean latitude = 32.4° ± 1.3; male mean latitude = 27.7° ± 2.2; $t = 4.4$; $df = 6.2$; $P = 0.004$; Table 2.2, Figure 2-2). We observed a similar, nonsignificant trend in great-circle (i.e., Haversine) distance traveled between breeding and non-breeding locations between the sexes with males tending to travel almost 200 km further ($t = -2.5$, $df = 5$, $P = 0.06$; Table 2.2). We found no difference among nonbreeding longitude between females and males (female mean longitude = -115.4° ± 3.6; $t = -0.8$; $df = 4.1$; $P = 0.5$; male mean longitude = -113.5° ± 4.2; Table 2.2, Figure 2-2). Between sexes, we found no evidence for a statistical difference in fall migration duration, spring migration duration, migration timing, or length of time spent on the nonbreeding grounds (Table 2.2). Female wing chord (64.0 ± 1.5 mm, $n = 51$) was 0.6 mm shorter than male wing chord (64.6 ± 1.8 mm, $n = 83$; $t = -2.2$, $df = 120.5$, $P = 0.03$). Tail length was similar between females (60.3 ± 2.6 mm, $n = 34$) and males (60.4 ± 3 mm, $n = 70$; $t = -0.07$, $df = 74.2$, $P = 0.94$). Females (12.96 ± 0.8 g, $n = 23$) were 0.66 g heavier than males (12.29 ± 0.7 g, $n = 85$) when including only female vireos that were confirmed not to be gravid ($t = 3.6$, $df = 33.3$, $P < 0.001$).

2.4 Discussion

We used geolocators to track Gray Vireo migration for the first time and show that adult females wintered significantly farther north compared to males and that migratory connectivity was moderate among three breeding populations. We did not find any evidence for apparent negative effects caused by geolocators or harnesses. We provided the first tracking-derived estimate of Gray Vireo population- and sex-specific nonbreeding distributions and underline the need for more annual cycle data on Gray Vireos, female songbirds, Western Nearctic-Neotropical migrants, and other under-studied and overlooked species.

2.4.1 Sexual Segregation

Interestingly, we found that Gray Vireo females wintered almost 5°, or > 500 km, farther north than males, contrary to examples in other songbirds in which females are generally described as wintering farther south and migrating longer distances (Komar et al. 2005, MacDonald et al. 2015, Briedis and Sauer 2018). To our knowledge, the trend we observed is only evident in 1 other North American songbird, 1 woodpecker, and species in a few other avian orders (Johnston 1970, Komar et al. 2005, Gow and Wiebe 2014; see Cristol et al. 1999 for a few cases in raptors and shorebirds). Specifically, Gow and Wiebe (2014) found that female Northern Flickers (*Colaptes auratus*) wintered farther north and migrated shorter distances compared to males. In a study of latitudinal sexual segregation in 45 songbird species, Komar et al. (2005) found that of 9 species that were segregated by latitude during the nonbreeding period, only Indigo Buntings (*Passerina cyanea*) segregated by females occurring farther north, further described by Johnston (1970).

There are many hypotheses that explain sexual segregation in birds (Ketterson and Nolan 1983, Cristol et al. 1999), the most common of which are the body size, arrival time, and social dominance hypotheses (Cristol et al. 1999, Gow and Wiebe 2014). The body size hypothesis predicts that, in songbirds, the smaller-bodied (usually females) individuals migrate further because heavier-bodied individuals may be able to tolerate colder temperatures associated with northern latitudes (Ketterson and Nolan 1983, Cristol et al. 1999, Gow and Wiebe 2014). The arrival time hypothesis states that males generally select nonbreeding sites further north, or closer to the breeding site, to take advantage of earlier arrival for territory establishment (Cristol et al. 1999). Lastly, the social dominance hypothesis states that socially subordinate groups (e.g., females) migrate further because they are outcompeted (Cristol et al. 1999). Of these three hypotheses, only the body size hypothesis helps partially explain the sexual segregation we observed.

Adult female Gray Vireos weighed more than males, consistent with previous data (female 12.7 ± 0.4 g, male 12.1 ± 0.6 g; Pyle 1997, Barlow et al. 1999) and with the body size hypothesis, which may help explain sexual segregation in Gray Vireos but is likely not the full story. Many previous sexual segregation studies focus on species that occur in colder climates (e.g., Dark-eyed Juncos [*Junco hyemalis*]), and may not reflect the same driving forces for arid land songbirds such as Gray Vireos. Latitude alone may not be a good predictor of habitat quality or of segregation, which is likely more complex in most species. Segregation is not explained by the arrival time hypothesis in Gray Vireos because. Contrary to common patterns of males arriving earlier to breeding sites (Barlow et al. 1999), we did not find a difference in arrival time between females and males in our geolocator data, and both sexes appear to arrive over a relatively similar period at our study sites (S.E. Fischer, personal observation). However, we acknowledge that a more robust sample size of individually tracked birds would help confirm a lack of timing trends or elucidate potential differences. Additionally, the social dominance hypothesis does not explain segregation in Gray Vireos unless there is an undescribed dominance by females for which we have observed no evidence. Gow and Wiebe (2014) also predicted that parental care may influence migration distance and nonbreeding site selection, showing that male Northern Flickers traveled farther potentially because they invest more in parental care than females and will elect to migrate further to take advantage of benign southern habitats. However, Gray Vireo sexes generally invest similar energy in parental care (i.e., both females and males contribute to nest building, incubate, feed broods, and care for juveniles post-fledging); if anything, females likely invest more energy and should occur farther south than males.

How morphology influences migration and other aspects of avian ecology is complex and may depend on interactions between sex, age, and breeding latitude (Gray 2019). Theory predicts that species with longer, pointier wings (i.e., higher aspect ratios) migrate further (Lo Valvo et al. 1988, but see Mönkkönen 1995), but how does this combine with the body size hypothesis and sexual segregation? What about individuals and/or sexes of a species? We found that Gray Vireo female wing chord was ~1 mm shorter than males, which is consistent with literature (female 61-67 mm, male 62-68 mm; Bates 1987, Pyle 1997, Barlow et al. 1999). A previous study also showed that female wingspan was 205.3 ± 1.7 mm compared to 208.7 ± 9.5 mm in males (Pyle 1997, Barlow et al. 1999). However, we did not record additional morphological measurements, such as wingspan or wing aspect ratio, that may help explain latitudinal sexual segregation in Gray Vireos. Future research involving tracking bird migration, especially those tracking different subgroups such as females and different age classes, should include as many morphometric measurements as possible, including wing aspect ratio (Gray 2019).

It is possible that female Gray Vireos are selecting entirely different habitats than males, (e.g., not relying as heavily on elephant trees), as shown in Hooded Warblers (*Setophaga citrina*; Morton 1990, Gray 2019) and Golden-winged Warblers (*Vermivora chrysoptera*; Bennett et al. 2019). However, Bates (1987) described presumably female Gray Vireos using elephant trees like males, although without reliable sexing methods. Bates (1987) suggested that, based on museum specimens, males and females may overlap on nonbreeding grounds; however, those birds could have been from different breeding populations. Additionally, sexual segregation may also occur more locally (i.e., in microhabitat preferences) via sex-specific differences in elevation, ambient temperature, or a combination of factors (Komar et al. 2005), warranting further study on factors associated with Gray Vireo nonbreeding habitat selection and quality and the implications for their survival or potential carryover effects.

Relatively few climate data are available for the northern part of the nonbreeding range (e.g., the border region, including both the Sonoran and Chihuahuan Deserts) in the USA and Mexico (Wilder et al. 2013) where female Gray Vireos appear to be most abundant. Northwestern Mexico is generally more prone to droughts than other Mexican regions (e.g., mainland Mexico) and is heavily influenced by tropical storms and El Niño-Southern Oscillation (ENSO; Roy et al. 2019). A "seesaw" pattern persists during which northern Mexico is usually dry while southern Mexico is wet and vice versa (Méndez and Magaña 2010); therefore, females and males may experience drastically differing conditions on their nonbreeding grounds with potential effects that could carry over into the breeding season (Rockwell et al. 2012, Latta et al. 2016). In general, climate projections for Mexico highlight a hotter, drier future, and importantly show evidence for decreasing winter precipitation and increasing winter temperature as influenced by ENSO (Wilder et al. 2013, Roy et al. 2019).

Conservation efforts in the border region may be beneficial to female Gray Vireos and other animals (e.g., Ferruginous Pygmy Owl [*Glaucidium brasilianum*] and desert bighorn sheep [*Ovis canadensis mexicana*]; Flesch et al. 2010, Ogden 2017), especially considering the severe socioeconomic vulnerabilities and water scarcity in the region, where mass immigrations of people occur and where land fragmentation (e.g., construction of border infrastructure) is occurring at an increasingly rapid rate compared to most of the Baja Peninsula (Goodwin 2000, Wilder et al. 2013, Ogden 2017, Peters et al. 2018). Conservation and management may require trans-border coordination and cooperation, which may prove difficult in the context of geopolitical climate, economic disparities and differing values, but can be fruitful through shared land stewardship and collective natural heritage (Goodwin 2000, Ogden 2017).

2.4.2 Population Comparison

We found evidence that Kirtland birds, despite breeding < 100 km apart from Sevilleta birds, wintered farthest east, suggesting these populations occurring in different “sky island” mountain ranges may be more distinct than we assumed. This raises questions about potential genetic differences among Gray Vireo populations and those of other bird species occurring in sky islands because certain aspects of migration are likely genetically determined in vireos and other Nearctic-Neotropical migratory songbirds (McCormack et al. 2008, Liedvogel et al. 2011, Delmore et al. 2016, Toews et al. 2019). If Gray Vireo breeding populations are genetically distinct, and if dispersal, especially of juveniles, is reduced (as is common in isolated habitats), reduction in gene flow could ensue, which could potentially enhance sensitivity to climate change (Waters et al. 2020). Future research could examine Gray Vireo genetics range-wide to determine whether certain populations are closed, and whether juvenile dispersal occurs among sky island mountain ranges. Currently, there are no subspecies of Gray Vireos recognized, but two subspecies have been previously suggested (Stephens 1890, Barlow et al. 1999). Additionally, further inquiry into the migratory ecology of other Gray Vireo populations is warranted, especially in severely declining breeding populations, such as in California (Hargrove and Unitt 2017).

2.4.3 Migration Characteristics

We found a southwestward movement pattern from breeding to nonbreeding locations in Gray Vireos, compared to a southeastern movement pattern in two relatively closely related species, the Cassin's Vireo (*Vireo cassinii*; Hedley 2019) and Red-eyed Vireo (*Vireo olivaceus*; Callo et al. 2006). Migration duration in Gray Vireos (~26 days in fall and ~24 days in spring) and Cassin's Vireos (~24 days in both fall and spring) appears to be similar (Hedley 2019). The apparent patterns we observed with a modest sample size underlines the need to study inter-annual variation in migration ecology, to track more individuals, and to obtain repeat migration tracks from individuals (i.e., is migration plastic?), as patterns might be more apparent, or might be found to vary among years, with a larger sample size and longer study duration.

We attempted to describe migration stopovers, but it appears that most Gray Vireos either do not make many stopovers or that because they are relatively shortdistance migrants, stopovers can be difficult to elucidate using geolocator technology, especially compared to longer-distance migrants (see information about stopover definition in Lisovski et al. 2019). Even using conservative cutoff probabilities, we did not detect many stopovers, and these results are consistent with previous predictions that Gray Vireos make relatively few stopovers during migration (Bates 1992, Unitt 2000).

2.4.4 Baja Peninsula and Gray Vireo-Elephant Tree Associations

Gray Vireos, along with Ash-throated Flycatchers (*Myiarchus cinerascens*), have been described as the primary seed disperser of the elephant tree, and the vireos and trees have likely co-evolved (Bates 1987, 1992a-b). This hypothesis is further supported by the high degree of overlap between our geolocator-marked Gray Vireos and their current nonbreeding distribution with that of the elephant tree (see Bates 1987, Unitt 2000). It is likely that their migration timing (i.e., arrival during or after September) is tied to the phenology of elephant tree fruit abundance (Bates 1987). Fruit production seems to peak in September, arils become ripe in November, and fruits generally remain during the entire nonbreeding period, at least in Sonora (Bates 1987). The Baja peninsula receives most of its annual precipitation between November and March (Wilder et al. 2013), which is when Gray Vireos are present and elephant tree fruit abundance likely peaks. If Gray Vireos are the primary seed dispersers of elephant trees, then they are an important, seasonal link in Sonoran Desert ecosystems, especially considering many other songbirds consume these fruits too (Bates 1987, Unitt et al. unpublished data).

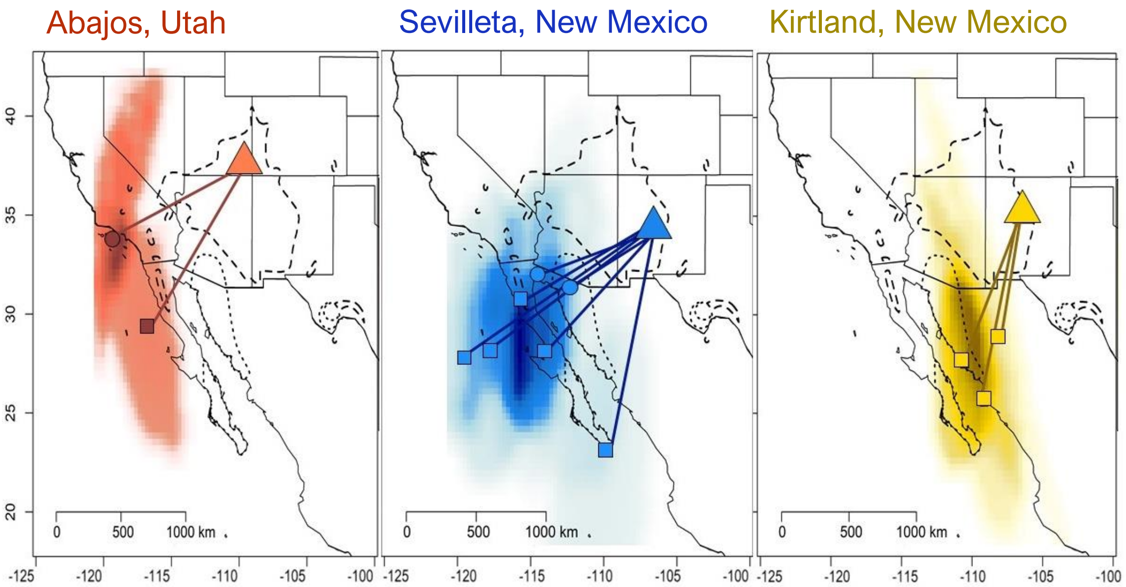

Figure 2-1: Estimated nonbreeding locations of Gray Vireos (*Vireo vicinior*) from three breeding populations: Abajo Mountains (Abajos), Utah (orange, left), Sevilleta National Wildlife Refuge (Sevilleta), New Mexico (blue, center), and Kirtland Air Force Base (Kirtland), New Mexico (yellow, right). Darker hues indicate the highest degree of overlap in each population. Squares (males) and circles (females) depict individuals; triangles depict breeding locations (i.e., deployment sites). Lines between breeding populations and individuals represent the spread of each population, not migration routes.

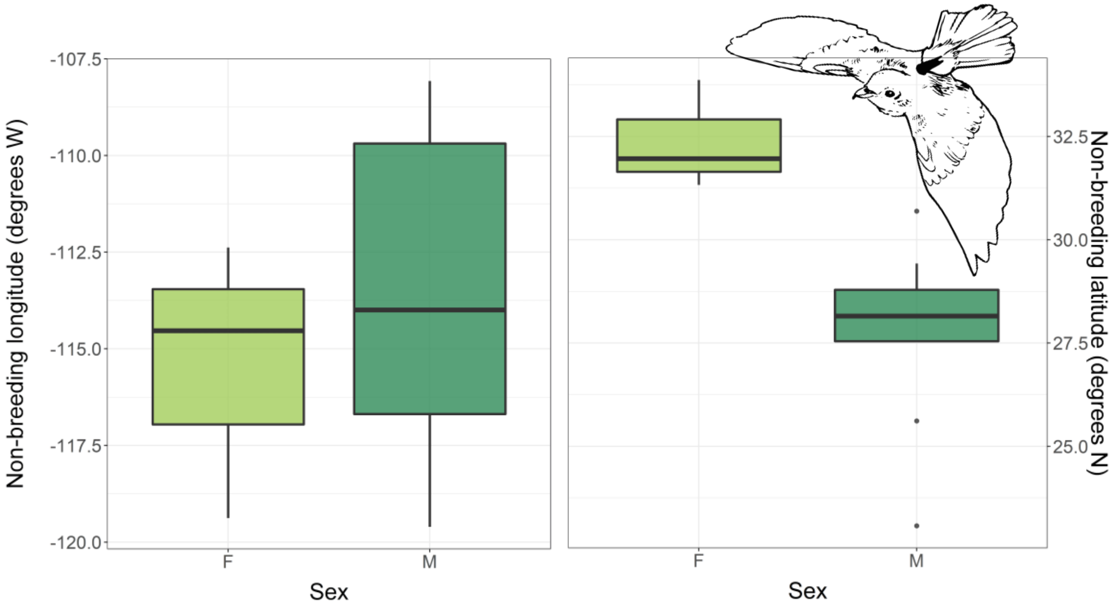

Figure 2-2: Nonbreeding longitude (left) and nonbreeding latitude (right) of Gray Vireo (*Vireo vicinior*) females (*n* = 3) from two populations and males (*n* = 9) from three populations.

Table 2.1. Mean values ± SD for nonbreeding (NB) longitude, NB latitude, and migration characteristics of Gray Vireos (*Vireo vicinior*) from 3 breeding populations (Sevilleta National Wildlife Refuge, New Mexico [Sevilleta], Abajo Mountains, Utah [Abajos], and Kirtland Air Force Base, New Mexico [Kirtland], USA). *P*-values are given for a one-way ANOVA test, and superscripts indicate significance at $\alpha \leq 0.05$ using Tukey's HSD post-hoc test.

Factor		Population		F_{df}	*P*
	Sevilleta (*n* = 7)	Abajos (*n* = 2)	Kirtland (*n* = 3)		
NB longitude	-114.8 ± 3.3° W^{a}	-118 ± 1.9° W^{b}	-109.3 ± 1.2° W^{ab}	$6.6_{2,9}$	0.02
NB latitude	28.7 ± 3 °N	31.6 ± 3.1 °N	27.3 ± 1.6 °N	$1.4_{2,9}$	0.28
Breeding departure	Sep 7 ± 24	Aug 18 ± 12	Sep 22 ± 5	$1.9_{2,9}$	0.21
NB arrival	Oct 5 ± 13	Sep 19 ± 9	Oct 7 ± 5	$2.0_{2,9}$	0.20
NB departure	Apr 20 ± 14	May 15 ± 4	Apr 10 ± 12	$4.2_{2,8}$	0.06
Breeding arrival	May 14 ± 22	May 29 ± 0	Apr 24 ± 1	$1.3_{2,8}$	0.33
NB period length (days)	197 ± 19^{a}	239 ± 13^{b}	183 ± 12^{ab}	$5.6_{2,8}$	0.03
Fall duration (days)	29 ± 23	33 ± 4	15 ± 7	N/A	N/A
Spring duration (days)	25 ± 21	14 ± 4	20 ± 13	N/A	N/A
Gr. circle distance (km)	1053 ± 293	1030 ± 107	901 ± 184	$0.4_{2,9}$	0.70

Table 2.2. Mean values ± SD for nonbreeding latitude, longitude, and migration factors of female and male Gray Vireos (*Vireo vicinior*) including data from 3 breeding populations* in New Mexico and Utah, USA. *P*-values are given for a *T*-test with significance at $\alpha \leq 0.05$.

Factor	Female (n = 3)	Sex Male (n = 9)	T_{df}	P
Nonbreeding longitude	-115.4 ± 3.6	-113.5 ± 4.2	-0.8_4	0.47
Nonbreeding latitude	32.4 ± 1.3	27.7 ± 2.2	4.4_6	0.004
Breeding departure	Aug 24 ± 27	Sep 12 ± 19	-1.1_3	0.35
Nonbreeding arrival	Sep 23 ± 9	Oct 6 ± 11	-2.2_5	0.08
Nonbreeding departure	May 3 ± 13	Apr 18 ± 17	1.6_5	0.17
Breeding arrival	May 21 ± 8	May 12 ± 22	1.0_9	0.32
Nonbreeding period length (days)	224 ± 21	194 ± 22	-11.6_4	0.12
Fall duration (days)	30 ± 22	25 ± 18	N/A	N/A
Spring duration (days)	18 ± 7	23 ± 21	N/A	N/A
Gr. circle distance (km)	795 ± 157	1083 ± 225	-2.5_5	0.06

*Data from females are only from Sevilleta National Wildlife Refuge, New Mexico, and Abajo Mountains, Utah.

Chapter 3

Molt: Fusing Art and Avian Ecology to Explore Gender Using Scientific Metaphors

> *"Realizing that I have nothing left to lose in my actions I let my hands become weapons, my teeth become weapons, every bone and muscle and fiber and ounce of blood become weapons, and I feel prepared for the rest of my life…all I can feel is the pressure all I can feel is the pressure and the need for release"*
>
> — David Wojnarowicz (1991)

3.1 Introduction

Artists, like scientists, pose questions about world phenomena and systems. Both art and science use tools in experimentation, creativity, and problem solving in practice to collect data and information (Root-Bernstein and Root-Bernstein 2001, Hoy 2016, Chomaz 2018, Freeman et al. 2018). Where science generally aims to provide concrete answers to these questions, art may prompt from viewers additional questions or visions of future worlds, tugging at their emotions to incite awareness and action (Wallen 2012, Harrower et al. 2018, Pandey 2020). However, perhaps comparing the dissimilarities of art and science is a binary itself. When combined, "ArtScience integrates synesthetic experience with analytical exploration" to offer a lens through which to view a more complete understanding of the world (Root-Bernstein et al. 2011) at a critical time when humans are dramatically affecting the planet and its processes.

Anthropogenic threats, such as climate change and habitat loss, are fundamentally altering the global biosphere (Urban 2015). Model-generated climate scenarios predict a hotter, drier, and less predictable future, especially in arid and semi-arid lands (e.g., the American Southwest; Seager et al. 2007, MacDonald 2010), leading to phenological mismatch, increased wildfire risk, and accelerating rates of species extinction and "biological annihilation", among other changes (Both et al. 2010, Urban 2015, Ceballos et al. 2017, Renner and Zohner 2018, Spooner et al. 2018). These climate changes can be directly tied to "social organization"; in other words, the systems that seek to profit from humans and nonhumans alike are to blame (Ribot et al. 1996). It is through such systems that we have effectively and systematically become experts at reducing "Others", or those we perceive as different from the self, as commodities, ultimately linking the exploitation of queer bodies and the environment under capitalism (Wainwright 2010, Milton 2013, Pandey 2020). Simultaneously we have forced our understanding of the world into binaries and heteronormativity, effectively "Othering" and oppressing those that do not fit (e.g., gender non-conforming, queer, and trans people, multidisciplinary ArtScience, etc.; Stryker et al. 2008, Mortimer-Sandilands and Erickson 2010, Milton 2013). For example, we have created a false dichotomy that queerness is deviant and somehow separated from nature (Mortimer-Sandilands and Erickson 2010).

Importantly, marginalized and resource-stressed groups are and will continue to be disproportionately affected by climate change (Ribot 1996, Adger 2003, Sörlin 2012, Leichenko and Silva 2014, Mirzoeff 2014, Sultana 2014). Ironically, it is these marginalized groups that are often blamed because of the very systems (e.g., capitalism) that they are forced to participate in to survive (Wainwright 2010). For example, in *The Ecological Other: Environmental Exclusion in American Culture*, Ray (2013) shows that mostly white settler-colonialists in the United States have raised concerns over immigrants' ecological impacts on the borderlands of the Organ Pipe Cactus National Monument, as described by Seymour (2014).

Scientists of many disciplines are actively pursuing research on climate change and both species' and ecosystems' responses. Many species remain critically under-studied, but the primary challenge for addressing climate change lies in shifting human behavior (Aslan et al. 2013) and the very systems (e.g., capitalism) under which many societies operate. Past attempts have been made to advocate for the environment by describing its services and monetary value, but these attempts have mostly failed (Sörlin 2012). Solving the climate crisis will require diverse, transdisciplinary approaches that involve using the humanities to communicate science creatively to stakeholders (Jacobson et al. 2007, Sörlin 2012, Root-Bernstein et al. 2011, Aslan et al. 2013), as well as recognition that meaningful change will take place within a multi-species, intersectional context that necessarily goes beyond science and requires reimagining futures (Bird Rose et al. 2012, Woelfle-Erskine and Cole 2015, Chomaz 2018). Conservation science has embraced a transdisciplinary approach, but art is often not considered as a tool in the process (A'Bear et al. 2017).

Many scientists have failed to communicate their work to non-science (i.e., public) audiences because they lack training, motivation, or reward for doing so (Treise and Weigold 2002, Brownell et al. 2013, ElShafie 2018). Traditionally, science is communicated to other scientists via peer-reviewed journal articles; however, these technical articles are seldom read by or accessible to public audiences (Dietz 2013, Gates-Stuart et al. 2016), and are becoming more difficult to read and understand over time, often because of jargon (Plavén-Sigray et al. 2017). Public audiences will likely not retain or care about science unless they understand and form a connection with it (ElShafie 2018). In response, there is a rising trend of science communication ("sci-comm") aimed to generate public awareness and understanding of science, especially as it relates to and predicts a changing climate (Treise and Weigold 2002, ElShafie 2018).

Luckily, scientists, too, can benefit from creativity, identity-building, and communication while simultaneously helping connect science to broader audiences (Aslan et al. 2013, A'Bear et al. 2017, ElShafie 2018, Risien and Storksdieck 2018). When scientists and artists collaborate, their resulting, combined creativity can spark new ideas, questions, and networking, reciprocally benefitting both parties (Root-Bernstein 2000, Aslan et al. 2013, Gates-Stuart et al. 2016, A'Bear et al. 2017). Scientists who also create art (i.e., "polymaths" or "ArtistScientists") are significantly more likely to be successful compared to those who do not (Root-Bernstein et al. 2008). One type of communication, ArtScience, can be a vehicle for meaningful change and a method of bringing science to new contexts to animate it beyond labs and journal articles (Root-Bernstein et al. 2011).

Art, and more specifically ArtScience, can transform data to elicit emotion, engage multiple senses, inspire critical thinking, and encourage participation and changed behaviors or values (Jacobson et al. 2007, Chandler et al. 2014, Freeman et al. 2018). Viewers and participants of ArtScience can be instilled with a sense of place and their relationship to it (Wallen 2012), even without having experienced such places firsthand (and some maybe be imaginary futures; Harris 2018, Nieto et al. 2018). Historically, art has been an important proxy for cultural discourse about issues such as politics, sociology, class, and environmental changes (Belfiore and Bennett 2007), as well as the inherent intersection of these structures. ArtScience has the potential to dissolve boundaries (e.g., binaries, disciplines, etc.), enhance ecological connectedness, and cause us to broadly re-interpret our roles and actions in a changing world (Chandler et al. 2014). Art can be intervention ("ecovention"; Spaid 2002, Wallen 2012) and activism; of particular importance is work that goes beyond critiquing systems and moves to healing (Gablik), rituals, and hope (Wallen 2012) and is both proactive and reactive. In *Close to the Knives: A Memoir of Disintegration*, David Wojnarowicz wrote that "To make the *private* into something *public* is an action that has terrific repercussions in the preinvented world…One of the first steps in making the private grief public is the ritual of memorials" (Wojnarowicz 1991).

The prefix *trans-* itself means "to cross", implying movement but often on the binary and as a means to and end (Stryker et al. 2008, Woelfle-Erskine and Cole 2015, Seymour 2016). I use this idea of transgender movement in combination with animal migration and ritual memorial (as described by Wojnarowicz) in *Molt*. Migration in birds, as opposed to other movements (e.g., foraging and dispersal), is a complex phenological and often endogenously controlled (i.e., through hormones) return to specific areas that are tied to stages in the annual life cycle and away from areas that are seasonally unfavorable (e.g., the breeding and nonbreeding seasons in songbirds; Salewski and Bruderer 2007, Klaassen et al. 2012, Cornelius et al. 2013). Migration can be considered risky, with increased susceptibility to predation and physiological demands (Klaassen et al. 2012). In preparation for and during migrations, as induced by the endocrine system, birds often molt feathers in addition to other physiological changes. The urge to migrate can produce physical, anxious restlessness (i.e., *zugunruhe*). Similarly, being trans- can be "risky"; visual perception of trans- people often begets discrimination and violence against them, especially for trans- women of color (Stryker 2008). Just as birds undergo changes prior to and during migration, many trans- people experience intense physiological changes through hormone replacement therapy and a similar *zugunruhe gender restlessness* (though not all trans- people take hormones).

Here I used ArtScience to simultaneously create a body of work, *Molt*, while conducting my graduate research on the annual cycle ecology of Gray Vireos (*Vireo vicinior*). I considered the scientific process as a necessary component of my artmaking practice, and vice versa. I used data collected in the field and results and conclusions from these data as visual metaphors to explore my gender identity and queerness while invoking the ritual memorial. I drew parallels between migration of and bodies of birds with my own body as a queer, transsexual ArtistScientist who began hormone replacement therapy concurrently with this thesis. I argue that my gender transition, while risky, is a particular and continuous migration of my emotional and physical homecoming and a constant coming out process, but not as a means to an end and not with a desire to be cisgender; being trans- is "*transgressive*" in itself (Woelfle-Erskine and Cole 2015). As explained by Stryker et al. (2008), genders are "…potentially porous and permeable spatial territories (arguably numbering more than two), each capable of supporting rich and rapidly proliferating ecologies of embodied difference". The impacts of global climate change on migratory songbirds, and I argue on trans- people in this "embodied difference", are of critical concern. It is my goal with *Molt* to use ArtScience and my gender transition as a ritual memorial, to offer a new, hopeful, transdisciplinary and transgressive lens through which to view a world currently understood in binaries.

3.2 Methods

3.2.1 *Pre-Migration Wishing Well*: Mold-making and Glassblowing

I created a two-part plaster-based "cold blow mold" from a curved concrete brick (see Figure 3-7 for process photos). I used this plaster blow mold with glassblowing techniques to create 44 hollow glass bricks at Bowling Green State University, Ohio (see Figure 3-4 for process photos), which were assembled to create *Pre-Migration Wishing Well* (Figures 3-1 and 3-2). Briefly, I clamped the plaster mold together and gathered molten glass on a blowpipe from a furnace (i.e., crucible). I shaped the molten glass into a circular form using wooden blocks and newspaper while a partner blew the initial bubble (i.e., parison) into the glass. I worked the glass into a cylindrical shape, reheating it in the "glory hole" when the glass became cool or unpliable. Once the glass cylinder was in the correct shape, I heated it until malleable, and inserted it into the plaster mold, blowing on the pipe until the glass filled the brick form. A partner then removed the clamps from the mold and freed the glass brick, which I took back to the workbench to cut a neckline above the brick using “jacks”. I then removed the glass brick from the blowpipe and placed it in the annealer at ~920 °F, slowly ramping the temperature down to avoid stress fractures or cracks. I then cold-worked the 44 bricks to remove the non-brick necks using a circular diamond saw blade. Bricks were transported and installed as *Pre-Migration Wishing Well* at Sevilleta National Wildlife Refuge, New Mexico (Figures 3-1 and 3-2).

3.2.2 *An Offering After Drought* and *Burning House Reincarnated*: Mold-making and Lost Wax Kiln Casting

In general, I used the lost-wax kiln casting technique to create glass Gray Vireo nests, fledglings, and *An Offering After Drought* (Figures 3-3: 3-6; see Figure 3-7 for process photos). I used mold-grade rubber to create molds of fledgling Gray Vireo wax positives, juniper branches, and a Gray Vireo nest. I poured hot wax (~170-190 °F) into these rubber molds to generate multiple wax positives for sculpting purposes. I manipulated the wax models to the desirable forms (i.e., fledglings, nests, and *An Offering After Drought*) and added sprues to the final wax models. I then created plaster-silica-based investments (i.e., refractory molds), which consisted of plaster powder, silica powder, and water in equal ratios, with “grog” (i.e., sand or ground ceramic for additional mold stability) in the outer two layers, which altogether form “investment” when mixed. I added investment in three layers around each wax model and, once dry, steamed out the wax, forming a cavity for molten glass flow. I used a water displacement technique to estimate the mass of cullet glass (i.e., cristalica) needed to fill each investment mold (for *Nests* and fledglings). For *An Offering After Drought*, I used molten furnace glass billets instead of cold glass cullet due to the large investment mold size. I used kiln firing schedules (created by A.N. Hoag) that ramped up to 1575 °F to accommodate thin glass details, especially in the nests and fledglings. After firing, I divested glass from the plaster-silica investments and cold-worked each piece using a diamond saw to remove the sprue, and other tools, such as a lathe and rotary tool, to remove unwanted material (e.g., leftover plaster, glass deformities) and polish the final pieces.

I installed *An Offering After Drought* on the Sevilleta National Wildlife Refuge amongst the land that prompted its creation. I was interested in creating a nonhuman collaboration, allowing animals and abiotic processes to act as active viewers and participants. I installed a trail camera to document animal encounters and environmental cues (e.g., wind) that caused the motion sensor to capture images (Figure 3-5).

3.3 *Molt* Artist Statement

Under capitalism, we exploit and “Other” both bodies and the environment, reducing these “Others” (e.g., queer bodies and/or people of color, songbirds, trees, etc.) to mere commodities. Simultaneously we have forced our understanding of sex, gender, and discipline into binary boxes, effectively “Othering” the in-betweens (e.g., gender non-conforming and trans- people, nonhumans, multidisciplinary ArtScience, etc.). However, nature and discipline do not dwell in the binary, but along spectrums. Because of our commodification of nonhuman animals, plants, and land, the global climate is changing, and consequently species diversity is shrinking via biological annihilation. Future climate projections predict a hotter, drier, and less predictable world (especially in arid lands), with potentially dire consequences for many species and people, especially "Others".

I see the Gray Vireo (*Vireo vicinior*), a drab and under-studied arid land migratory songbird, and the habitats they occupy (e.g., piñon-juniper savannas and elephant tree deserts) as examples that mirror the way we tend to "Other" bodies and identities different than our own. Gray Vireos generally breed in overlooked, remote habitats across the southwestern USA and northwestern Mexico and migrate to rugged nonbreeding sites primarily along the Baja Peninsula and mainland Mexico within the Sonoran Desert. Migration, in a sense, is about returning and homecoming. The urge to migrate can be felt in the body in the form of anxious restlessness (i.e., *zugunruhe*), induced by the endocrine system (e.g., hormonal changes). Prior to and even during these migrations, Gray Vireos and other migratory songbirds must prepare for their journeys.

*Molt*ing by definition is a profound disturbance of endogenous metabolism, a process wherein animals shed worn tissue, such as feathers, hair, and exoskeletons, that is often prompted by life cycle stages such as the transition from breeding season to migration. In the series *Molt*, I use process as memorial to draw parallels between my transition through hormone replacement therapy (i.e., testosterone) as a queer, transsexual person and the transition between annual life cycle stages that many migratory songbirds, such as Gray Vireos, undergo. Both avian migration and testosterone injections cause profound physiological changes, or *molting*, of the past, and both involve repeated "homecoming". I use my ecological research on Gray Vireos as visual metaphors with multimedia techniques in glassblowing, kiln casting, drawing, and printmaking, to explore gender and queerness while engaging viewers with wildlife science and conservation. This series, *Molt*, exists at the tension point of our tendency to force the notion of binary on gender and discipline. *Molt* is a transgressive ritual intervention, an offering of sorts, that argues against the binary and is ultimately both a memorial to the former and an ushering-in of new futures.

Figure 3-1: *Pre-Migration Wishing Well*, 2019-2020, 30 x 30 x 25 in., blown glass bricks. Created at Bowling Green State University, Bowling Green, OH; installed at Sevilleta National Wildlife Refuge, New Mexico. (© Silas Fischer)

Figure 3-2: Detail photos of *Pre-Migration Wishing Well,* 2019-2020, blown glass bricks. Created at Bowling Green State University, Bowling Green, OH; installed at Sevilleta National Wildlife Refuge, New Mexico. (© Silas Fischer)

Figure 3-3: *An Offering After Drought*, 2019-2020, 24 x 24 x 1 in., kiln cast glass. Created at Bowling Green State University, Bowling Green, OH; installed at Sevilleta National Wildlife Refuge, New Mexico. (© Silas Fischer)

Figure 3-4: Detail photos of *An Offering After Drought*, including examples of individual Gray Vireo fledgling castings incorporated into the final sculpture. 2019-2020, kiln cast glass. Created at Bowling Green State University, Bowling Green, OH; installed at Sevilleta National Wildlife Refuge, New Mexico. (© Silas Fischer)

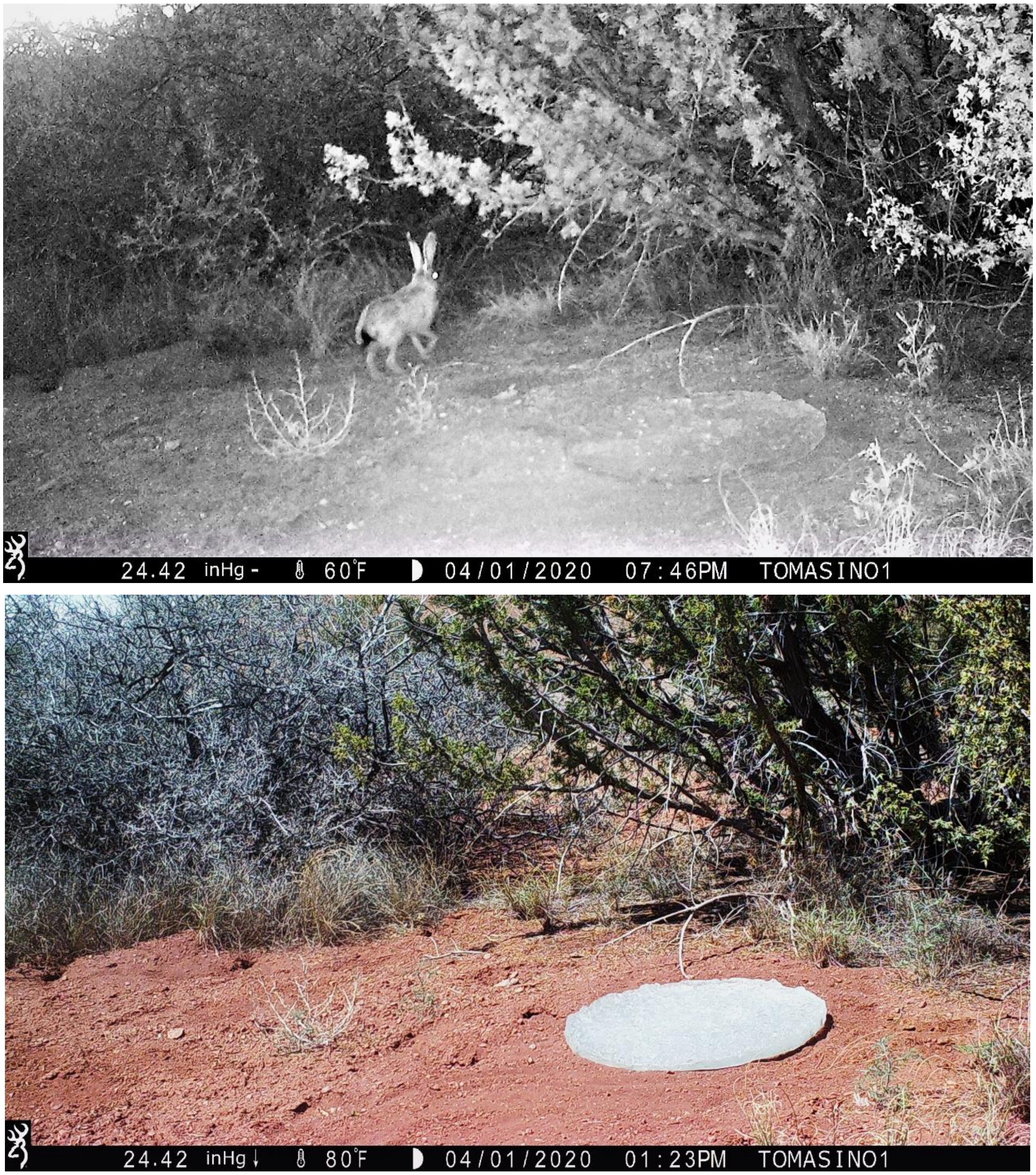

Figure 3-5: Motion-activated trail camera photos from 01 April, 2020, of *An Offering After Drought*, 2019-2020, variable dimensions, kiln cast glass, trail camera, and animal and abiotic participants. Created at Bowling Green State University, Bowling Green, OH; installed at Sevilleta National Wildlife Refuge, New Mexico. (© Silas Fischer)

Figure 3-6: *Burning House Reincarnated* (*Homage to Wojnarowicz*), 2019-2020, kiln cast glass and oneseed juniper tree. Created at Bowling Green State University, Bowling Green, OH; installed at Sevilleta National Wildlife Refuge, New Mexico. (© Silas Fischer)

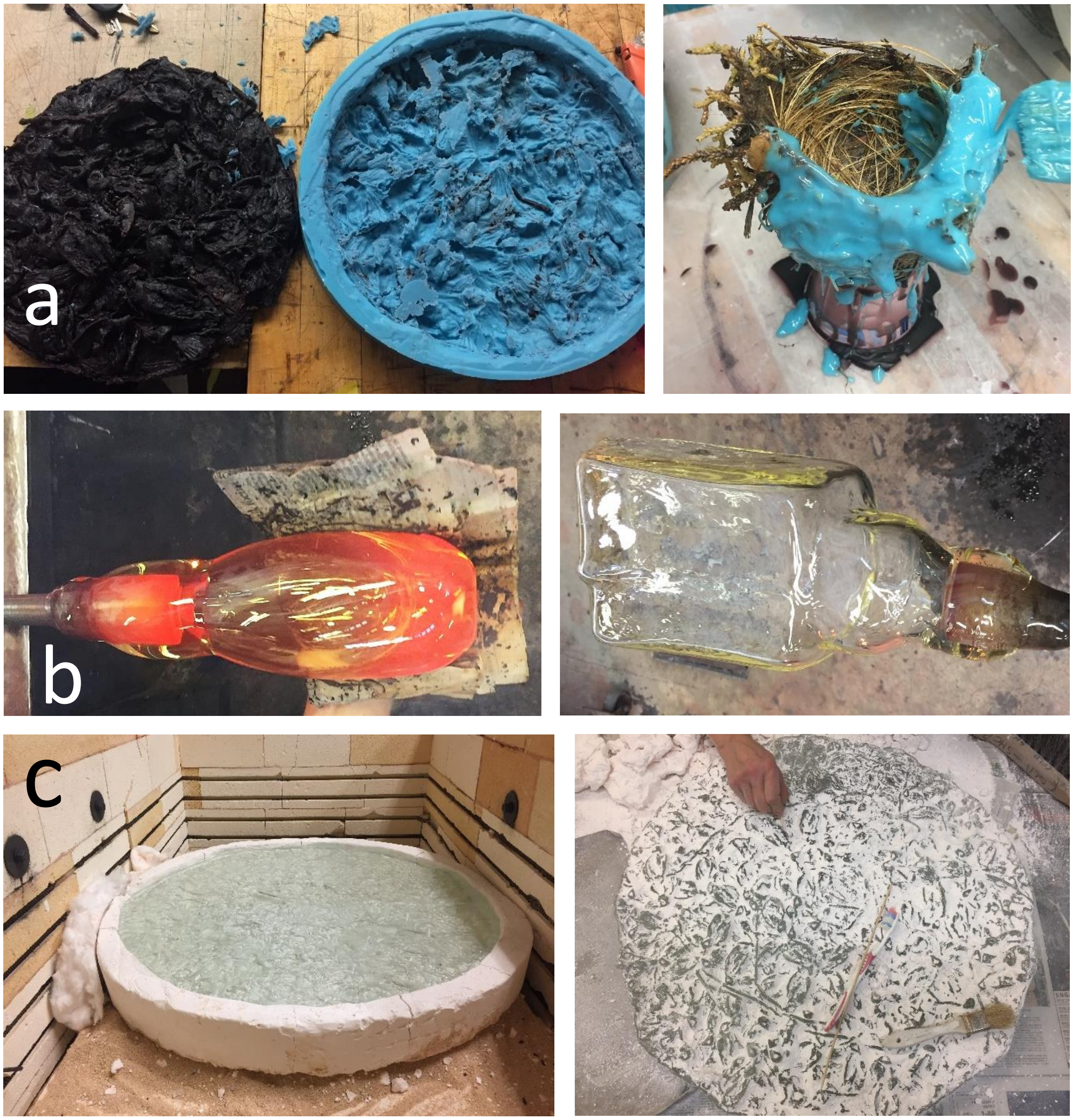

Figure 3-7 Process photos from *Molt* series using techniques in mold-making (a), glassblowing (b), and lost-wax kiln casting (c). (© Silas Fischer)

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